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METEOROLOGY AND AGROFORESTRY

W. S. Reifsnyder
and
T. O. Darnhofer
(Editors)

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METEOROLOGY AND AGROFORESTRY

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International Workshop on

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Preface

On 9 February 1987, more than sixty scientists from around the world gathered in Nairobi to discuss the role that the atmospheric sciences could play (and have played) in the development and practice of agroforestry. The meeting was hosted by the International Council for Research in Agroforestry (ICRAF) and co-sponsored by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP).

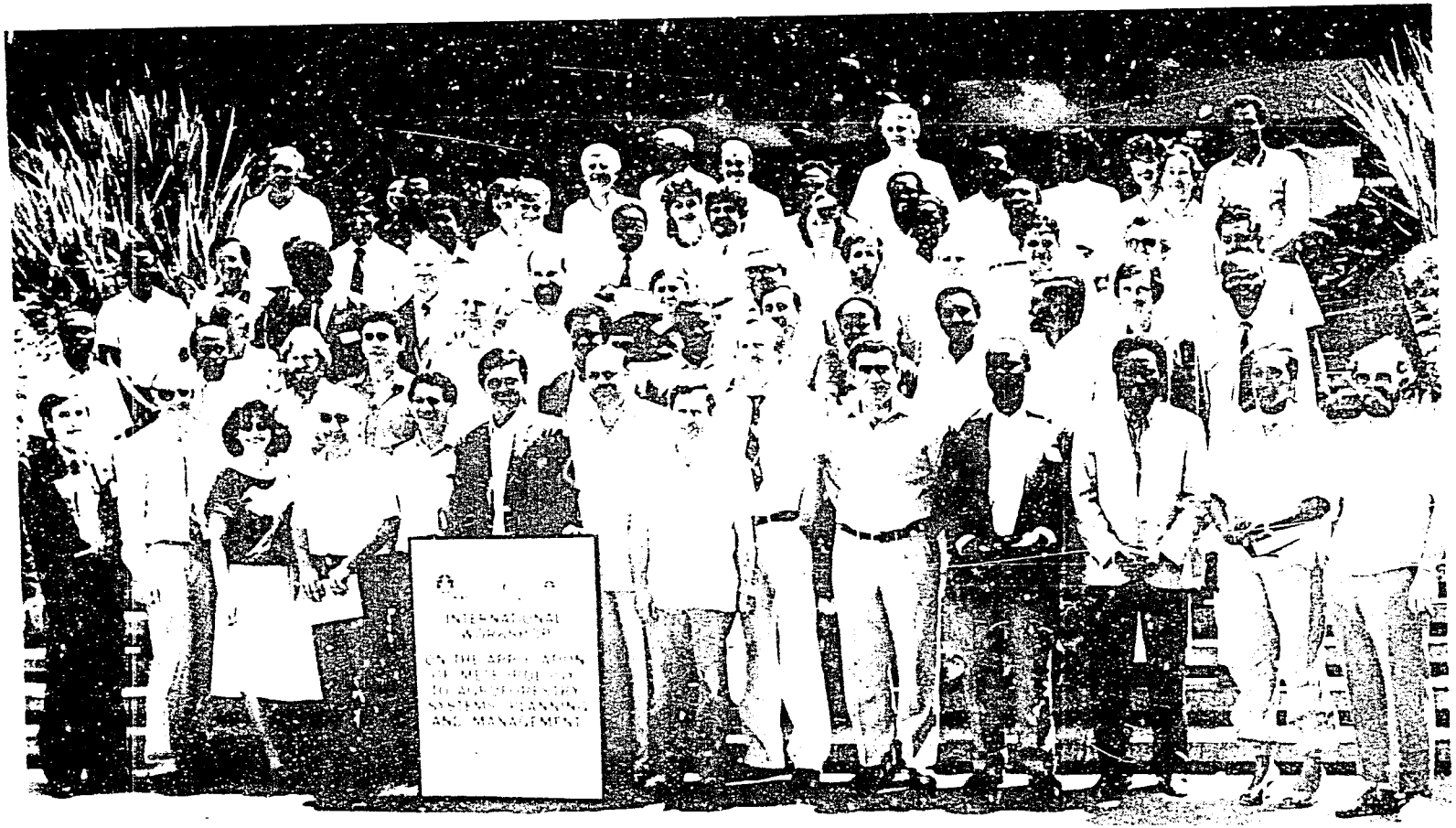
Fifty of the papers prepared for the conference are in these proceedings. The first three chapters provide an introduction to the relationship between the environment and agroforestry. The next six chapters present information basic to understanding how meteorology and climatology can be used in agroforestry systems. The next fifteen, fully one-third of the book tell how meteorology and climatology have been integrated into agroforestry practice around the world; or, in many cases, how they could or should be so integrated. Following are nine technical papers that discuss in useful detail ways that the environment can be measured, how experiments can be designed, and how they can be analyzed to elicit useful information. Nine more chapters give the results of various agroforestry experiments, most of them conducted by ICRAF scientists. Three papers that give the results of experiments involving animals are presesented as a group, as are three experiments involving windbreaks.

Two themes are apparent in this assembly of papers: the first is that there is intense interest on the part of the agroforestry community over how knowledge of the atmospheric sciences can contribute to agroforestry practice; and second, how little hard information exists at present. Most basic information comes from experiments and measurements in the temperate zone. Some of this may be transportable to tropical regions with little or no adaptation. However, much cannot. Many of the papers address this problem; but it is clear that much remains to be done in adapting existing knowledge to the practice of agroforestry in tropical regions.

Thus one finishes reading these papers with some sense of frustration: there is a lot of information out there, but how can we assemble it, test it, and apply it to agroforestry systems? The task is daunting, but the encouraging result of the conference and the proceedings is that there are many people and organizations working hard to bring this about. It is the hope of the sponsors, the participants, and the organizers of the conference (and the editor as well!) that this volume will be not only a compendium of useful information, but also a goad to scientists and administrators throughout the world to increase research activity on the role of meteorology and climatology in agroforestry practice.

Editing this volume has been a rewarding educational experience for me. Some authors may have felt that I wielded the editor's red pencil too heavily. My excuse is that I have tried to enforce some consistency of style on papers, many of which were written by scientists whose native language is not English. I also did most of the copy-editing and thus am responsible for errors. The staff of ICRAF, and especially Dr. Till Darnhofer, spent many hours in helping the publication process along. Without their prodigious efforts, there would have been no conference and no proceedings.

William E. Reifsnyder
Questa, New Mexico, January 1989


INTERNATIONAL
ON THE APPLICATION
SYSTEMS PLANNING
AND MANAGEMENT

Participants

Mr. M. A-AS-SAQUI
Ministry of Agriculture
P.O. Box 3929
Monrovia
LIBERIA

Mr. A.L. ALUSA
Director Kenya Met. Department
P.O. Box 30259
Nairobi
KENYA

Pastor J. AUMA
Evangelical Fellowship of Kenya
P.O. Box 465
Homa Bay
KENYA

Dr. T.H. BOOTH
CSIRO Queen Victoria Terrace GPO
Box 4008
Canberra ACT 2600
AUSTRALIA

Miss J. CORLETT
ICRISAT Patancheru P.O.
Andhra Pradesh 502 324
INDIA

Dr. G. DE LAS SALAS
Consultant on Agroforestry
Apartado aereo 12803
Bogota
COLOMBIA

Miss T. DEANE DE ABREU SA
DINIZ
Agroclimatologist
EMBRAPA/CPATU C.P.48
Belem Para
BRAZIL

Dr. I.P. ABROL
ICAR, Krishi Bhawan
Dr. Rajendra Prasad Road
New Delhi - 1
INDIA

Dr. A. AMIN
Pakistan Agriculture Research Council
L-13, Almarkaz,
P.O. Box 1031
Islamabad
PAKISTAN

Mr. F. BARROSO PEQUIVEN
Carretera Moron-Coro
Apartado No.66
Moron
VENEZUELA

Prof. D.J. CONNOR
University of Melbourne
Department of Agriculture
Parkville
Victoria 3052
AUSTRALIA

Dr. C.L. COULSON
Department of Crop Science
University of Nairobi
P.O. Box 30197
Nairobi
KENYA

Mr. H.A. D'SOUZA
Agriculture Development Corporation
P.O. Box 47101
Nairobi
KENYA

Dr. M. DICKO
Directeur Projet Apiculture
BP 2057
Bamako
MALI

Mr. P.C. ESPINDOLA FROTA
Agroclimatologist
R. Samuel Ucnoa 969
60000 Fortelaza Ceara
BRAZIL

Mr. G. GUYOT
INRA Station de Bioclimatologie
B.P. 91 Domaine St. Paul
84140 MONTFAVET
FRANCE

Mr. A. HAMID
c/o JARDP
P.O. Box 9025
Khartoum
SUDAN

Mr. A.K.S.HUDA
ICRISAT
Patancheru P.O.
Andhra Pradesh 502324
INDIA

Dr. P. HUTCHINSON
c/o EEC Delegation
P.O. Box 943
Mogadishu
SOMALIA

Mr. R. KEDIR
Energy Development International
P.O. Box 62360
Nairobi
KENYA

Mr. M. KONATE
Direction, Météorologie Nationale
B.P. 237
Bamako
MALI

Mr. L.I. LEONTIADES
Director Dept. of Forests
Ministry of Agriculture
Nicosia
CYPRUS

Mr. A. GETAHUN
International Council for Research in Agroforestry
P.O. Box 30677
Nairobi
KENYA

Prof. M. HARIDASAN
Dept. de Biologia Vegetal
Universidade de Brasilia
C.P.152790
Brasilia D.F.70.910
BRAZIL

Prof. A. HOCEVAR
Univerza Edvarda Kardelja v Ljubljani
61000 Ljubljana
Jamnikarjeva 101
YUGOSLAVIA

Prof. S. HUOVILA
Vourikatu 24
Box 503
SF-00101 Helsinki
FINLAND

Prof. J.E. JACKSON
East Malling Research St.
East Malling Maidstone ME19 6BJ
Kent
GREAT BRITAIN

Prof. Dr. M.A. KISHK
Soil Science Department
Faculty of Agriculture Minia University
Minia
EGYPT

Dr. S. LANGTON
Rothamsted Exp. Station
Harpenden,
Herts AL52JQ
GREAT BRITAIN

Mr. H.P. LINIGER
Coop. Tech. Swiss
P.O. Box 144
Nanyuki,
KENYA

Mr. H. LOVENSTEIN
Desert Run-off Farms Unit
Jacob Blaustein Inststitut for
Desert Research
Ben Gurion Univ. of the Negev
Sede Bager Campus 84990
ISRAEL

Mr. P. MBUTHI
Kenya Renewable Energy Development
Programme
P.O. Box 21552
Nairobi
KENYA

Mr. P.M. MUNG'ALA
The Kenya Woodfuel
Development Programme
The Beijer Institute
P.O. Box 56212
Nairobi
KENYA

Mr. S.H. MWANDOTO
Meteorologist
Kenya Meteorological Department P.O.
Box 30259
Nairobi
KENYA

Dr. S. NEWMAN
Open University
Walton Hall
Milton Keynes MK76AA
GREAT BRITAIN

Mr. A. NIANG
SAFGRAD c/o ICRAF
P.O. Box 30677
Nairobi
KENYA

Mr. C. OBAGA
Tea Research Foundation of Kenya P.O.
Box 820
Kericho
KENYA

Mr. N.M. MAJID
Faculty of Forestry
Universiti Pertanian Malaysia
43400 Serdang
Selangor
MALAYSIA

Dr. W. MIGONGO-BAKE
SAFGRAD c/o ICRAF
P.O. Box 30677
Nairobi
KENYA

Mr. D.N. MUNGAI
University of Nairobi
P.O. Box 30197
Nairobi
KENYA

Mr. M. NEGASH
Agro-Ecologist
Land Use Planning Department
Ministry of Agriculture
P.O. Box 5580
Addis Ababa
ETHIOPIA

Mr. NGO SI GIAI
Hydromet.
Serv. of Biet No.4
Dang Thai Than
Hanoi
VIETNAM

Dr. K.W. NYAMAPFENE
Head Dep. of Land Management
University of Zimbabwe
P.O. MP 167
Harare
ZIMBABWE

Dr. C. ONG
Principal Agronomist
ICRISAT Patancheru P.O.
Andhra PRADESH 502 324
INDIA

Mr. P.K. ONNO
National Met. Service
P.O. Box 1240
Boroko
PAPUA NEW GUINEA

Dr. A.B. OGUNTALA
Principal School of Forestry
Forestry Research Institute of Nigeria
Private Mail Bag 5054
Ibadan
NIGERIA

Mr. P. PIETROWICZ
GTZ
P.O. Box 41607
Nairobi
KENYA

Prof. W.E. REIFSNYDER
Yale University
School of Forestry
Marsh Hall-360
Prospect Str
New Haven 06511 CT
USA

Miss J. RILEY
Rothamsted Exp. Sta.
Herpenden
Herts AL5 2JQ
GREAT BRITAIN

Mr. B.P. SAPITULA
Agroforestry Department
Don M. Marcos M. University
Bacnotan
La Union
PHILIPPINES

Mr. R.K. SHUMA
The Kenya Woodfuel
Development Programme
The Beijer Institute
P.O. Box 56212
Nairobi
KENYA

Dr. R. OTSYINA
SAFGRAD c/o ICRAF
P.O. Box 30677
Nairobi
KENYA

Mme A. PERRIER DE LA BATHIE
Consultant
ICRAF
P.O. Box 30677
Nairobi
KENYA

Mr. F. QUESADA
Institutional Coordinator CATIE
Av.7 C.15y 17, Casa #1561
San Jose
COSTA RICA

Dr. D. RIJKS
WMO Geneva
41 Giuseppe-Motta
Case Postale No 5
CH-1211 Geneve 20
SWITZERLAND

Mr. C. RIOU
INRA
Centre de Recherches de Bordeaux B.P.
131 3140
Point de la Maye
FRANCE

Dr. P.S.N. SASTRY
Senior Scientist
Agriculture Meteorology
Indian Agricultural Research Institute
New Delhi - 110012
INDIA

Prof. C. SREEDHARAN
College of Horticulture
Vallanikkara
Trichur 680654
Kerala
INDIA

Prof. C.J. STIGTER
TTMI Visiting Professor
Department of Physics/Meteorology
6701 AP Wageningen
Duivendaal 1
Wageningen
THE NETHERLANDS

Mr. C.G.B. TIBANYENDA
Directorate of Meteorology
P.O. Box 3056
Dar es Salaam
TANZANIA

Mr. Y. ZOHAR
Dept of Nat Res (Forestry Sec)
Agricultural Research
Org The Volcani Centre
P.O. Box 6
Bet Dagan 50250
ISRAEL

Mr. S. TEWUNGWA
UNEP
P.O. Box 30552
Nairobi
KENYA

Mr. V. YELISETTY
Ministerio da Ciencia e Tech
Inst de Pesquisas Espaciais
Av Dos Astronautas 1758
CX Postal 515
12201 - San Jose Dos Campos - SP
BRASIL

ICRAF STAFF MEMBERS
P.O.Box 30677
Nairobi,
KENYA

Dr. E. AKEAMPONG
Mr. E. AKUNDA
Mr. J. BASHIR
Dr. M. BAUMER
Mr. P.v.CARLOWITZ
Dr. T. DARNHOFER
Mr. D. DEPOMMIER
Dr. M. DJIMDE
Mr. D. GATAMA
Dr. P.A. HUXLEY
Dr. F. KWESIGA
Dr. B. LUNDGREN
Dr. P.K.R. NAIR
Prof. D. NGUGI
Mr. P. ODOUL
Dr. S. SCHERR
Mr. G. WOLF
Prof. A. YOUNG

Synthesis and recommendations

The following conclusions and recommendations were formulated as a synthesis of the discussions following the presentation of the papers and of the reports by the five working groups.

General

1) The Workshop recommends that all development of methods and all collection of data take account of the multidisciplinary nature of agroforestry and that maximum benefit be obtained from the contributions of the different disciplines involved. It also recommends that for all research and all applications of the results of the research, thorough considerations be given to the different scales in space and time and that socio-economic aspects of agroforestry interventions must not be ignored.

Information requirements

2) The Workshop recommends that the ranges of different climatic parameters and conditions (climatic profiles), both for survival of specific components and for their relatively successful performance, be determined for the most prominent woody species. It furthermore recommends that the component requirements be combined into system requirements.

3) The Workshop recommends that site-specific macro climatic conditions, as they are relevant to agroforestry components and systems, be determined.

4) The Workshop recommends that further quantification be made of aspects of existing techniques of microclimate management and manipulation in agroforestry, to assist the development of viable systems and practices.

Methods and techniques in agroforestry

5) The Workshop recommends that the existing environmental data bases be extended with further specific data needed in different agroforestry techniques.

6) The Workshop recommends that as a preliminary activity, available models of component processes be collected and tested. The methodology for comprehensive models for agroforestry should be developed.

7) The Workshop recommends that further studies be made of tree/crop interfaces, notably of processes and co-production functions under different management.

8) The Workshop made the following recommendations regarding the design of experiments:

   – that designs should take the results of preliminary model tests into account
   – that designs should aim both to measure environmental conditions and test solutions

- that the advantages of 'systematic' and 'traditional' designs should be considered, especially in preliminary screening
- that new designs are required for use in agroforestry
- that plot size considerations should also include:length of data run; number of treatments; number of replications; nature of climatic and biological parameters to be measured; soil variability; outside environmental factors
- that the number of treatments should be limited if extensive environmental observations are to be collected
- that on-station trials should be complemented by on-farm trials
- that the biological responses should be measured not only in 'laboratory/scientific' terms but also in terms of farmers' acceptability.

9) The Workshop recommends that all improved techniques should be evaluated for specificity to area, site, season and system.

10) The Workshop recommends that long term observation plots be set up for monitoring the impact of climate on soil degradation and for the development and testing of management techniques to prevent and reduce such degradation.

Data collection

11) The Workshop recommends that all data collection be made towards specific objectives, to avoid the collection of unneccessary data.

12) The Workshop recommends that guidelines be prepared both for meteorological and biological data sets required by different models.

13) The Workshop recommends that techniques for generating climatic data from existing sets in different formats, required by models for assessing long term impacts of agroforestry interventions, be made available.

14) The Workshop recommends that as a minimum the following daily climatic data: maximum and minimum temperature, rainfall, humidity and evaporation be collected, and that if possible wind speed and direction, solar radiation, soil and plant temperature, and soil and plant water balance be estimated.

15) The Workshop recommends that the WMO Commission for Instruments and Observations promotes the development of appropriate instruments, that give few or no operational problems in field conditions, for the measurement of the parameters mentioned in Recommendation 14; that this includes equipment from the most simple instruments to data loggers; that training be given in their proper use and maintenance; and that the equipment or the capacity to produce it be provided to developing countries.

16) The Workshop recommends that quantitative equations be refined for the measurement of soil losses as influenced by weather (especially rainfall, wind) and land-use management techniques.

17) The Workshop recommends that the potential of using operational remote sensing techniques in agroforestry be actively explored.

Application of research

18) The Workshop recommends that techniques to match agroforestry components and system requirements to known and described climatic conditions be actively developed and applied.

19) The Workshop recommends that the research in agroforestry in semi-arid and arid zones includes aspects of water harvesting systems.

20) The Workshop recommends that in all agroforestry research due attention be paid to the influence of climate on the development of pests, plant/animal diseases and birds damage.

Dissemination of information

21) The Workshop recommends the publication of:

- an inventory of data analysis methods
- an inventory of available appropriate instrumentation
- an inventory of available models used in agroforestry with a comparative study of the different models
- a study on the agrometeorology of trees as a component in agroforestry systems
- an inventory and annotated bibliography on wind break studies relevant to agroforestry interventions
- guidelines to use agroforestry techniques to reduce or prevent soil degradation.

22) The Workshop recommends that, where possible, simulation programmes be made available on diskettes or in other computer usable form.

23) The Workshop recommends that extension agents, agricultural development personnel etc. be associated with on-farm trials and demonstrations, preferably where farmers will have a major role.

Feedback on technical and economic value

24) The Workshop recommends that the assessment of the value of proposed agroforestry systems takes account of the sustainability of the system, and of the long-term effects on the yield of both annual and perennial crops; that these considerations should cover the modification at both meso- and micro-scale; that both short-term and long-term cost/benefit analyses be made.

Training

25) The Workshop recommends that, jointly with all organizations concerned, training in the assessement, proper use and maintenance of equipment be organized in developing countries, together with training in quality analysis of the data obtained with this equipment.

Working group reports

REPORT OF WORKING GROUP I

Macroclimatic aspects for the preselection of agroforestry systems and components

With regard to the preselection of agroforestry systems and components, macroclimatic () aspects should be considered with reference to the following:

1. Objectives

a) **Definition of the information and methods necessary to determine climatic component () requirements.**
In a first approach the
- climatic range for component survival has to be defined and in the second, information on the
- range of relatively successful component performance has to be included.

subsequently it is important to
- combine component requirements into system requirements

b) **Definition of site-specific climatic conditions relevant to agroforestry system and component selection.**
This can be achieved by
- using existing climatic or agroclimatic classifications (which although often not satisfactory, do have their recognized merits)

or by
- exploiting the possibility of 'purpose-specific' classifications using modern technologies such as computers and remote-sensing.

2. Implementation of methodologies

a) **Parameters and datasets required**
A first assessment of a 'minimum dataset' includes the following informations and parameters:
- Basic Geographical Data (latitude, longitude, altitude)
- Temperature
  Maximum air temperature; monthly and 10-day means
  Minimum air temperature; monthly 10-day means
  Absolute minimum temperature

'Macroclimatic' scale see WMO guide

'Components' = agroforestry components (woody plant species, crops, pasture grasses, animals). In the present context special reference is made to woody species.

- Rainfall
  - Monthly and 10-day totals
  - Number of rain days
  - Rainfall intensity
- Sunshine
  - Monthly and 10-day duration
- Air Humidity
- Wind
- Evaporation (+ method)

b) **Measurements**
- as by WMO Guidelines
- current remote-sensing techniques

c) **Data Processing**
- As no general data-processing standards exist an inventory of wider used methods should be established.
- The development of analysis methods, and especially those which allow the computerized modeling of 'purpose-specific' classifications, should be monitored and promoted.
- Tested data analysis techniques should be published in appropriate journals.

d) **Data and analysis presentation**
- Reports, graphs, maps
- Computer-compatible supports

e) **Matching component requirements and climatic conditions**
The matching of available information on tree requirements and given climatic con ditions can most effectively by computerized methods. However any traditional methods such as graphical and manual comparison could also be used if necessary. (Reiterative methods will contribute to the refinement and improvement of a chosen approach.)

f) **Establish climatic tree profiles**
- Analysis of the climatic conditions in the natural distribution areas of a given tree species
- Improvement of these requirement profiles with information as it becomes available in field trials
- Phenological, physiological and other performance observations.

3. Recommendations

a) **Establish the agrometeorological requirements of trees with an agroforestry potential**
- Describe the upper and lower climatic conditions for survival and for relative successful performance for a shortlist of multipurpose trees in the 4 major ecological zones of the tropics, using information available in literature and in various data bases.

b) **Collaborate with appropriate institutions to establish climatic 'surfaces' to characterize conditions suitable for af systems and components.**

c) **Promote actively the development of techniques to match component requirements to given climatic conditions.**

REPORT OF WORKING GROUP II

Assessment of the environmental impact of agroforestry interventions

1. Preliminary modeling

Modeling as a preliminary activity is more necessary in agroforestry research than it is in sole-crop systems. In agroforestry, a purely experimental approach without preliminary assessment of the literature and sieving of ideas for field trials within a modeling framework would be exessively expensive in time and resources because:

- The units (individual treatment plots) in agroforestry are very large,
- the time-scale is considerable because of the life span of trees,
- the complex nature of agroforestry (trees and crops) leads to a very great number of possible arrangements in space and time.

The process of constructing, validating and using the models in itself involves a very critical search of the literature, identification of missing information and therefore of new directions of future research.

At the present the models that are of the greatest direct use are sub-models of processes in agroforestry systems, particularly those of light interception and of water use. These models should be identified, their value assessed against current available problems and available data and made generally available in user-friendly forms.

Although at this stage of the development of agroforestry research the sub-models of component process developed in agriculture and horticultural research are likely to be the most immediately useful – e.g. those of the effects of light interception on intercrops in relation to tree size, spacing and orientation – attention should be paid to the development of comprehensive models of agroforestry systems. Such models will concentrate on the interaction between component processes e.g. between light, water, nutrients and management. Attention needs to be given to appropriate structures for such models and the level of detail required relative to individual problems and to the current understanding of the component processes. Crop modeling research is now beginning to use the expert systems approach, a technique which has much promise for the complex interactions of agroforestry systems. It provides a logical scheme for the selection and integration of sub-models of appropriate detail and precision from the set of currently available alternatives.

2. Design of agroforestry studies and experiments

Initial discussion centred upon the role of observation versus experimentation. It was generally acknowledged that much agroforestry investigation is still at the observation stage because there remains great uncertainty about the performance of combinations of species at different sites and at different stages of growth.

The purpose of experimentation was established to clarify the discussions. Experimentation is both for the estimation of the magnitude of effects as well as for the testing of hypotheses. Randomisation and replication are essential for either objective.

The discussion of experimental design concentrated on the relative utility of systematic versus traditional and upon 'new' designs in the following way:

a) Systematic designs

These designs were acknowledged as powerful exploratory tools in agroforestry research - more so than in crop experimentation since the large size of individual trees could be accommodated easily at each point of a systematic grid. Systematic designs are best suited to screen a wide range of spacings of given tree/crop combinations. From this range a few can then be selected for further, possibly more detailed, study.

Problems do exist with such designs however. Since trees live for many years it is necessary to monitor such experiments for an appreciable period until the response of trees to spacing can be fully established. Replication is required to avoid bias caused by trends and other directional effects. The value of each individual tree in a systematic design was stressed as being vital compared to those in, say, a randomized block design. The loss of a single tree in a systematic design alters the spacing of the neighbouring trees. Early replacement with material of equivalent genotype and age should be made when possible.

The types of systematic designs, viz. parallel and simple diagonal row designs, were discussed. No single design was accepted as being fully appropriate for agroforestry investigations although the parallel row design was seen to be particularly useful because of the ease of its modification to incorporate secondary treatments, such as fertilizer treatments or management strategies.

Statistical guidelines are required to enable systematic designs to be used effectively, particularly to give information about the choice of the range of treatments and the required spacings.

Information is available in the literature about suitable systematic designs for annual crops but little or none is currently available for agroforestry experiments. Guidelines may be available from experiments with trees in horticulture or forestry and assistance can be expected from process models of tree response e.g. light, wind and water use.

b) Traditional designs

These were proposed for the second stage of experimentation once a small selection of spacing treatments and crop combinations had been established. Traditional designs, viz. randomized blocks, latin squares etc., are robust designs which have been used successfully for experimentation with annual crops. Discussion centred on the size of plots. It was accepted that plots and hence agroforestry experiments would of necessity be large. However, no conclusions were possible because of the need to establish the species involved and the inherent variability of the plants and soil at particular sites. Emphasis was again made of the need for recommendations for the use of traditional designs in agroforestry research. The horticultural literature is a potential source of such information.

c) New designs

The group expressed the hope that 'new' designs specifically appropriate for agroforestry might be developed. No specific directions emerged although the use of nearest neighbour analysis was suggested and discussed. The special need for designs appropriate to the study of multi-layer agroforestry systems was acknowledged.

3. Tree/crop interface

The basic unit of all agroforestry systems is the combination of woody and non-woody species. The study of the interaction can be made at two scales of aggregation:

- the interface of individual trees with harbaceous plants, and
- the interface between blocks of trees and the herbaceous component.

The study of the tree/crop interface is an important starting point. ICRAF's Design and Diagnosis Methodology is useful and should be consulted at this stage.

There are so many combinations of interfaces that observation will probably precede experimentation. Small exploratory trials are valuable; and once again models, such as those of light and shade, should be useful in designing appropriate experiments.

Interface experiments are made at two levels:

- Development of co-production functions of the component species which can then be used directly for the design of many varied systems involving these components; and
- Experiments including micrometeorological observations which provide an understanding of the competitive and complementary interactions and hence for the more general design of interfaces in agroforestry systems.

Experiments with interfaces must be replicated and include directional variability where appropriate. Directional variability will not be a possibility in some systems, e.g. on sloping land.

Experiment with interfaces should include and specify the management variables. This is particularly important with respect to the tree component which has the opportunity to dominate the system.

The information already available and the understanding that has been developed of the performance of windbreaks is an essential starting point in the design of block interface experiments.

There is a need to acknowledge that interface systems and their study will involve more than just plant-plant inter- actions. Their establishment will introduce other biotic considerations – diseases and pests of many kinds (birds, insects etc).

To date there are no experimental designs suitable for multi-strata systems. The extent to which they can be studied separately and combined is unknown.

4. Models as tools for assessment of alternative arrangements, productivity, stability and environmental impact

It was acknowledged that models, particularly comprehensive models, will play an important role in the prediction of the long term impact – individual, regional and global – of agroforestry systems. Their development is a goal which will not, however, be quickly achieved. Crop models are potential components of agroforestry models and although simpler and relatively well advanced are not yet used convincingly as predictive tools. Discussion of the available models of the wheat crop, for example, acknowledged their use in assessing the response of the crop to production strategies, weather and climatic change. Such studies provide a valuable glimpse of the possibilities of models for the assessment of agroforestry systems.

Whilst the development of comprehensive predictive models is a long term goal it was again agreed that in the meantime individual process models can play an important role not only in the design of agroforestry systems but also in the prediction of their performance.

The ultimate use of models of agroforestry systems to assess environmental impact will require a good coverage of climatic and other site specific data. The preparation of data banks or, in the case of climatic data, of weather-generating models, should not await the availability of the models themselves because they can be put to other, e.g. classificatory uses, in the meantime.

REPORT OF WORKING GROUP III

Environmental monitoring for agroforestry experiments and interventions

The working group comprised of eleven participants from seven countries representing the disciplines of agrometeorology, agroforestry, agronomy, statistics and crop physiology. Consensus was reached on practically all major issues discussed and the recommendations are divided into the following sections:

1. Main objectives for environmental monitoring
2. Guidelines and considerations for field experiments
3. Hardware and measurement techniques for wind speed, humidity, temperature, radiation, soil moisture
4. Data loggers - current status and cost-effectiveness
5. Sampling procedures and data handling
6. Interpretations
7. Training needs

1. Main objectives for environmental monitoring

The main objectives for environmental monitoring for agroforestry experiments are concerned with the modification of the environment at the meso or micro level by the presence of trees and how this may affect the yield of the understorey crops or vegetation. Modification of both the above- and below-ground environment should be considered. Such information is required for the modeling of agroforestry systems, the sustainability of production and the interaction between trees and crops.

2. Guidelines and considerations for field experiments

- The selection of a site which is close to a long established meteorological station with say 30 years of continuous data is essential so that a base line information is available for comparison with future trends in agroforestry systems.
- Also the guideline for plot size will depend on the dominant environmental factor likely to be modified by the presence of trees. For example, where windspeed is the dominant factor the fetch should be 10x to 20x the maximum height of the vegetation. However, if the main modification is rain interception then the diameter of the measurement area should be approximately twice the height of the trees. The optimum plot size for agroforestry therefore decreases in the following order of environmental variables: wind, humidity, temperature, light. Of course, a reduction in wind speed and an increase in radiation will tend to increase the radiation load.
- In the first attempt the treatment should be reduced to the minimum of two, say crop with or without trees as plot size may be quite large and the minimum requirement for hardware may be a constraint. Replications of measurement in space is also highly recommended.

- Soil problems: Large variation in soil physical and chemical properties is common in many areas and such inherent variability should be avoided or accounted for by appropriate statistical designs. A good knowledge of soil variability could be obtained by using a cover crop prior to the laying out of the agroforestry plot. Common soil differences are due to changes in depth, fertility and pH.

3. Hardware and measurement techniques see (*)

a) Wind speed

Cup anemometers are widely used but they only pick up wind above 60° cm/sec therefore sonic or hot wire anemometers may be used to monitor lower speeds. There appears to be no special difficulty in measuring wind speed.

b) Humidity

There is very little technical problem concerned with humidity measurement using either ventilated psychrometer or other techniques.

c) Temperature

Leaf or stem temperatures are difficult to measure because of poor contact with tissue or response time is not satisfactory. Fine bead thermistors are most appropriate.

d) Radiation

Filtered tube solarimeters suffer from high temperature and many authors reported condensation occurring in the tubes. Line quantum sensors are more robust and useful under humid conditions.

e) Soil moisture

Soil moisture blocks are considered to be unreliable and sensitive to soil physical condition. Neutron probe techniques are still most widely used but installation of access tubes pose a major problem in gravelly or strong soils. Gravimetric sampling is still the most popular for surface soil. Soil psychrometers and thermometers also give problems but this is probably due to poor quality control or local soil conditions.

4. Data loggers

Data logger is extremely cost effective even in developing countries and many smaller units are appearing in the market which are competitively priced. Problems associated with power supply have also been eliminated by low power consumption with 6 - 12 months battery life.

5. Sampling procedures and data handling

Sensors should not interfere with the microenvironment and transects across crop/tree interface should be attempted. With data loggers frequency of measurement is not a problem. Standard software packages for editing of data or format should be utilised where possible rather than write your own software which is time consuming.

* WMO Publication 8.

6. Interpretations

All too often the accuracy or frequency of environmental measurements greatly exceed the requirement needed to interpret biological responses which are measured over a much longer time scale. If possible the measurement of biological response should match the time scale or vice versa otherwise it would be impossible to determine the significance of environmental modifications. A useful addition is to incorporate treatments which uncouple the effects of above- and below- ground changes. Root studies are usually neglected and techniques like placement of herbicides may be useful to determine rooting depth.

7. Training needs

These could be divided into three levels:

(a) proper use of instruments for scientists,
(b) technicians for maintenance of equipment and
(c) for design and analysis of data collected.

UNEP and WMO have regional training program which should concentrate on field work rather than on laboratory practice. These courses should be made available to technicians who could learn to service and repair equipment. It is recommended that there should be more frequent exchange of personnel and information between institutes to encourage more efficient use of equipment.

REPORT OF WORKING GROUP IV

Improvement of the microclimatic conditions by or within an agroforestry system through management practices

1. Aims

The following aims in agroforestry with respect to the field of microclimatology and micrometeorology were brought forward:

- to understand microclimate management and manipulation aspects of present farming practices with agroforestry components;
- to see what we can learn in this respect from such practices, what their limitations are and how we can contribute to the development of more viable systems and practices with respect to presently existing socio-economic problems such as population pressure and land management changes;
- to involve local extension agents and farmers in defining problems and validating solutions in our joint attempts to understand and control their agricultural environment for specific management goals such as sustained timber and food production;
- to pay attention to appropriateness of instrumentation, site-specific conditions, details of management, cost/benefit ratios and differences between long- and short-term interests in agroforestry research design.

2. Problems

The following main problems facing the application of micrometeorology and microclimatology to agroforestry systems planning and management were observed:

- How to get agroforesters to formulate the right questions in order to obtain appropriate information from meteorological data sources for their purposes;
- A lack of quantification of relevant phenomena in traditional and more recently-developed systems (shifting cultivation, intercropping, alley cropping etc.). Few cause-and-effect relationships are adequately known.
- A lack of biophysical knowledge at the specific requirements of the crops concerned in terms of micrometeorology;
- How to improve the capability in terms of trained staff and equipment of those local institutions having to deal with the above situations;
- How to develop interdisciplinary teams that can effectively find operational solutions;
- How to cope with the present short-term funding situation considering the need for incorporating differences over several seasons (seasonal distribution problems), the necessity to include the many effects showing up only after several years of treatments/practising and the time needed for some agroforestry systems to mature and stabilize;

- How to decide between on-station and on-farm trials and on taking those observations and measurements which will provide us with the relevant trends in space and time and the level of quantification needed.

3. Conditions for solutions

The following conditions for solutions were brought forward:

- Leading farmers should be encouraged to demonstrate and explain their successes to others by organization of meetings with extensionists and fellow-farmers. When farmers are involved in on-station trials they themselves should make the decision to get involved in on-farm trials. No farmer should be demanded to do on-farm trials for the validation of modifications in his farming system management, when he runs any risk of failure for which he will not be compensated.
- Improvement of microclimatic conditions through management practices should be considered as being area-specific (e.g. high potential highlands, high potential lowlands, semi-arid highlands, semi-arid lowlands), site-specific, season-specific or system-specific. For each area one or several limiting factors on which the improvement is most imminent can be distinguished for each site, season and system, which can all be very heterogeneous.
- Microclimatic management aspects do not stand on their own. For example, competitional aspects within the systems with respect to light, water and nutrients in crop space and changes in the occurrence of pests and diseases ask for complementary attention in every management attempt.
- Equipment to quantify effects of management decisions is in respect to microclimate only readily available for temperature, humidity and, to a certain extent, evaporation. Air movement, radiation (total and PAR), soil moisture, plant moisture and surface temperature remain difficult to sample on a routine basis and sufficiently dense with respect to time and space. For some parameters such as soil moisture at low ranges and plant moisture transport, reliable field methodology is still lacking almost completely. For many of the other parameters operationability of equipment remains low. Basic research suffers less from these drawbacks but applied research is in need of increasing attention to equipment.
- In on-farm and on-station research, management results in actual farmers' conditions have to be quantified. Simple monitoring of environmental trends in space and time may be sufficient to find the significant differences we are interested in. Development and validation of simple operational methods for such purposes therefore deserves priority, including phenological and other indicative plant aspects.

REPORT OF WORKING GROUP V

Climatic aspects of soil conservation in agroforestry

It is recognized that appropriate agroforestry techniques have an important role in rehabilitating degraded soils and in reducing or preventing degradation of soils subjected to one or more degradational processes. The group deliberated on the possible role of meteorological considerations in proper planning of agroforestry management practices for sustained productivity of these lands.

Following are the major types of degraded lands and lands undergoing degradation, resulting in reduced soil productivity:

- Soils of low fertility (including soil degraded through mining activity, soils of shallow depth etc)
- Soils subject to water erosion
- Soils subject to wind erosion and to drought conditions (soils of the dry regions)
- Soils degraded through salinity, alkali, waterlogging

The above degradation processes can be attributed to natural causes but are largely a result of human intervention in one form or another.

1. Soils of low fertility

In general, there appears little direct role of meteorological factors in planning for agroforestry for such soils. However, the meteorological parameters have an indirect influence on processes like accumulation and decomposition of litter/crop residues and soil organic matter, recycling of nutrients etc. These processes are strongly influenced by such factors as soil temperature, microclimate of the surface layers etc.

There is need to set up long term observation plots with selected agroforestry alternatives to monitor fertility changes, nutrient cycling, etc., on major soil groups.

2. Soils subjected to water erosion

Of the various meteorological parameters, rainfall has a profound influence on erosional processes. Frequency, intensity, duration and structure of rainfall are particularly important parameters.

There is need to refine and test quantitative expressions, e.g. the universal soil loss equation, for predicting erosional behaviour of soil in relation to alternative agroforestry management techniques.

3. Soils subjected to wind rosion and drought conditions (soils of dry regions)

In dry regions two factors that limit production and encourage degradation are erosion due to wind and inadequacy of soil moisture during part or most of the growing season. Meteorological parameters of importance for agroforestry planning include data on wind velocity and potential evapotranspiration. Data on rainfall characteristics would aid in planning for water-harvesting strategies which become important in areas with

limited water supplies. Similarly, planning agroforestry on a watershed basis requires detailed information on rainfall characteristics.

Contribution of dew to ET can be substandard in many areas. Its measurement and role in managing agroforestry systems in dry regions appears important.

Soil temperature and its management through appropriate practices is yet another important factor having a role in planning agroforestry techniques.

4. Soils degraded through salinity, alkali, waterlogging

All climatic factors that influence water balance of an area will also influence the accumulation and removal of salts in the rhizosphere and water shed. Efforts to predict water balance in response to selected agroforestry practices will enable the definition of management alternatives for such soils.

SECTION 1

General

- The environmental basis of agroforestry. — A. Young
- Some principles and problems of collecting and interpreting climatic data for the description of tree and shrub species. — P.G. von Carlowitz
- Agroforestry systems in major ecologic zones of the tropics and sub-tropics. — P.K.R. Nair

The environmental basis of agroforestry

Anthony Young

International Council for Research in Agroforestry
P.O. Box 30677, Nairobi, Kenya

Abstract

The physical environment affects and interacts with agroforestry systems through tree and crop growth, animal performance, management operations and interactions between the tree/shrub and non-tree components (abbreviated to tree/crop interactions). Interactions take place mainly through the media of microclimate, soil moisture and soil. They may have beneficial or adverse effects, for tree and for crop. Where the ecological interactions are on balance adverse, agroforestry designs with a large tree/crop interface, such as alley cropping, should be avoided. Agroforestry has a particular potential to help check or reverse degradation of soil, forest and pasture resources. An environmental basis for agroforestry requires detailed information on climate, soils and, for sylvipastoral systems, vegetation, together with important basic, but less detailed, information on landforms, hydrology and fauna. Environmental information in five ICRAF data bases is compared. An environmental classification is presented, based on climatic regions combined with distinctive situations of landforms and soils. Agroforestry systems could be designed to suit virtually any set of environmental conditions in the tropics and subtropics. The greatest potential contribution that agroforestry can make is in densely-populated steep lands.

Objectives

The aim of this paper is provide an overview of the environmental basis of agroforestry as a framework for the more detailed chapters in this volume. In particular, it draws attention to aspects which are primarily non-climatic, indicating how these interect with meteorology. It also draws attention to some basic questions raised by such a review, and indicates the extent to which they can be answered. Part of what is said overlaps with, or anticipates, later chapters.

The role of environment in agroforestry systems

Agroforestry systems

Agroforestry systems involve:

1. Growth: of trees, crops, pastures, animals;
2. Management: of climate, water, soil, plants, animals;
3. Interactions: tree/crop, tree/pasture, tree/animal.

Under growth and management, we draw upon large fields of existing knowledge: tree growth from forestry (e.g., the site quality concept); crop/climate and crop/soil relations

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from agriculture; pasture ecology; moisture conservation in drylands; soil erosion and conservation; soil fertility; tropical livestock management – even summarily listed, these are nine massive areas of relevant research.

But it is the interactions that are the distinctive field of agroforestry, albeit that we can already draw upon a tenth research area, that of intercropping. Specifically, our trade is that of interactions between the tree (i.e., tree or shrub) and non-tree components of agroforestry systems. This is represented in the phrase from the standard definition of agroforestry, '.....in which there is both an *ecological* and an *economic interaction* between the tree and non-tree components'. Herein lies the distinction from social forestry and farm forestry, despite the large overlap. Plant a block of trees along roadside or in the corner of a farm, manage it largely or entirely for wood products, and you have social or farm forestry; but compromise on wood production for the sake of forest grazing, and you introduce an ecological interaction that is the essence of agroforestry.

So an environmental basis for agroforestry must cover effects of environment upon trees, crops and animals and their management, plus the distinctive features of interactions between the tree (and shrub) and the non-tree components, referred to henceforth as tree/crop interactions.

Environment and tree/crop interactions

Table 1 and Figure 1 show some tree/crop interactions of significance in agroforestry. Note that both positive and negative effects may be in either direction: tree upon crop (scan pasture, animal) or crop upon tree.

For the first factor, called displacement, the effect is always mutually negative. If the tree is low, as in alley cropping, land under trees cannot be undercroped, and their combined areas add up to 100%. Multi-layer systems such as homegardens can attain combined tree and crop covers of 200% or more.

The remainder of the table is self-explanatory. Microclimate and soil are the two main areas through which interactions are effected. Positive interactions are numerous, but there are four major negative ones:

1. Displacement;
2. Shading;
3. Moisture competition; and
4. Nutrient competition.

The aim of agroforestry design should be to maximize positive interactions and minimize negative ones. Sometimes we may tolerate negative ecological interactions for the sake of positive economic ones, e.g., accept some crop yield reduction for the sake of fodder produced. Interactions take place where trees and crops meet: at the tree/crop interface. They may be side by side, or one above the other. If the net ecological interaction is beneficial, then let us have it in plenty. But if negative, and we are tolerating it for the sake of economic gain, then let us reduce it as much as possible.

These ends can be attained by designs that have a larger or smaller tree/crop interface. Huxley expands on this in Section 2, but let me indicate the orders of magnitude involved. Suppose you want (say for economic reasons) 25% of your land under trees. Figure 2 shows five ways (among many) in which this can be achieved. Looking at the tree/crop interface from a 'side-by-side' point of view, the lengths, as metres of interface per hectare of land, are shown in Table 2.

Table 1. Environment and tree/crop interactions in agroforestry.

Factor	Agency	Interactions: Positive	Interactions: Negative
SPACE	Displacement	---	Crop by tree Tree by crop
CLIMATE	Shade	Tree on a few crops Tree on animals Tree on man	Tree on many crops
	Shelter	Tree shelter to crop from wind Tree check to wind erosion	--- ---
	Water	Trees to reduce evapotranspiration Water from depth via tree leaf to livestock	Tree/crop competition ---
SOIL	Organic matter	Tree litter via soil to crop (physical conditions, nutrient release)	---
	Nutrients	N-fixing trees to crop Nutrient retrieval by tree roots to crop, including mycorrhiza	Tree/crop competition
	Erosion control	Role of trees in control of water erosion (Wind erosion, see above)	---
VEGETATION	Forest	Reduce pressure, degradation, by tree supplying fuel, etc.	---
	Pasture	Reduce pressure, degradation, by tree supplying fodder Plus many of the above climate and soil effects applied to pastures	Bush encroachment
HYDROLOGY	River flow	Stabilization, via role of agroforestry in watershed planning	---
FAUNA	Animals	---	Animal damage to tree
	Pests	Tree inhibits crop pests	Tree harbours crop pests

The results are striking. Contrary to common supposition, the system with the largest length of interface, for a standardized area of tree cover, is not scattered, isolated trees, but alley cropping. So unless you are very sure that net benefits arise from the existence of an interface, try almost anything else. Wherever there are problems at the interface, then of all forms of agroforestry, alley cropping is the least likely to succeed.

Figure 1 Environment and tree/crop interactions in agroforestry.

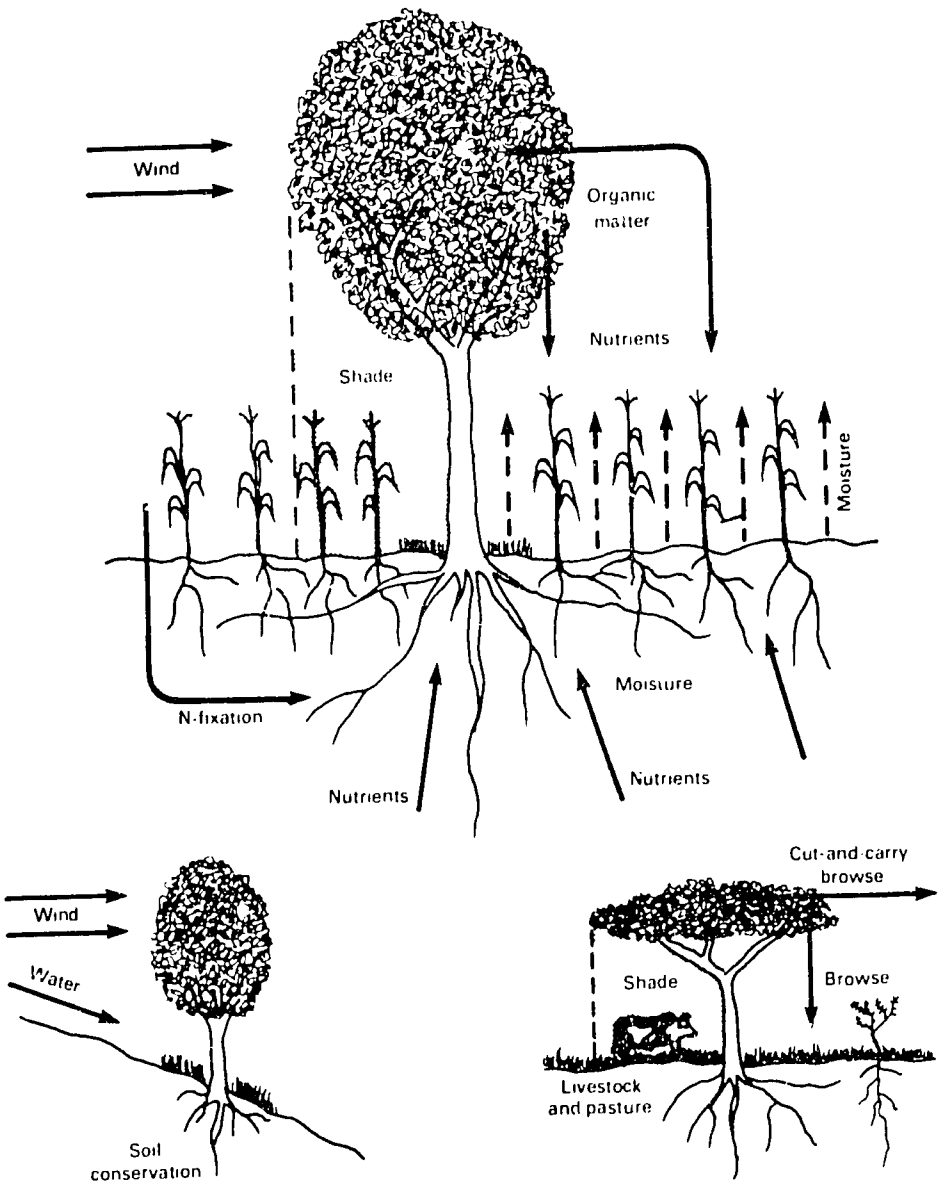
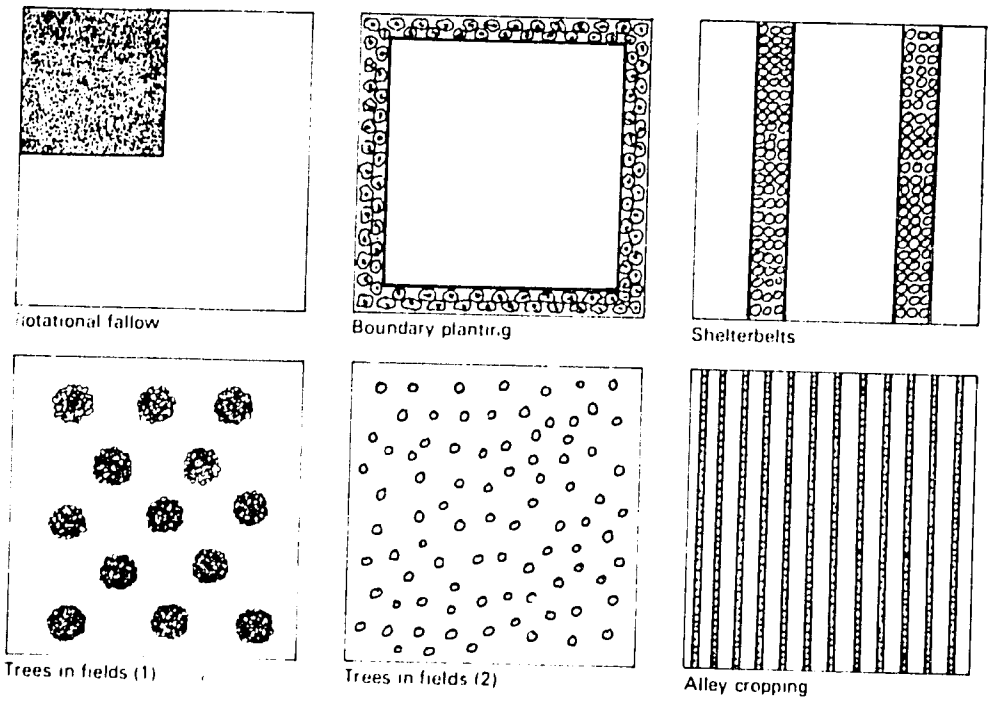


Table 2 Lengths of tree/crop interface for different agroforestry designs, standardized at 25% tree cover.

AF practice	Design	Tree/crop interface (m per hectare)
Rotational fallow	Block 50 x 50 m	100 (to max. 200)*
Boundary planting	Belt 6.25 m wide	350 (to max. 750)*
Shelterbelts	2 belts 12.5 m wide	400
Trees in fields	10 trees, radius 8.9 m	560
"	20 " " 6.3 m	790
"	50 " " 4.0 m	1250
"	100 " " 2.8 m	1770
Alley cropping	Rows 2 m tree, 6 m crop	2500
"	" 1 m " , 3 m "	5000

* Including effects on adjacent farms.

Figure 2 Six ways of arranging a 25% tree cover on one hectare. Within-field lines are tree/crop interfaces. Based on the concept developed by Huxley (1985).



Problems of the land

We have already mentioned the role of agroforestry in making better what has got worse – in solving, or at least ameliorating, problems. In the diagnosis and design approach, the primary focus is upon problems of the farmer: shortages of food, fuelwood, fodder or cash, for example.

Such shortages, however, are frequently linked with problems of the land. Table 3 lists environmental problems for which agroforestry has a potential to assist. Most are forms of degradation. The potential of agroforestry for control of water erosion and soil fertility decline has recently been reviewed by ICRAF (Young 1986b, 1987a, 1989). The chapters that follow address questions of the control of wind erosion, as well as the difficult problem of the extent to which agroforestry can assist, directly or indirectly, in meeting the drought problem in drylands.

More generally, it is ICRAF's view that one of the major contributions of agroforestry is in improving the sustainability of land use systems; that is, in maintaining systems at a productive level, through conservation of the natural resources on which that productivity depends.

Table 3. Environmental problems which agroforestry has a potential to alleviate.

Soil erosion :	–water erosion –wind erosion
Soil fertility decline :	–physical degradation –chemical degradation –biological degradation
Forest resource loss :	–forest clearance –forest degradation
Pasture degradation	
River degradation (?) :	–flow regime –sediment load
Pest attack	
Drought (?)	

An environmental basis

Factors of the physical environment

This summary puts us in a position to ask the question, What information on the physical environment is needed as a basis for research into agroforestry? What kinds of information are relevant, and in how much detail?

Table 4 shows the relevance of the major factors of the physical environment to four aspects of agroforestry systems: tree and crop growth, land management, tree/crop interactions, and environmental degradation. Effects of one factor upon another are added in the last column. Climate and soils are the factors of greatest importance, followed by vegetation in those land use systems that make use of it in a natural or semi-natural state, primarily silvopastoral systems. Land forms appear mainly as a cause of soil erosion hazard: there is now an identifiable body of knowledge about land use, including agroforestry, on steep lands (Novoa and Posner 1981; Siderius 1986; Young 1986a). Only the underlying geology is unrepresented: its effects are considerable, but operate indirectly, via landforms, hydrology and soils.

Table 4 Effects of the factors of the physical environment on agroforestry systems. Fauna includes pests and diseases. The last column refers to initial letter of factors in the first column. // = major effect, / = effect.

ENVIRONMENTAL FACTOR	Effects related to				
	Plant growth	Land system management	Tree/crop interactions	Environmental degradation	Other factors
GEOLOGY					L, H, S
LANDFORMS		//			H, S
CLIMATE	//	/	//		H, S, V, F
HYDROLOGY	//	/		/	S, V
SOILS	//	/	//	//	V, F
VEGETATION	//	/	/	//	F
FAUNA	/	/	/		V

So as an environmental basis for agroforestry, we need:

1. Substantial detail on climate and soils;
2. Substantial detail on vegetation for sylvopastoral systems;
3. Important basic information on landforms (mainly slope) and hydrology (mainly drainage and depth to water table); and
4. Information on fauna, pests and diseases;

whilst those of us who are environmental scientists cannot 'think interactions' without knowing basic elements of the geology.

An environmental data base

In 1983, ICRAF set up an Environmental Data Base (EDB) for agroforestry. This consisted of a set of basic items of information, with descriptors and classification systems, together with a computerized base for input, storage and selective retrieval (Young 1985). Recognizing the varied requirements of different users, three levels, or degrees of detail, were included: summary, intermediate and detailed. The input form to the data base is given as Table 5 (Appendix), and examples of outputs at summary and

detailed levels as Table 6 (Appendix). Data input at any level can be output at the same or a less detailed level.

The concept of how the environmental data base should be used is shown in Figure 3. Having identified a site or area of interest, it should be possible to select five kinds of data, drawn from comparable environments around the world: suitable trees, suitable crops, existing agroforestry systems, recent or current research work, and publications. This would form a first gathering of data to which, as with all computerized data bases, the skill, experience and judgement of designers of agroforestry systems could then be applied.

Let it be said that this ideal has not yet been achieved: the data base, as a framework, has not yet been expanded into a store or data bank. It is possible that this may be done in the future, although substantial manpower and funding will be required. However, the aims of the EDB may soon be achieved through the combined efforts of four other data bases: those on agroforestry systems, multipurpose trees, experimental work and the ICRAF Library (Nair, Section 1, this volume; von Carlowitz, 1985, 1986 and Section 1, this volume; Huxley 1985b; Labelle 1987). The agroforestry systems and multipurpose tree inventories both contain sections on environment, with a substantial although not complete identity with the EDB on kinds of information collected and descriptors used (Table 7). The data base on current agroforestry experiments uses the EDB as part of its input, whilst the computerized library index allocates publications, where relevant, to a broad climatic zone, and makes use of environmental terms as keywords.

By the end of 1987, it may thus become possible to achieve substantially the aim pictured in Figure 3:

1. You have an environment; tell us this, this and that about it;
2. Here are multipurpose trees, crops, existing agroforestry systems, current research work, and publications, from similar environments around the world;
3. Now start thinking!

An environmental framework

Do you sincerely need a classification system? That is, do your purposes require a set of boxes, with defined boundaries, into which information can be poured? I suspect that most readers, with respect to their climatic speciality, might answer 'no' – that they would rather be given basic climatic data for a site than be told it falls into climate XYZ. And of course, the soil scientist cannot get very far by being told she has an Orthic Ferralsol, she needs full soil profile descriptions supported by analytical data.

But wait a minute ! As a background to your biometeorological analysis, do you really want the full gamut of soil description? Would it not be helpful to group your soil moisture research into results obtained 'on Vertisols', regardless of whether they are Pellic, Chromic, or do or do not have a strong, coarse blocky structure? Well, conversely, soil scientists are wont to group climates into a small number of broad classes, within which the fascinating variety of soils occur.

Broad classes come into their own when planning research programmes. To have several stations, in different countries, directing attention at common problems, the environmental framework within which they are grouped has to be quite frighteningly generalized. The ICRAF Agroforestry Research Network for Africa (AFRENA) groups the immense variety of tropical African environments into just four very broad ecozones.

With respect to soil classification, it has been said that 'scientists who are otherwise calm and reasonable people are liable to behave quite differently when discussing this

Figure 3 Using environmental information on agroforestry. Modified from Young (1985).

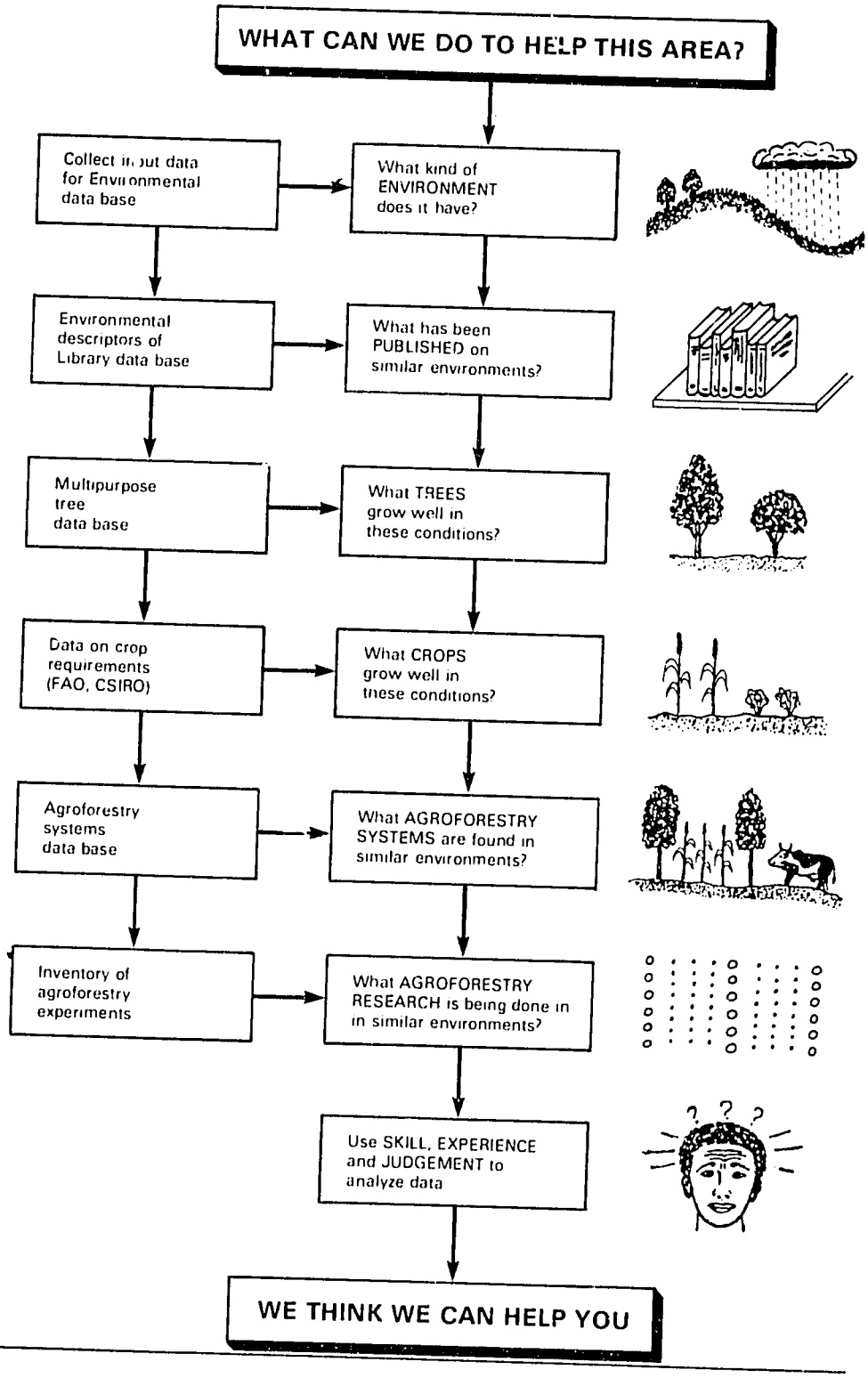


Table 7 Environmental information included in four ICRAF data bases. Properties which can be derived from data collected are included. Items additional to those shown are included in some descriptions in the Agroforestry Systems data base. The Library data base allots a class only for ecozone (climate); other factors are represented by indexing terms, shown by asterisks.

Variable	Environmental data base: Summary level	Environmental data base: Detailed level	Agro-forestry systems data base	Multi-purpose tree data base	Library data base
Latitude	/	/	/	/	
Longitude	/	/	/	/	
Altitude	/	/	/	/	*
GEOLOGY:					
class	/	/			
LANDFORMS:					
class	/	/	/		*
CLIMATE:					
general class	/	/	/	/	/
Köppen class	/	/	/	/	
annual temp.		/	/	/	
mean maximum temp.				/	
mean minimum temp.				/	
absolute minimum temp.				/	
frost occurrence		/			
annual rainfall		/	/	/	
rainfall regime		/	/	/	
monthly rainfalls		/		/	
HYDROLOGY:					
drainage class	/	/	/	/	*
depth groundwater		/		/	
SOILS:					
general class	/	/	/		*
FAO class	/	/			
specified class		/		/	*
texture		/	/	/	*
reaction		/		/	*
shallowness		/		/	
salinity		/		/	*
VEGETATION:					
class	/	/	/		*
LAND USE:					
class	/	/	/	/	*
agroforestry class	/	/	/	/	*

subject,' and it may well be that the same applies to climatic classification. A recent review of classifications of climate, soil and vegetation was written as the basis for a CGIAR review of agro-ecological characterization (Young 1988). Let us, like the young ladies set upon by robbers in 'The Wallet of Kai Lung', rush away from this subject, screaming loudly to conceal the direction of our flight.

Table 8 is an attempt at a set of broad environmental classes, intended for those whose purposes require 'large boxes'. There is no doubt that climate must be the starting point, with all else superimposed (and I speak as a soil scientist!). The principle is to start from the basic climatic regions, with their associated vegetation; then for each of them, to consider what is the 'normal' situation with respect to the other factors, and what conditions constitute special cases.

Taking first climate, let us start with the three worlds of the tropics: the humid or rain forest lands, the subhumid lands or savannas, and the dry lands. Some people show a strange reluctance to recognize as a distinct zone the subhumid or 'wet-and-dry' tropics, best described by Köppen's untranslatable term, *wechselfeuchten*, 'changing-wet' (as opposed to *immerfeuchten*, always wet). This gives three large boxes for the tropics. Mediterranean and temperate climates would be added to extend such a basic classification beyond the tropics.

Next, we have the indisputable fact that conditions at 2000 m altitude are not the same as at sea level. But where to draw the line? Köppen splits A, hot, from C, warm, climates where the mean temperature for the coldest month drops below 18 °C. The FAO agro- ecological zones system puts the limit at a mean (24-hour) temperature of 20 °C during the growing period (FAO 1978/81). From a physiological viewpoint, there is an argument for the (substantially higher) point where frost appears. If you must use an altitude surrogate, some 1200 m at the equator, falling to sea level near 30° latitude, is a crude approximation, corresponding to what many would loosely call the 'highland' tropics.

Finally, take out the climates with two clear dry seasons as distinctive, and we have 9 boxes for the tropics. Sad to relate, IITA lies very close to the dry boundary of the humid tropics, whilst ICRAF's Machakos field station could be put as highland or lowland, and oscillates from year to year between bimodal subhumid and that rather rare climatic type, semi-arid with two crop failures instead of one.

Now let us dispose of all the other factors with as little complexity as possible. Vegetation may be subsumed under climate.

For landforms, let gentle to moderate slopes be considered 'normal', i.e., tacitly assumed unless specified otherwise. There are three distinctive conditions: steeplands, with steep and moderate slopes dominant; flat lands, the alluvial areas, with landforms of depositional origin; and valley floors, the *dambos, mbugas, fadamas* and the like of Africa.

For soils, the 'normal' circumstance can be taken as the zonal soil: ferralsols and acrisols (US Oxisols and Ultisols) for the rain forest zone, luvisols (US Alfisols) for the savannas, and the various kinds of calcimorphic soils for the semi-arid zone. By attribution, steep lands have zonal soils together with shallow lithosols, and flat lands have alluvial soils and gleys. This leaves the following as special cases, on which there is known, or believed, to be a distinctive role for agroforestry:

1. Soils developed from basic rocks (nitosols, no US equivalent), which are usually more fertile;
2. Soils developed from felsic rocks and/or on erosion surfaces, which are usually less fertile (not well identified in FAO or US classification systems; variously

Table 8 A simplified classification of tropical environments as a basis for agro-forestry. Modified from the ICRAF Environmental Data Base. (Young 1985).

Stage 1 Three worlds of the tropics: climate and vegetation.

HUMID TROPICS Rain forest zone Forest Köppen Af, Am	SUBHUMID TROPICS Savanna zone Broadleaf trees tall grassland Aw	SEMI-ARID TROPICS Semi-arid zone Thorn trees short grassland BS	ARID ZONE BW MEDITERRANEAN Cs, BShs TEMPERATE CLIMATES Cb, Cc, D

Ann. rainfall: c1500 mm c.600 mm c.250 mm
Growing periode: 270 days 120 days 75 days

Stage 2 Climate: rainfall, temperature and seasonality.

HIGHLAND TROPICS			
HUMID Cfa	SUBHUMID Cw	SEMI-ARID BSk	coldest month 18 °C or mean growing period. (annuals) 20 °C
	Cw" BIMODAL Aw"	BS"	
Af, Am	Aw	BSh	
LOWLAND TROPICS			

c. 1500 mm c. 600 mm c.250 mm
270 days 120 days 75 days

Stage 3 Landforms and soils.

LANDFORMS	'Normal':	Gentle to moderate slopes
	Special cases:	Steeplands - steep slopes Flatlands - alluvial landforms Valley floor sites (*dambos, fadamas,* etc.)
SOILS	'Normal':	Normal landforms: zonal soils for climate Steep lands: zonal soils plus lithosols Flat lands: alluvial soils and gleys Valley floors: alluvial soils and gleys
	Special cases:	Soils derived from basic rocks Acid sandy soils Vertisols Saline and alkaline soils

called weathered ferrallitic soils, granite sands, sandveld soils, leached pallid soils or cerrado soils; (Young 1975, 1976 p. 142);
3. Vertisols; and
4. Saline soils.

But remember, all these are boxes; they are thus made of ticky-tacky – and they all don't exist!

Land evaluation and agroforestry

Following upon the principles set out in the 'Framework for land evaluation', sets of detailed guidelines have been published on evaluation procedures for rain-fed agriculture, forestry, extensive grazing and irrigated agriculture. How simple it might appear to be, by combining these, to devise a system of land evaluation for agroforestry! What needs to be done, and why it is not so straightforward, has been set out elsewhere (Young 1984, 1987b).

The present discussion will be restricted to the two basic questions asked in land evaluation:

1. A piece of land in mind: what best to do with it?
2. A kind of land use in mind: where best to practise it?

On the first of these, a substantial part of the efforts of ICRAF and others has been directed at showing how well-designed agroforestry systems, provided they function as it is hoped they will, are an improvement on present forms of land use. This has been appraised in terms of economics, sustainability and the welfare of the people.

The second question might be rephrased in our context as, 'Which agroforestry system, where?' If an agroforestry system is specified in detail (as what is called, in land evaluation terminology, a land utilization type), there must logically be a set of environmental conditions where it functions very well – the trees grow, the crops grow, and the interactions are mutually beneficial. It other environments, the same system will work rather less well, and in many others not at all – the trees will die of drought, aluminium toxicity or attack by pests.

Neither the agroforestry land utilization types nor their optimum environments have yet been systematically described and evaluated. There are some obvious relations: homegardens work best in the humid tropics, windbreaks in the semi-arid zone. Alley cropping, did you say? Some think it is a system primarily for the humid zone, where research has been concentrated until recently. Others believe that its potential may be as high or greater in the savanna or even the semi-arid zone. Can agroforestry provide a solution to the intractable problems of the sandveld (cerrado) soils? Research in progress should provide support for our presently unsubstantiated assertions.

Finally, the 10-million-dollar question (the cost of a typical development project). You cannot invest in agroforestry development everywhere at once. Where will it give you best value for money? Here are three deflections of this question, followed by one answer.

1. The question cannot be answered in terms of environment alone. The potential of agroforestry, for any given environment, becomes higher where the problems that

arise under present land use are of particular kinds (e.g. fuelwood shortage, soil fertility decline).

2. Almost everywhere. Rarely does an agroforester reply, when called in to help with problems, 'Sorry, we can't help you'. Plausible agroforestry systems could certainly be designed for every environmental box in Table 8.
3. Not on flatlands. At least two viable systems are known for rice paddy lands, boundary planting (on field bunds) and intercropping of trees grown as an annual. On balance, however, this is not a priority environment. (The most unsuitable crop for agroforestry? Sugar cane)

So where is the need for agroforestry, and its potential as an improvement over present land use, greatest? In *densely-populated steeplands.* In more detail:

> In areas of humid or subhumid, lowland or highland, climate, dominated by moderate and steep slopes, that are densely populated. Soils are of moderate, sometimes quite high, natural productivity, but have been degraded by erosion and over-cultivation. Forest has been largely cleared, what remains is degraded by overcutting, and there is a fuelwood shortage. The remaining pastures are degraded and fodder shortage is endemic. There is less base flow to the rivers. The young men are leaving.

In such conditions, there is potential for agroforestry in the control of soil erosion, improvement of soil fertility, production of fuelwood, fodder and cash products, and (given a powerful institutional framework for planning) improvement of pastures and watershed management (Young 1986a). Do you know of such lands?

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Appendix : Table 5 and Table 6 next pages.;

Table 5. ICRAF Environmental data base: sites file, input form (Young, 1985).

ICRAF ENVIRONMENTAL DATA BASE: SITES FILE, INPUT FORM.

S Type of data..... ....
Title ....
Subtitle .....
Reference: Letters..... Number ..... Input by..... Date: D..... M..... Y.....
Sources ..... Suitability level .....

LOCATION
Country ..... Location .....
Latitude ..... – ..... NS Longitude .... – ..... EW ..... Rel..... .....
S Altitude ..... – ..... m ..... Rel..... .....

GEOLOGY
S Class. ..... Rel.....
Description .....
Level 2 data Grain size ..... Formation .....
Age ..... Lithology .....

LANDFORMS
S Class ..... Rel.....
Description .....
Slope angle ..... – ..... degrees or ..... – ..... %
Relative relief ..... – ..... m
Level 2 data Slope shape ..... Slope Position.....

CLIMATE
S Class: general ..... Rel.....
S Köppen: code ..... class ..... Rel.....
Alt. zone ..... – ..... m Rainfall regime .....
Ann. temp ..... – C
Ann. rainfall..... – ..... mm with..... – ..... dry months
Level 2 data
Mean temp.: Hottest month .... – ..... C Coldest month ..... – C
Driest month..... mm Occurence of Frost .....
Mean annual Eo ..... – ..... mm By which method? .....
Humidity index r/Eo = ... – ..... Growing period..... – .....days

Mean Monthly Rainfall, mm
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC YEAR
....
Climatic details for ..... Distance from site ..... km Altitude.....

S – Summary level data ..... Rel - Reliability

(Table 5 continued)

HYDROLOGY

S Class .....Rel.....
Groundwater.....Depth: Average ..... – ..... m
Level 2 data Groundwater depth: lowest ..... – .....highest..... – ..... m
River regime.....Degradation. .....
Flooding .....

Soils

S Class: general.....Rel. .....
S FAO Code .....Class. .....Rel. .....
Other .....on.....classification
Properties: Texture .....Reaction .....
Drainage.....Other .....
Level 2 data Texture class: topsoil ..... – .....subsoil .....– .....
Reaction (pH): topsoil..... – .....subsoil ..... – .....
Drainage.....Lim.horizon .....
Degradation: Severity.....Type ..... .
Vegetation
S Class: gen. Area.....Rel.....
Site .....
Unesco.....Rel.....
Description. ....
Association ....
Level 2 data Degradation: Severity.....
Type .....

FAUNA AND DISEASE

Affecting plants.....Rel.....
Affecting animals .....

LAND USE

S Class .....Rel.....
S AF class .....Rel.....
Description .....
.....

NOTES

.....
.....

ADDITIONAL DATA Name of variable Value

1:
2:
3:
4:

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Table 6 Examples of outputs from the ICRAF Environmental Data Base. A. Summary level.

ICRAF Environmental Data Base: EXPERIMENT STATIONS
Summary level

ICRAF MACHAKOS FIELD STATION

Ref.*EXPT / 1* Source Input by *AY* Date *11.09.84*

				Reliability
LOCATION				
Country	*KENYA*	Location	*MACHAKOS, 60 KM ESE NAIROBI*	
Latitude	*1.30S* to	Longitude	*37.10E* to	*1*
GEOLOGY	*CRYSTALLINE*			*1*
LANDFORMS	*GENTLE TO MODERATE*			*1*
CLIMATE	*SUBHUMID TROPICS*			*1*
Köppen	*Aw"* *SUBHUMID TROPICS, TWO WET SEASONS*			*1*
Alt. zone	*1500-2000*			
HYDROLOGY				*1*
SOILS	*LATOSOLS*			*1*
FAO	*ORTHIC, FERRIC LUVISOLS, SOME LITHOSOLS*			*1*
VEGETATION				
Area:	*THORN SAVANNA*			*1*
Site:	*THORN SAVANNA, PARTS PLANTED*			
LAND USE	*FORMERLY GRAZING, NOW AGROFORESTRY*			*1*
Agroforestry	*AGROSYLVICULTURE: VARIOUS TECHNIQUES*			*1*

Table 6 B. Detailed level.

ICRAF Environmental Data Base: EXPERIMENT STATIONS *Level 2*
ICRAF MACHAKOS FIELD STATION

Ref.*EXPT / 1* Source Input by *AY* Date *11.09.84*

LOCATION

Reliability

Country *KENYA* Location *NR. MACHAKOS, 60 KM ESE NAIROBI*
Latitude *1.30S TO* Longitude *37.10E TO* *1*
Altitude *1500 TO 1590 m* *1*

GEOLOGY

Class *CRYSTALLINE* *1*
Description *BASEMENT COMPLEX GNEISSES* *1*
Grain size Formation
Age *PRECAMBRIAN* Lithology *BIOTITE GNEISS*

LANDFORMS

Class *GENTLE TO MODERATE*
Description *VALLEY SIDE, FROM CREST, THROUGH CONVEX SLOPE TO RIVER* *1*
Slope angle *0 – 13* degrees or *(0 – 22%)*
Rel. relief *90 TO* m
Slope shape *CONVEX* Slope Position

CLIMATE

Class: gen *SUBHUMID TROPICS* *1*
Köppen *Aw"* *SUBHUMID TROPICS, TWO WET SEASONS* *1*
Alt. zone *1500 – 2000* m Rainfall regime *BIMODAL*
Ann. temp. *21* – C
Ann. rainfall *750* – mm with *7* – dry months
Mean temp. Hottest month 23. C Coldest month 19. C
Driest month 3 mm Occurrence of Frost NEVER
Ann. evapotn 1930 – mm by PAN
Humid. index r/Eo = 0.39 – Growing period 90 – + 90 days

Mean Monthly Rainfall, mm

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
37	44	96	137	74	8	4	3	4	0	185	95

Climatic details for EST. FOR STATION from site 0 km, alt. 1580 m

Table 6 continued

HYDROLOGY *1*

Class *NO WATERLOGGING*
Groundwater *FRESH*
Depth: Average . – m Lowest .–. Highest .–.
River regime *SEASONAL* Degradation *ABSENT*
Flooding *NEVER*

SOILS *1*

Class: gen. *LATOSOLS*
FAO *Lo,lf, I: ORTHIC, FERRIC LUVISOLS, SOME LITHOSOLS* *1*
or *UNr1m, UNr2m, UNb4p* on *KENYAN* classification
Properties: Texture *LOAMY TO CLAYEY* Reaction *ACID*
Drainage *WELL DRAINED* Other *SHALLOW PATCHES*
Texture class: topsoil *SCL –* *Subsoil* *SC –*
Reaction (pH): topsoil *6.0 – 6.5* Subsoil *6.2 – 6.4*
Drainage *WELL DRAINED* Lim. horizon – cm
Degradation: severity *ABSENT* Type

VEGETATION *1*

Class: gen.Area *THORN SAVANNA*
Site *THORN SAVANNA, PARTS PLANTED*
Unesco *IIIB MAINLY DECIDUOUS SCRUB* *2*
Description *SAVANNA, MAINLY THORN, PART BROADLEAF*
Association *AC. TORTILIS, COMMIPHORA AFRICANA; ERAGROSTIS, THEMEDA*
Degradation: Severity *ABSENT* Type

FAUNA AND DISEASE *9*

Affecting plants *NO DATA*
Affecting animals *NO DATA*

LAND USE *1*

Class *FORMERLY GRAZING, NOW AGROFORESTRY*
Agroforestry *AGROSYLVICULTURE: VARIOUS TECHNIQUES* *1*
Description *AGROFORESTRY DEMONSTRATION STATION, MANY TECHNIQUES INCLUDING ALLEY CROPPING, SOIL CONSERVATION, MPTs*

NOTES *BIMODAL UPLAND SUBHUMID CLIMATE, CLOSE TO BOUNDARY WITH SEMI ARID, DROUGHT HAZARD INCREASED BY TWO WET SEASONS, BOTH SHORT AND UNRELIABLE: KOPPEN Aw" BUT CLOST TO BOUNDARIES WITH BOTH BS AND Cw". SUBSTANTIAL EROSION HAZARD ON STEEPER PARTS.*

ADDITIONAL DATA

Some principles and problems of collecting and interpreting climatic data for the description of tree and shrub species

P.G. von Carlowitz

International Council for Research in Agroforestry (ICRAF)
P. O. Box 30677, Nairobi, Kenya

Abstract

The development of climatic profiles for woody perennials used in agroforestry is indispensable. Without them any description of species would be incomplete and render species selections for identified sites impossible.

Based on the experience of several years of data collection for ICRAF's Multipurpose Tree & Shrub (MPTS) Data Base the considerations and problems of obtaining climatic data are outlined. One of the considerations is associated to the objectives of the data base for which climatic data are collected and used. ICRAF's MPTS Data Base deliberately includes as wide a range of species as possible, most of which are little known. It must, therefore, be restrictive in its selection of parameters. A carefully considered balance between data that are desirable and those that are indispensable for a reasonably reliable climatic species description must be maintained.

Even if restricted to a minimum set of climatic data, the problems of obtaining them are manifold. They range from inavailability of even the basic data in the field, to the absence or insufficiency of climatic data in relevant literature. Consequently it is recommended to promote the importance of climatic data, particularly among non-climatology informants. It is further advocated that species trials should be equipped with climatological instruments. As a means of closing gaps in climatic species descriptions, informations relevant to plant growth should be calculated from easily obtainable actual data.

Introduction

In comparing conventional agriculture with agroforestry systems, the distinctive feature of the latter is the deliberate introduction and management of woody perennials for their expected beneficial environmental and economic effects.

From the topoclimatic and microclimatic point of view, the presence of trees and shrubs, so different in stature from most crops, is bound to make a considerable impact. This is well demonstrated by the effect of shelterbelts, on which a substantial body of research results exists. Also the negative or positive tree/crop interface, often observed but not yet well understood or researched, demonstrates microclimatic implications associated with the introduction of woody perennials.

Unlike the situation in forestry with a comparatively small number of species to consider, restricted production objectives and a clear lead with regard to related research,

the woody perennials considered for use in agroforestry systems encompass a wide array of species, most of which are little known. Therefore one is faced with a situation in which are site-specific choices of most crops based on a rather high level of knowledge whereas for most multipurpose trees and shrubs, in the absence of such knowledge, decisions are largely left to speculation.

In order to close this wide-open gap, substantial research is required. Data need to be collected, on topics such as, taxonomy, morphology, phenology, response to tree manipulation and management, environmental requirements in general and climatic information in particular. Considering that we are dealing with a previously neglected part of the plant community, there is a wide range of problems. Information on climate as an important prerequisite for plant growth is one of the most crucial.

Based on several years of experience in designing and operating a multipurpose tree and shrub data base it is the intention of this paper to expose some of the principles, considerations and problems of data collection with particular respect to climate.

Objectives and principles

Not only in agroforestry situations but also in general terms, the description of woody perennials, their properties, uses and limitations would be incomplete, if not to say of little value for all practical purposes, should environmental requirements and tolerances not be included. Without the questions answered as to where and under which soil, hydrological and climatic conditions any given species can grow, any further qualifications and properties of a species are of anecdotal rather than practical value. Therefore due consideration has to be given, among other factors, to the collection of climatic data.

Basically, climatic aspects in connection with woody perennials in an agroforestry situation have to be approached from two different angles. One set of information deals with the specific requirements and tolerances of tree and shrub species, another set with the topoclimatic and microclimatic impact which the tree/shrub component makes on its environment. Although both aspects deserve an equal ranking, only the one dealing with species-specific requirements is discussed here.

With this restriction in mind and considering that relevant information has to be obtained from various sources which include non-specialist informants, the following principles are to be observed:

1. The questions asked to obtain data should be simple and comprehensible to non-specialists in climatology.
2. The level of detail in obtaining climatic data has to be decided on by taking into consideration on the one hand the scope and range of species dealt with, and on the other the likelihood of data availability in 'field' situations.
3. The minimum data set decided upon must be sufficient to allow any given species to be assigned to a defined climate type.

Obviously the level of detail with which climatic data are collected, interpreted and used for the assessment of climatic requirements and tolerances of plants depends on the following considerations:

1. The objectives of the data collection and consequently the focus on certain aspects (e.g. taxonomy oriented, specific-use orientated, environment orientated) will determine the degree to which climatic data assume importance.

2. An inventory-type data base (e.g. ICRAF's Multipurpose Tree and Shrub Data Base), which is intended to provide an overview over as wide as possible a range of species, will have to be less detailed in climate description, as opposed to a data base directed towards a selection of a few species in which more elaborate data could be employed.
3. The general level of knowledge on the plant material to which the data collection refers may influence the level of detail applied to collection of climatic data. Aiming at a maximum set of climate-oriented information for plant material which in the majority of cases is characterized by a general lack of knowledge appears to be superfluous, inappropriate, unbalanced and unnecessarily burdensome. However, in the case of a data base, such as ICRAF's on multipurpose tree and shrub, in which the species covered range from 'little known' to 'much known', either a multilevel approach (discussed briefly hereunder) or an acceptable compromise has to be adopted.
4. For data collections restricted to woody perennials it may be acceptable to describe climatic aspects in broader terms as compared to such an exercise directed towards crops. The more robust stature of woody perennials and their distinctive root morphology provides in most cases a higher degree of flexibility towards climatic variability.

The above-mentioned considerations are indeed reflected in various data bases and their respective conceptual approaches. Hackett (1983), in his modular system of describing the qualities of plant species, not only allows for a description of both woody perennials and non-woody annual plants, but also goes to greater length in his choice and number of descriptors, as is the case with data bases which are restricted either in the kind of plant material dealt with (e.g. woody perennials only), or in the ecological zone to which description of the plant material is limited. In the latter case certain climatic aspects, as, for example, amount of precipitation and Koeppen classes, are narrowed down already; and consequently the climatic description may dispense with some of the otherwise necessary descriptors.

SEPASAT (Wickens 1986), a data base which originally had been limited to arid and semiarid environments, provides an example. Climatic descriptors are restricted to total rainfall, rainfall distribution, daily and seasonal temperature variation, and occurrence of frost. The INSPIRE Data Base (Webb et al. 1984) is another example in as far as the self-imposed limitation lies in the exclusion of all non-woody plant material. Climatic descriptors are reduced to mean annual rainfall, seasonality of rain, number of dry months, hottest and coldest months and mean annual temperature, obviously in an attempt to provide an overview which allows a comparison of many species, rather than to extend into detailed climatic description of a few well-known and better researched species.

In view of the pros and cons of detailed climatic description of plants and of the various arguments provided in this connection, the multi-level approach, as adopted by Young (1985) in his concept of an Environmental Data Base for agroforestry, appears to be particularly attractive. In climatic terms the lowest or summary level confines itself to a generalized climatic class, as for example, humid tropics, and to Koeppen classes. The highest, level 2, adds to these the following descriptors: altitude zone, rainfall regime, mean annual temperature, mean annual rainfall, number of dry months, mean monthly rainfall, hottest and coldest months, driest month, frost occurrence, evaporation, humidity index and growing period.

Because this method caters for the whole range of possible levels of data availability, it is certainly less exposed to criticism of being either too elaborate for certain purposes

or too vague for others. However, from a practical point of view and considering that an output programme may be designed aimed at comparability with a view to species selection for certain site specifications, this method also has its disadvantages.

ICRAF'S multipurpose tree and shrub data base

ICRAF's multipurpose tree and shrub data base is an inventory-type data base. Its objectives can be summarized as follows:

- rapid screening of many species in a comparable manner;
- gauging the biophysical range of these species;
- providing the basis, by objective criteria, for the identification of priority species for further development;
- providing guidelines for pre-selection of species by site-matching;
- responding to requests for information on multipurpose trees and shrubs.

Within the boundaries of these objectives the use of Koeppen climate classes proved to be reasonably satisfactory for the following reasons:

- the Koeppen class system is acknowledged and applicable world- wide;
- the climatic parameters required to determine Koeppen classes are fairly simple;
- the probability that the required basic climatic data (rainfall and temperature) are available also in 'field' situations is relatively high;
- the system allows each species to be assigned to a defined climate type, although with some limitations discussed below.

Apart from determining the Koeppen class by processing the data on rainfall and temperature by means of a computer subroutine programme, some additional information relevant to plant growth and to assessing the climatic requirements of individual species can also be generated from the information contained in the data base. Day length, an important aspect with regard to such phenological criteria as flowering and fruit-setting, can be determined by the latitude obtained as part of the geographic site definition. Lengths of dry periods, wherever applicable, can be extracted from the values of mean monthly rainfall that are provided. Based on these monthly means, contained in the data base as part of the description of any one species in a given location, the Koeppen class-specific range of rainfall can be narrowed down to the actual rainfall reported, thus refining the assignment of Koeppen classes to individual species.

Limitations and problems in the collection and interpretation of climatic data

As mentioned earlier, the number of descriptors by which climatic data are collected is restricted and comparatively simple. Nevertheless, in the course of the actual data collection a number of drawbacks and problems have been experienced.

Availability of climatic data in field situations

Site-specific records, as loaded into the computer, are formatted descriptions of a tree or shrub species growing at a particular site. Such data, obtained from informants in the field, are original and authentic and are particularly suitable for gauging the biophysical range of individual species described at various sites. Records of this kind form the backbone of the data base.

As the bulk of the species concerned are not well known and not yet subject to species trials, they are described in either their natural range or in farmland and pasture situations where the availability of meteorological equipment is the exception rather than the rule. Consequently the climatic data provided by informants are often incomplete, based on estimates with an undetermined degree of reliability or obtained from meteorological stations at varying distances from the growing site of a species described. Anticipating the problem of unavailability of climatic data on site, informants are requested to name the location of the nearest meteorological station from which data are quoted and to state its distance from the growth site. This may allow a rough assessment of the applicability of data provided. but the position remains doubtful as considerable differences in climatic conditions may occur over short distances if the area is marked by a heterogeneous topography. Even with descriptions obtained under experimental conditions there is often a certain degree of unreliability of data, with the exception of meteorologically well-equipped research stations.

Species field trials may be equipped with at least a minimum set of instruments, such as rain gauges and minimum-maximum thermometers, and monitoring may be done regularly. However, due to limited project durations the observation period with regard to climate is often too short to take account of long-term variability, particularly of rainfall. Means obtained from short-period observations may deviate from the actual average condition and could, particularly in borderline cases, lead to a wrong Koeppen class assignment and subsequently to inappropriate definitions of species-specific climatic requirements.

Availability of climatic data in literature on woody perennials

The site-specific records mentioned above are complemented by species records generated from the literature. Most contain relevant information on taxonomy, morphology, phenology and uses which constitute valuable additions to the data base. However, this information is usually not accompanied by a description of climatic requirements and tolerances. If in some cases reference is made to climate, it often suffers from so broad a generalization that it does not permit derivation of Koeppen classes for the species.

The relationship between altitude, latitude and temperature

Those publications which represent already a summary description of species and are based both on references to competent secondary literature and/or research results usually prove to be a valuable source of information. Publications like the ones by the National Academy of Sciences (1980, 1983), Webb et al. (1984) and Little (1983) are formatted in a way that provides guidance for species selection by various criteria and therefore include environmental information, although at varying levels of detail.

A common feature, often observed in screening literature of this kind, is the assignment of altitude ranges to individual species that is not fully crompehensible. If a wide altitudinal range of, for example, 0 to 1800 m asl is combined with a wide latitudinal

range of 30° and more, this summarized information on altitudinal tolerance of a species is reduced to an almost anecdotal status as it ignores the correlation between altitude and latitude with regard to temperature. However, if a specific altitude related to species tolerance is mentioned in combination with a specific latitude it may offer an opportunity not only to support temperature data which for whatever reason suffer from a low degree of reliability, but also to estimate temperature ranges, within tolerable margins when data are not available at all.

Conclusions and recommendations

It has to be acknowledged that the effect of certain climatic events on the growth performance of woody perennials is not as yet always fully understood and researched. For example a tree species which grows well in one location, described by annual rainfall, seasonality of rains, length of dry period and mean annual temperature, may be unsuccessful at another site although these specific climatic characteristics are the same. The reason may be water stress, recognizing that defining a dry season only by its length is insufficient; with higher temperatures and wind velocity during the dry period, evapotranspiration may cause an earlier and more intensive water stress at one site than at another, thus exceeding the drought tolerance of a species at one site but not at the other. The conclusion is that more climate-oriented research is needed to assess not only the site-specific climatic conditions, but also the impact that different climatic parameters make on individual species.

However, until considerable progress has been achieved in this vast field of agroclimatic research, ICRAF's multipurpose tree and shrub data base is faced with the problem of categorizing a large number of mostly lesser-known species of woody perennials by comprehensive, broad climate types to which the species can be assigned.

Considering the generally low level of knowledge on most species that still prevails, such a strategy probably provides the best summary assessment of multipurpose tree species presently available. The assignment of a large number of species to standard climatic types allows a quick comparison of these species, at least in broad terms, and a shortlisting of candidate species for defined climatic conditions.

With regard to the lack of availability of even simple climatic data in 'field' conditions, it could be argued that the density of the network of meteorological stations is sometimes insufficient. However, it is likely that financial constraints will prohibit the establishment of many more. Furthermore, it is doubtful whether a greater density of stations would result in a high degree of reliability of climatic data at the growing sites of trees. What has to be done is to promote awareness among non-climatology researchers engaged in data collection that climatic data are indispensible components of plant description and that special efforts to obtain them are therefore justified.

It also should be stressed that species trials should be equipped, as a matter of routine, with climatological instruments.

For arriving at more and better climatic description, another possibility which needs to be explored is to derive information relevant to plant growth by means of calculation from actual data that are easy to obtain. One such example is to assess the possibility of developing an equation or formula to establish the interdependence between latitude and altitude in determining site-specific temperature data. The practical relevance of the successful establishment of such an equation is obvious for reasons which have been mentioned earlier.

National meteorological institutions and their staff and all climatologists should accept the challenge to help and cooperate in this field. Such cooperation is certainly of mutual interest and is likely to be beneficial for both parties.

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Agroforestry systems in major ecological zones of the tropics and subtropics

P.K.R. Nair

International Council for Research in Agroforestry (ICRAF)
P.O. Box 30677, Nairobi, Kenya

Abstract

During the past five years, ICRAF, through its Agroforestry Systems Inventory (AFSI), has collected, evaluated, synthesized and disseminated information on existing agroforestry (AF) systems and practices from different parts of the tropics and subtropics. The systems have been classified according to various criteria such as their structure, function, socio-economic aspects, ecological spread, and so on. But the primary step in classifying them is on the basis of their structure; thus there are three basic types of AF systems

- *agrosilvicultural (crops land trees)*
- *silvipastoral (trees and pasture/animals), and*
- *agrosilvipastoral (crops + pasture/animals + trees).*

Under each of these major AF types, several systems have been recorded in the AFSI data base. But the distinct AF practices that constitute these systems are only a few; these are discussed in the paper.

An ecological analysis of the spread of various AF systems shows that the existence / adoption of an AF system in a given area is determined primarily by the ecological potential of the area, but socio-cultural and economic factors determine the complexity of the system and the degree of intensity of its management. From a purely ecological point, certain types of systems can be identified as characteristic of each major ecological region. Examples are:

humid/subhumid lowlands	- *home gardens,*
	- *plantation crop combinations,*
	- *multilayer tree gardens,*
	- *alley cropping and other intercropping systems*
semi-arid/aridlands	- *silvipastoral systems*
	- *windbreaks/shelterbelts,*
	- *MPTs for fuel/fodder*
	- *MPTs on farmlands.*
highlands	- *soil conservation hedges*
	- *silvipastoral combinations*
	- *plantation crop systems.*

There are certain types of systems that are present in almost all ecological regions; however, the nature of components in each will vary from region to region depending on the ecological potential of the regions .

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Introduction

ICRAF has just completed a global inventory of existing agroforestry systems and practices in different parts of the tropics and subtropics. Initiated in September 1982 with partial financial support from the United States Agency for International Development (USAID), the project had the general objective of increasing the understanding about the extent of existing agroforestry systems, and their various productive and protective roles in land use systems in the developing countries. The exercise consisted of collection, collation, synthesis, evaluation and storage of data, and publication of various results and outputs concerning the existing land use systems of relevance to agroforestry, and it involved a large number of institutions and individuals interested in and knowledgeable about agroforestry from all over the world. This project has gathered information on a few hundreds of agroforestry systems, and this information is available in the form of:

1. Agroforestry System Descriptions, being serialized in *Agroforestry Systems* (published by Martinus Nijhoff, The Hague). A list of the system descriptions is attached (Appendix page 93-94);
2. A computerized Agroforestry Systems Register at ICRAF containing data entries on about 150 systems and/or practices;
3. Various miscellaneous publications from the project (Appendix page 94-95);
4. Unpublished records at ICRAF.

This paper is based on this vast information base on agroforestry systems. Additional details of any aspect of the project can be obtained from the author.

Types of agroforestry systems

In order to evaluate the existing agroforestry systems and develop action plans for their improvement, it is necessary to classify these systems and thus provide a practical and realistic framework. Depending on the main purpose to be served by a classification scheme, various criteria can be employed to classify the systems. The most common among these are the system's structure, functions, socio-economic scale and level of management and ecological (environmental) spread:

1. Structural basis – refers to the composition of the components, including spatial admixture of the woody component, vertical stratification of the component mix and temporal arrangement of the different components;
2. Functional basis – refers to the major function or role of the system, mainly of the woody components (these can be productive, e.g. production of food, fodder, fuelwood and so on), or protective (e.g. windbreak, shelterbelt, soil conservation and so on);
3. Socio-economic basis – refers to the level of inputs of management (low-input) or intensity or scale of management and commercial goals (subsistence, commercial, intermediate);
4. Ecological basis – refers to the environmental condition and ecological suitability of the systems, on the assumption that certain types of systems are more common in/appropriate for certain ecological conditions.

A classification scheme of agroforestry systems based on these approaches is summarized in Table 1. These underlying principles of classification are by no means independent or mutually exclusive. Indeed it is obvious that they have to be interrelated because the structural and functional bases relate to the woody components in the systems whereas the socio-economic and ecological stratifications refer to the organization of systems according to certain defined conditions (socio-economic or ecological). And in any defined socio- economic or ecological situation, the systems should still have specific structure (composition and arrangement or components) and function / role.

Nevertheless, in agroforestry land-use systems, there are only three basic sets of components that are managed by man, viz., woody perennials, herbaceous plants and animals. Therefore, a simple and logical first step in classifying agroforestry systems is to use this component composition as the basis, which will give three basic types of agroforestry systems (Nair 1985):

1. Agrisilvicultural (crops – including tree and shrub crops – and trees);
2. Silvopastoral (pasture with animals and trees); and
3. Agrosilvopastoral (crops + pasture with animals + trees).

Other specialized agroforestry systems such as apiculture with trees, aquaculture in mangrove areas, multipurpose tree lots, and so on, can also be specified. A generalized picture of the component composition of these basic types of agroforestry systems is given in Figure 1.

This categorization of agroforestry systems into three major types is so fundamental that any one of these can conveniently be used as a prefix to other terms emanating from other efforts to classify or group agroforestry systems in order to explicitly express the basic composition of constituents of any such system. For example, there can be an agrisilvicultural system for food production, a commercial silvopastoral system for fodder and food production in lowland sub-humid (or dry) tropics, an agrosilvopastoral system for food production and soil conservation in highland humid tropics, and so on. Therefore it seems logical, compatible and pragmatic to accept the nature of components as the basic criterion in the classification of agroforestry systems.

Agroforestry practices and technologies

A further evaluation of the organization of these various agroforestry systems shows that an agroforestry system involves extensive application of agroforestry practices, thus forming a significant form of land use in a locality or area, described according to the system's biological composition and arrangement, level of technical management, or socio-economic features. An agroforestry practice, on the other hand, denotes a specific agroforestry combination in a land-management unit, and consists usually of arrangements of agroforestry components in space and/or time. Several such practices are involved in the constitution and maintenance of an agroforestry system.

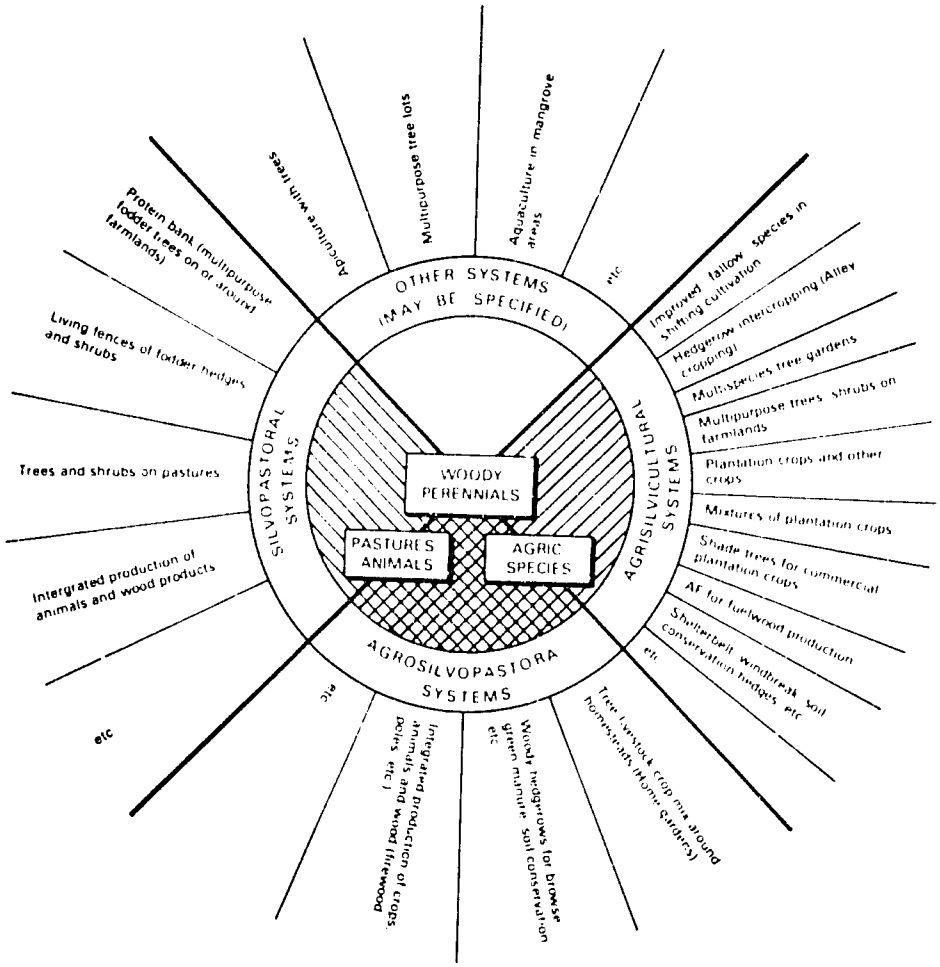
Although several agroforestry systems have been recorded from around the world, the distinctive agroforestry practices that constitute these systems in various ecoregions and locations are few in number. These most commonly found agroforestry practices and their essential characteristics are listed in Table 2 (Appendix page 72-77).

The scale of management and extent of adoption of these different practices in any particular system will vary considerably depending upon a number of factors. Any of these practices can become an agroforestry system when it is developed or spread to such an extent in a specific local area so as to form a distinct land utilization type in that

Table 1 Major approches in classification of agroforestry systems and practices (Nair 1985)

CATEGORIZATION OF SYSTEMS Based on their structure and function			GROUPING OF SYSTEMS According to their spread and management	
STRUCTURE Nature and arrangement of components especially woody ones		FUNCTION Role and/or output of components, especially woody ones	AGRO-ECOLOGICAL/ ENVIRONMENTAL	SOCIO-ECONOMIC AMD MANAGEMENT LEVEL
Nature of components	Arrangement of components			
Agrisilviculture (crops and trees incl. shrubs/trees and trees) Silvipastoral (pasture/animals and trees) Agrosilvopastoral (crops, pasture/ animals, and trees) Others (multipurpose tree lots, apiculture with trees, aquaculture with trees, etc).	In Space (Spatial) Mixed dense (e.g.: Home garden) Mixed sparce (e.g.: Most systems of trees in pastures) Strip (width of strip to be more than one tree) Boundary (trees on edges of plots/fields) In time (Temporal) Coincident Concomitant Overlapping Sequential (separate) Interpolated	Productive Function Food Fodder Fuelwood Other woods Other products Protective Function Windbreak Shelterbelt Soil conservation Moisture conservation Soil improvement Shade (for crop, animal, and man)	Systems in/for Lowland humid tropics Highland humid tropics (above 1,200 m a.s.l; e.g.: Andes, India, Malaysia) Lowland subhumid tropics (e.g.: savanna zone of Africa, Cerrado of South America) Highland subhumid tropics (Tropical highlands) (e.g.: in Kenya, Ethiopia)	Based on level of technology input Low input (Marginal) Medium input High input Based on cost/benefit relations Commercial Intermediate Subsistence

Figure 1 Categorization of agroforestry systems based on the nature of components (with examples of common sub-systems and practices under each system.)



area. One essential point to note here is that an agroforestry practice can be found to exist even in a non-agroforestry land-use system. An example is the practice of growing rows of *Sesbania grandiflora* on the bunds of rice paddies in Java, Indonesia. This woody species is harvested for its leaves as green manure, its flowers are eaten as a vegetable, it provides firewood and it adds to the fertility of the soil underneath through biological fixation of atmospheric nitrogen. Thus the woody species interacts ecologically and economically with the crop (rice) production system; in other words, it is an *agroforestry practice* in a crop production system.

Another term that is commonly used in all land use systems including agroforestry is 'technology'; it is usually used in combination with a particular production system or land-use system as the prefix; thus, agricultural technology, wood production technology, agroforestry technology, and so on. The word or suffix 'technology' in this sense

indicates an improvement or innovation, usually through scientific intervention, that can be applied with advantage in the management of the system or practice concerned. The inputs that are used for developing such technologies can sometimes be the most significant aspects, and these are called input technologies; e.g., improved varieties of plants, agrochemicals, and so on.

Most, if not all, of the practices mentioned in Table 2 (Appendix page 72-77) need to be improved scientifically and developed into modern agroforestry technologies. The success potential of an agroforestry practice (and therefore an agroforestry system) depends on the extent to which such technologies have been perfected, and made use of in the management of the practice (or the system).

Ecological spread of major agroforestry systems

Ecological zones of agroforestry significance in the tropics and subtropics

The major physical parameters that determine the ecology of a location in the tropics are rainfall (quantity and distribution) and temperature regimes. Altitude also is important because of its influence not only on temperature, but also on land relief characteristics. The FAO Agro-Ecological Zones inventory divides tropics into 'warm', 'moderately cool', 'cool' and 'cold' climates depending on the climatic (mainly temperature) regime during the 'growing period'. These growing periods refer to a few selected agricultural crops (that are seasonal) and therefore do not necessarily reflect the growing periods of perennial species (although it can be argued that the agricultural growing period represents the peak growing seasons of the perennial species also in most cases).

From the agroforestry point of view, the major ecological regions recognized in the FAO State of Food and Agriculture Reports (SOFA) are more relevant: these are temperate, mediterranean, arid and semi-arid, sub-humid tropical (lowland), humid tropical (lowland and highland. These classes, excepting the first (and possibly the second), represent the tropical and subtropical lands of agroforestry significance where agroforestry system. exist or have a potential. These major ecological regions of the tropics and subtropic. are presented in Figure 2, and the main characteristics of these major agro-ecological regions (adapted mainly from Young (1986)) are summarized in Table 3.

Agroforestry systems in lowland humid and sub-humid tropics

Characterized by hot, humid climates for all or most of the year, and an evergreen or semi-evergreen vegetation, the lowland humid and sub- humid tropics (but referred to as humid tropics) is by far the most important ecological region in terms of the total human population it supports, extent of area and diversity of agroforestry and other land-use systems. Because of the climatic conditions that favour rapid growth of a large number of plant species, various types of agroforestry plant associations can be found in areas with high human population. Various forms of homegardens, plantation crop combinations, and multilayer tree gardens are common in such regions. In areas with low population density, such as the low selvas of Latin America, trees on rangelands and pastures, other silvopastoral systems, improved fallow in shifting cultivation areas, multipurpose tree woodlots, etc., are the major agroforestry systems. Examples of agroforestry systems in humid tropical lowlands about which ICRAF has data entries in the computerized AFSI database are included in Table 4 (Appendix page 78-92).

Figure 2 Major ecological regions of the tropics and subtropics.

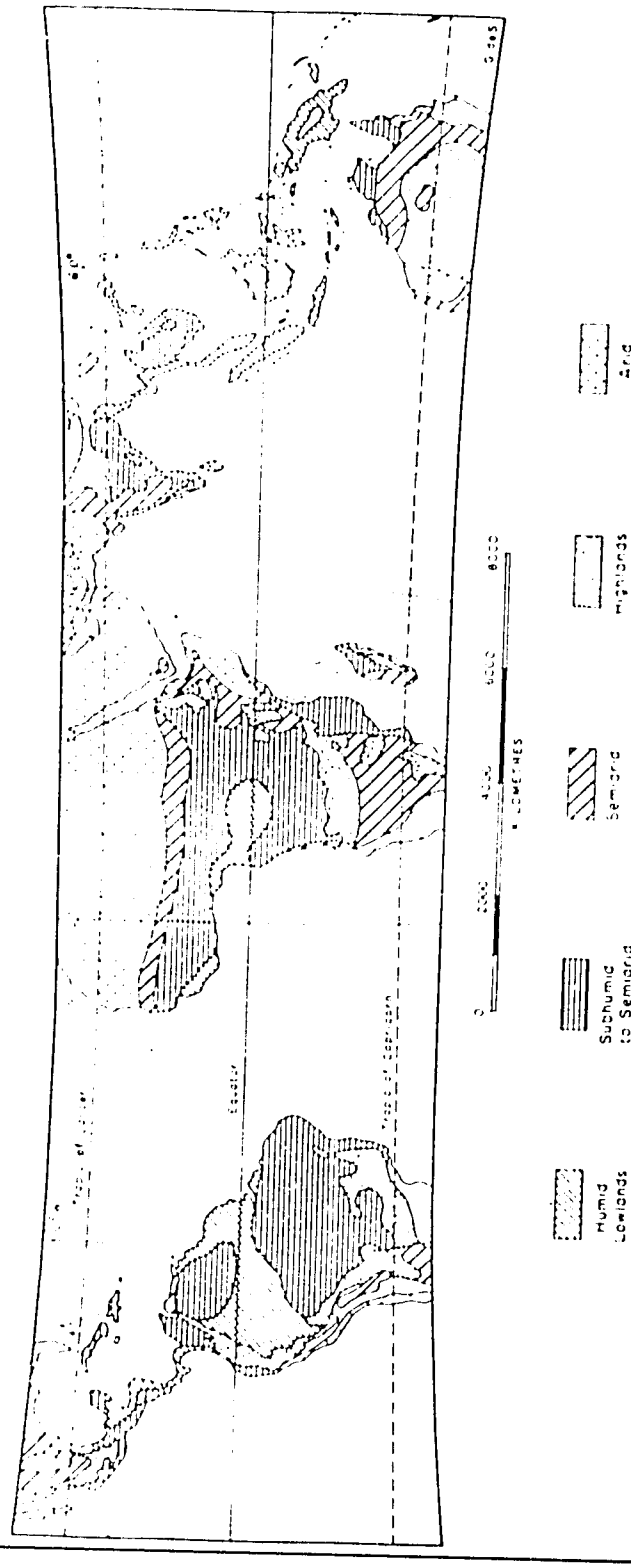


Table 3 Main characteristics of the major ecological regions of agroforestry importance in the tropics and subtropics. (Adapted from A. Young 1986; in consultation with A. Young.)

Characteristics	Humid/Sub-humid Lowlands	Dry Region (Semi-arid and arid)	Highlands
Climate	Hot, humid for all or most of the year, rainfall > 1000 mm; sometimes one or more extended dry periods per year; Köppen Af, Am and some Aw, esp Aw".	Hot, one or two wet seasons and at least one long dry period; rainfall < 1000 mm; Köppen Aw" (some), Aw', and B climates.	Cool temperatures, sub-humid or humid (arid highlands are of low AF potential); altitude over 1000 m; Köppen Ca, Cw agricultural growing period over 120 days).
Vegetation & Soils	Evergreen or semi-evergreen vegetation; Ultisols (Acrisols) and Oxisols (Ferralsols) and other acid, low-base tropical-soils.	Savannas with low or medium-high trees and bushes (Aw); thorn scrub and steppe grasslands (BS), Vertisols, Alfisols (Luvisols, Nitosols) and Entisols.	Evergreen to semi-evergreen vegetation depending on rainfall. Oxisols (Humic Ferralsols) and Ultisols (Humic Acrisols) Andosols (volcanic soils).
Major geographical spread (of areas with AF importance)	All tropical continents, especially Southeast and South Asia, West Africa and Central and South America; about 35% of tropical land.	Savanna and sub-Saharan zones of Africa, Cerrado of South America, semi-arid and arid parts of Indian subcontinent; approx. 45% of total tropical land.	Asia (Himalayan region, some parts of southern India and S.E. Asia), East and Central African highlands, Andes; about 20% of tropical land.

Table 3 page 2

Main land-use systems	Commercial forestry, agricultural tree crop plantations, rice paddies (esp. Asia), ranching S. America), shifting cultivation, arable cropping.	Arable farming, extensive ranching or nomadic pastoralism, perennial crop husbandry towards the more humid areas, forestry.	Arable farming, plantation agriculture and forestry, ranching (in S. & C. America), shifting cultivation.
Main land-use and ecological problems	Excessive deforestation (and consequent shortening of fallows, etc.) over-grazing, soil acidity and consequent problems, low soil fertility, high rainfall erosivity.	Drought (in areas with less rainfall), soil fertility decline caused by over-cultivation, over-grazing, degradation of deciduous wood-land, fuelwood/fodder shortage.	Soil erosion; shortening of fallows; over-grazing, deforestation and ecosystem degradation; fodder/fuel shortage.
Major agroforestry emphasis	Improved fallows, soil fertility improvement and conservation, food production.	Fuelwood/fodder production, soil fertility improvement, windbreaks and shelterbelts, food production.	Soil conservation, fodder/fuel production, watershed management, ecosystem stabilization and protection of rare species.

The lowland humid tropics also represents areas under natural rain forests. In such areas, cutting of rain forest at rates much faster than natural or managed regeneration is a common problem. This causes shortening of fallow periods in shifting cultivation cycles and resultant loss of soil productivity and accelerated soil erosion. The potential of appropriate agroforestry systems to combat these problems needs to be exploited in future land-use strategies in this zone.

Agroforestry systems in semi-arid and arid tropics

Extending over the savanna and Sudano-Sahelian zones of Africa, the cerrado of South America and large areas of the Indian subcontinent, the semi-arid and arid tropics are characterized by one or two wet seasons (Köppen Aw or Aw", respectively) and at least one long dry season. Drought is a hazard in the drier parts of the zone.

The main agroforestry systems in this zone also depend on the human population pressure; homegardens and multilayer tree gardens are common in the wetter areas with high population pressure. But generally speaking, the predominant agroforestry systems in this zone are:

1. Various forms of silvopastoral systems;
2. Windbreaks and shelterbelts; and
3. Multipurpose trees on crop lands, notably *Acacia albida*-based systems in Africa and *Prosopis*-based agrisilvicultural systems in the Indian sub-continent.

Fuelwood shortage is a major problem in most parts of the semi- arid and arid tropics. Agroforestry potentials in fuelwood production are well documented (e.g., Nair, forthcoming). Similarly, desertification and fodder shortage – the other major ecological problems in this zone – could be tackled to some extent through the agroforestry approach.

Agroforestry systems in tropical highlands

Approximately 20% of the tropical lands are at elevations from 900 to 1800 m, in about half of the Andean highlands of Central and South America, parts of Venezuela and Brazil, the mountain regions of the Caribbean, many parts of East and Central Africa, the Cameroons, the Deccan Plateau of India and some parts of the southeast Asia mainland. The altitude exceeds 1800 m in about 3% of the tropical area in the Andes, the Ethiopian and Kenyan Highlands, northern Burma and parts of Papua New Guinea. In the subtropical regions, the most important highlands are in the Himalayan region. These highland tropics with significant agroforestry potential are humid or sub-humid, such areas with dry climates being of very low potential.

Land-use problems in the highlands are similar to those in humid or dry lowlands depending on the climate, with the addition that sloping lands and steep terrains make soil erosion an issue of major concern. Moreover, annual temperatures are low in the highlands (for every 100 m increase in elevation in the tropics, there is a decline of 0.6°DC in the mean annual temperature), which affect the growth of certain lowland tropical species.

The main agroforestry systems in tropical highlands are:

1. Production systems involving plantation crops such as coffee and tea in commercial as well as smallholder systems;
2. Use of woody perennials in soil conservation and soil fertility maintenance;

3. Improved fallows; and
4. Silvopastoral combinations.

Agro-ecological analysis of existing agroforestry systems

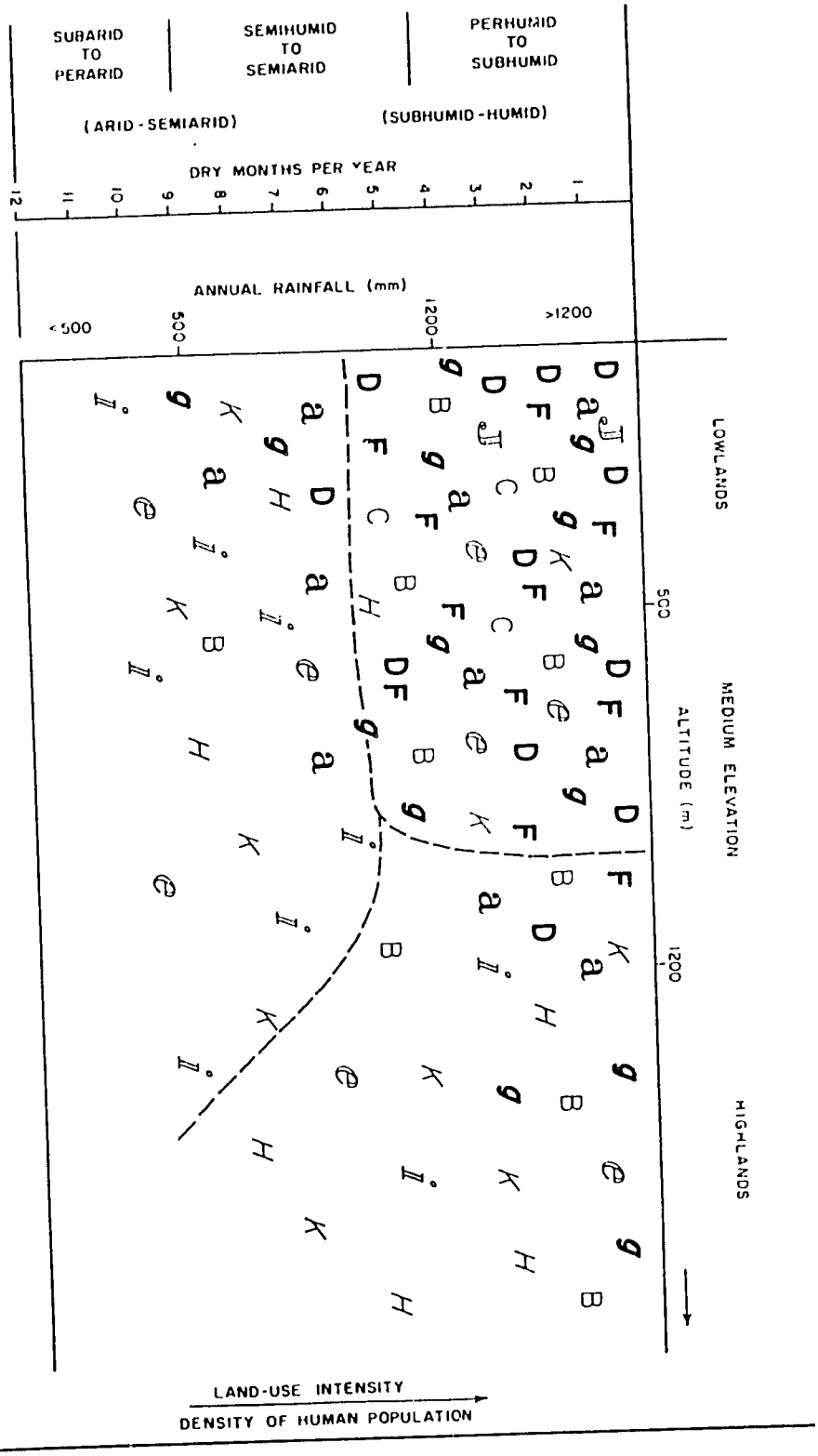
The existence of an agroforestry system or practice in a particular area is determined not only by the environmental and agro-ecological factors, but also by socio-economic considerations. In different areas with identical agroclimatic conditions, factors such as human population pressure, availability of labour and other production resources, proximity and accessibility to market sources, etc., are the main determinants of the types and forms of agroforestry systems. Even in the case of systems that are widespread in most ecological and geographical regions such as shifting cultivation and taungya, these systems have very many variants that are specific to certain defined situations. As a general rule, it can be said that while the ecological factors determine the major type of an agroforestry system in a given locality, the complexity of the system and the degree of intensity of its management increase in direct proportion to the population intensity and land productivity of the area. A typical example is the spread of the multi-species, multi-storied homegarden systems. Though found mostly in humid lowlands, the homegardens are common in pockets of high population density in other ecological regions also. Analysing the structural and functional aspects 10 selected homegarden systems from different ecological regions, Fernandes and Nair (1986) found that although the average size of the homegarden units is less than 0.5 ha, the units are composed of a large number of woody and herbaceous species, carefully structured to form 3-5 vertical canopy strata, and each component having a specific place as well as function in the multispecies complex.

There are some functional aspects of specific agroforestry practices that are emphasized or necessitated in specific agroecological situations. For example, the functional emphasis of agroforestry systems in sloping lands is erosion control and soil conservation; in wind-prone areas, woody species are successfully used in agroforestry practices of shelterbelts and windbreaks; the emphasis is on fuelwood production in areas with fuelwood shortage; there are also specific agroforestry approaches for the reclamation of degraded lands and other waste lands (such as highly eroded lands, areas with high levels of salinity or alkalinity, etc.)

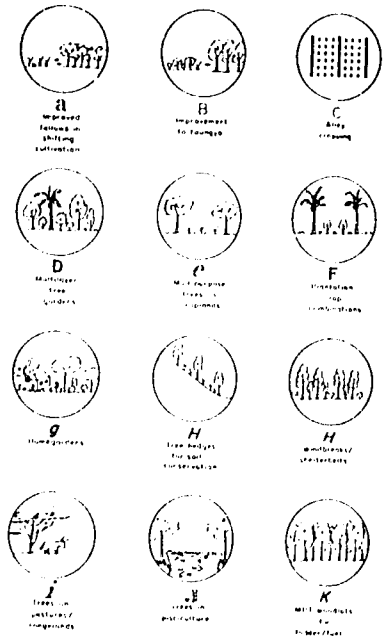
The ecological potential of an area is undoubtedly the prime factor that decides the adoption and spread of specific agroforestry systems in different parts. The preponderance of homegardens and other multi-species mixes in fertile lowlands and high potential areas at one end of the ecological scale and extensive silvopastoralism at the other end, with various systems in between gives a spectrum of agroecological adaptability and spread of various agroforestry systems. Figure 3 shows the general pattern of the major agroforestry systems in various ecological regions. It does not include all agroforestry systems, nor does it fully portray the relative spread (in terms of areas involved) or the level of management of the various systems. A further step in this direction is to indicate the major known areas of concentration of important agroforestry systems in the tropics and subtropics, i.e., something like a 'map of the agroforestry situation in the tropics and subtropics' (Figure 4).

This 'map' represents areas with relative abundance of specified agroforestry systems, but does not identify localized systems as well as systems whose presence is relatively less significant in an area. For example, as mentioned earlier, 'multipurpose trees on farmlands' can be found in almost all ecological and geographical regions. But there are only a few such systems that make them distinctly unique agroforestry systems. Examples include the arid zone systems involving *Acacia albida* (Miehe 1986; Poschen

Figure 3 Ecological spread of major agroforestry systems.



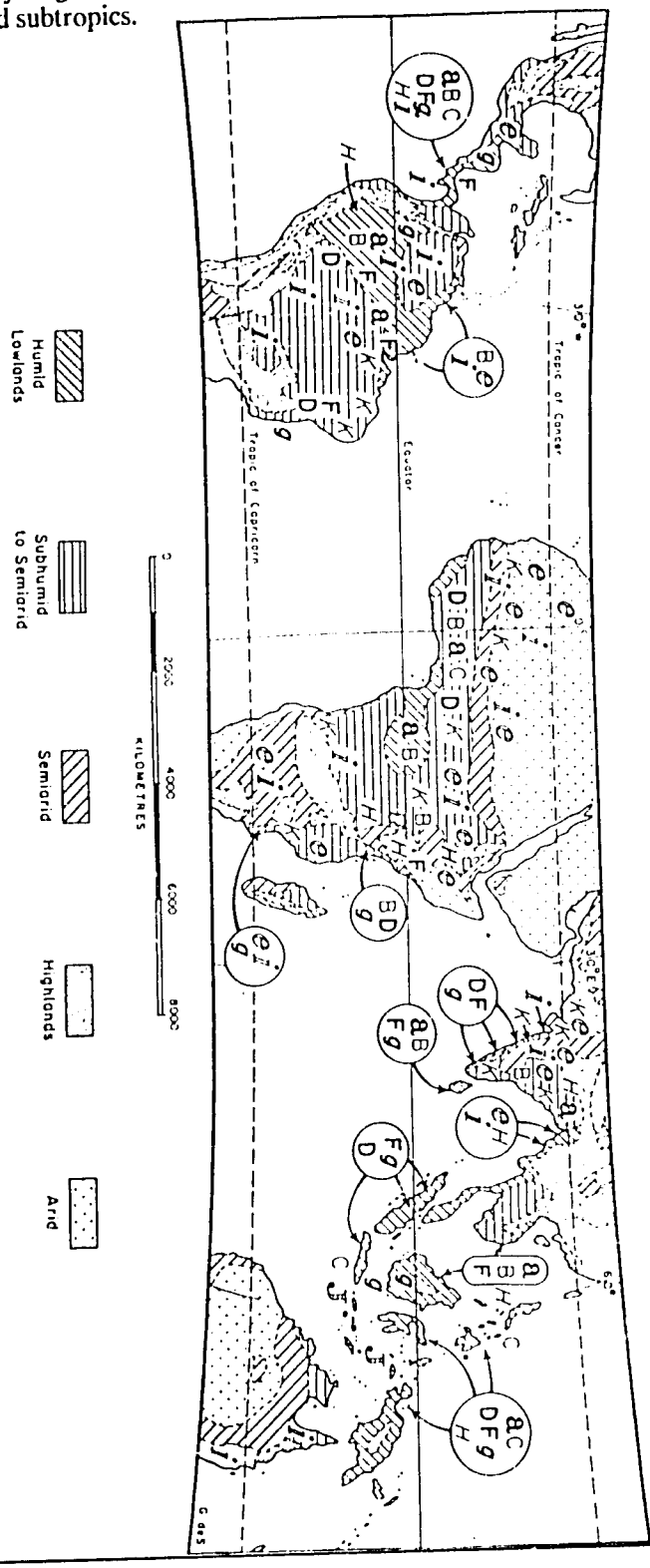
Legend for system names in Figure 3 and Figure 4



1986) and *Prosopis* (Shankarnarayan and Harsh 1987). Thus, only some such 'multi-purpose trees on farmlands' systems have been studied and/or described in some detail, and thus gone into ICRAF's Agroforestry Systems Inventory (AFSI) data records. The mention of the existence of any of these systems on Figure 4 therefore is mainly an indication that AFSI records are available. Indeed, innumerable location-specific agroforestry systems and practices do exist all over the tropics and subtropics and many of them are important in various ways. But most of them may not often be significant enough in terms of their individual importance in the overall economy and land-use pattern of the area where they exist, and thus may not merit a special mention on such a condensed and abstract global map.

This 'map' is an improvement over Figure 3 in that geographical spread of the systems is shown in relation to the ecological conditions in different places. One significant feature that emerges from this is that irrespective of the socio-cultural differences in different geographical regions, the major types of agroforestry systems are structurally similar in areas with identical ecological characteristics. The level of intensity at which these different systems are managed will, obviously, be different in various situations.

Figure 4 Major agroforestry systems in different ecological regions of the tropics and subtropics.



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Appendix:
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Table 2 Major agroforestry practices

Agroforestry practice	Brief description (of arrangement of components)	Major groups of components w: woody h: herbaceous f: fodder for grazing a: animals	*Main types of components interactions in space(s)/ time(t)	Primary role of woody component Prt: protective Prd: productive	Agroecological adaptability
A. AGRISILVICULTURAL SYSTEMS (Crops – including shrub/vine/tree crops – and trees)					
1. Improved fallow	Woody species planted and left to grow during the 'fallow phase'	w: fast-growing, preferably leguminous h: common agri. crops	t: sequantial (in rotational-cyles)	Prt: soil fertility improvement Prd: wood products	in shifting cultivation areas
2. Taungya	combined stand of woody and agric. species during early stages of establishment of plantations	w: usually planta tion forestry spp. h: common agri. crops	s: concomitant t: sequential (in rotational cycles)	Prd: addl. income from agric. crops; also management care for plantation species	in all ecol. regions (where taungya is practised); several improvements possible

Table 2 page 2

3.	Alley cropping (hedgerow intercropping)	woody species in hedges; agri. spp. in alleys in between hedges; microzonal or strip arrangement	w: fast-growing leguminous that coppice vigorously h: common agric. crops products	s: zonal (strip) t: concomitant to intermittent	Prt: soil improvement, and/or soil conservation Prd: addl. products from hedges	sub-humid to humid areas with high human population pressure and fragile (productive but easily degradable) soils
4.	Multilayer tree gardens	multispecies, multilayer dense plant associations with no organized planting arrangements	w: different woody com ponents of varying form and growth habits h: usually absent; shade tolerant ones sometimes present	s: mixed dense t: coincident	Prd: various types of outputs Prt: soil conservation and protection efficient nutrient nutrient cycling	areas with fertile soils, good availability of labour, and high human population pressure
5.	Multipurpose trees on crop lands	Trees scattered haphazardly or according to some systematic patterns on bunds terraces or plot/field boundaries	w: multipurpose trees and other fruit trees h: common agri. crops	s: mixed sparce t: interpolated	Prd: prod. of various tree products Prt: fencing, social values, plot demarcation	in all ecolological regions especially in subsistence farming; also commonly integrated with animals

Table 2 page 3

6.	Plantation crop combinations	1) Integrated multi storey (mixed, dense) mixture of plantation crops 2) Mixtures of plantation crops in alternate or other regular arrangement 3) Shade trees for plantation crops; shade trees scattered 4) Intercropping with agric. crops	w: plantation crops like coffee, cacao, coconut, etc., fruit trees (esp. in 1); fuelwood/fodder spp. esp. in 3 h: usually present in 4, and to some extent in 1; shade tolerant species	s: mixed dense (1,2,4) or mixed sparce (3) t: 1) interpoated 2) coincident or overlap ping 3) coincident 4) intermittent or concomittant	Prd: prod. of a large number of pro duces Prt: soil surface pro tection shade and windbreak	in humid lowlands or tropical humid/ sub-humid highlands (depending on the adaptability of the plantation crops concerned); usually in small-holder subsistence system
7.	Home gardens	Intimate, multistorey combination of various trees and crops around homesteads	w: fruit trees predominate; also other woody spp; vines, etc h: shade-tolerant crops	s: mixed dense t: coincident to interpolated	Prd: prodn. of various products Prt: soil surface protection	in all ecol. regions esp. in areas with high population density
8.	Trees in soil con-servation and reclamation	Trees on bunds, terraces, raisers, etc with or without grass strips; trees for soil reclamation	w: multipurpose and/or fruit trees h: common agri. species	s: zonal (strip) t: intermittent	Prt: soil conservation Prd: various tree pro-ducts	in slopping areas esp. in highlands, reclamation of de-graded, acid, alkali soils; and sand dune stabilization

Table 2 page 4

9. Shelterbelts and windbreaks, live hedges	Trees around farmlands/plots	w: combination of tall-growing spreading types h: agri. crops of the locality	s: zonal(strip/ boundary) t: coincident, interpolated	Prt: shelterbelts/ windbreak; fencing Prd: usually firewood	in wind-prone areas
10. Fuelwood production	Interplanting firewood species on or around agri. lands	w: firewood species h: agri. crops of the locality	s: zonal (strip/ boundary) t: coincident	Prd: firewood Prt: fencing; shelterbelts; boundary demarcatin	in all ecol. regions
B. SILVOPASTORAL SYSTEMS (trees + pasture and/or animals)					
11. Trees on rangeland or pastures	Trees scattered irregularly or arranged according to some systematic pattern	w: multipurpose; usually of fodder value f: present a: present	s: mixed sparse t: coincident	Prd: trees as fodder Prt: shade; environmental protection	extensive grazing areas
12. Protein banks	Production of protein rich tree fodder on farm/range lands for cut-and-carry fodder production	w: leguminous fodder trees h: present f: present	s: zonal t: coincident or interpolated	Prd: fodder prodn. Prt: soil and environmental protection depending on arrangement	usually in areas with high man: land ratio.

Table 2 page 5

13. Plantation crops with pastures and animals	example: cattle under coconuts in southeast Asia and the south Pacific	w: plantation crops f: present a: present	s: mixed sparse t: intermittent	Prt: shade and protection to fodder and animals Prd: plantation crop products	in areas with less human pressure on plantation crop lands
C: AGROSILVOPASTORAL SYSTEMS (trees + pasture/animals)					
14. Home gardens involving animals	Intimate, multi-storey combination of various trees and crops, and animals, around homesteads	w: fruit trees predominate; also other woody spp. a: present	s: mixed dense t: interpolated to coincident	Prd: various products Prt: soil surface protection; organic recycling	in all ecol. regions with high density of human population
15. Multipurpose woody hedge rows	woody hedges for browse, mulch, green manure, soil conservation, etc	w: fast-growing and coppicing fodder shrubs and trees h: (similar to alley cropping and soil conservation)	s: zonal (strip or boundary) t: intermittent to coincident	Prt: soil conservation Prd: various products, mainly fodder	humid to sub-humid areas with hilly and slopping terrain

Table 2 page 6

D. OTHERS

16. Apiculture with trees	Trees for honey production	w: honey producing trees (other components may be present)	s: boundary, mixed, sparse (or any other) t: (variable)	Prd: honey production Prt: location specific	depending on the feasibility of apiculture
17. Aquaforestry	Trees lining fish ponds, tree leaves being used as 'forage' for fish	w: trees and shrubs preferred by fish (other components may be present)	s: boundary planting t: coincident to intermittent	Prd: fish production Prt: bund stabilization around fish ponds	lowlands
18. Multipurpose woodlots	for various purposes, (wood, fodder, soil protection, soil reclamation etc.)	w: multipurpose species; special location specific spp (other components may be present)	s: zonal or mixed t: separate or overlapping	Prt: various protective Prd: various	various

*TEMPORAL ARRANGEMENTS OF COMPONENTS IN AGROFORESTRY SYSTEMS

----------COINCIDENT
----------CONCOMITANT
----------INTERMITTENT
----------OVERLAPPING
----------SEPARATE
----------INTERPOLATED
----------Woody species
----------non-woody compoent

Table 4 Major agroforestry systems and practices in different ecological zones of the tropics and subtropics (Source: AFSI Database, ICRAF)

System/Practice	Major output/ function	Country/Region	Socio-economic scale of production	Major woody species involved	Remarks
1. HUMID/SUB-HUMID LOWLANDS					
1.1 Agrisilvicultural Systems					
1. Improved 'Fallow' (in shifting cultivation areas)	Food and wood production; Soil fertility improvement	Indonesia	Subsistence	*Aleurites molucana* *Erythrina spp.* *Styrax spp.*	
		Nigeria	Subsistence	*Acioa barterii* *Anthonotha macro phylla* *Gliricidia sepium*	
		Also being tried in many other places		Various fruit trees also being tried	'Forest villages of Thailand"; Boonkird et al., 1984; AFSD-2; Annex. I. Allen, 1985; AFSD-9; Annex. I.

Table 4 page 2

2.	Hedgerow intercropping (Alley cropping)	Production of food and firewood; Soil fertility improvement and soil conservation	S.E. Asia Nigeria Now being tried in very many places, mostly on experimental basis	Subsistence (Experimental)	*Calliandra callothyrsus* *Leucaena leucocephala* and several other species	
3.	Multispecies mixes (Tree gardens)	Production of food, fodder and wood products for home consumption and sale for cash	Nigeria	Subsistence	*Daniellia oliveri* *Gliricidia sepium* *Parkia clappertoniana* *Pterocarpus africana*	'Compound gardens of Nigeria' (Okafor and Fernandes, 1987; AFSD 24; Annex. I).
			Pacific Islands	Subsistence	*Inocarpus edulis* *Morus nigra* *Spondias dulce*	
			India Sri Lanka	Subsistence, Intermediate	*Areca catechu* *Artocarpus spp.* *Cocos nucifera* *Mangifera indica* *Zyzygium aromaticum*	'Homestead agroforestry in Kerala, India' (Nair and Sreedharan, 1986; AFSD-18; Annex. I).
			Paraguay	Subsistence, Intermediate	*Melia azedarach* *Leucaena leucocephala*	

Table 4 page 3

			S.E. Asia	Subsistence_ Intermediate	*Albizia falcataria* *Artocarpus spp.* *Bambusa spp.* *Cinnamomum aromaticum* *Durio zibethinus* *Nephelium lappacium*	Agoforestry garden system of Sumatra' (Michon et al., 1986; AFSD 21; Annex. I).
4.	Multipurpose trees/shrubs on farmlands	Production of food, fuelwood, other wood products; Sustainability of production; Soil conservation	Brazil	Intermediate Subsistence	*Cassia excelsa* *L. leucocephala* *Mimosa scabrella*	
			India	Subsistence Intermediate	*Derris indica* *Emblica officinalis* *Moringa oleifera* *Tamarindus indica*	Jambulingam and Fernandes, 1986; AFSD-15; Annex. I.
			Kenya	Subsistence	*Anacardium occidentale* *Ceiba pentandra* *Mangifera indica* *Manilkara achras*	
			S.E. Asia	Subsistence Intermediate Commercial	*Acacia mangium* *Artocarpus spp.* *Durio zibethinus* *Gliricidia sepium* *Sesbania grandiflora*	Nair and Sreedharan, 1986;AFSD-18; Annex I.

Table 4 page 4

5. Crop combinations with plantation crops					Plantation crops involved *Anacardium occidentale* *Camellia sinensis* *Cocos nucifera* *Coffea arabica* *Elaeis guineensis* *Hevea brasiliensis* *Piper nigrum* *Theobroma cacao*	
(i) Integrated production of plantation crops and other crops	Production of plantation crops for sale (cash); Production of subsidiary (food) crops; Sustainability					
(ii) Mixtures of plantation crops		Brazil	Commercial to subsistence		*Bertholletia excelsa* *Copernicia prunifera* *Cordia alliodora* *Inga spp.* *Orbignya spp.* *Samanea saman*	Alvim and Nair, 1986; AFSD-13; Annex. I. Johnson and Nair, 1984; AFSD-8, Annex. I. May et al., 1985; AFSD-11; Annex. I.

Table 4 page 5

	(iii) Shade trees for commercial plantation crops		Costa Rica	Commercial to subsistence	*Cordia alliodora* *Erythrina poeppigiana* *Gliricidia sepium* *Inga spp.*	
			India, Sri Lanka	Subsistence to commercial	*Albizia spp.* *Cassia spp.* *Erythrina spp.* *Grevillea robusta*	Liyanage et al., 1984; AFSD-7; Annex. I.
			S.E. Asia	Commercial to subsistence	Various fruit trees	
			West Indies	Subsistence Intermediate	*Inga vera* Various spice trees	
			Western Samoa		*Erythrina variegata* *Gliricidia sepium* *Leucaena leucocephala*	
6.	AF for fuelwood production (Inter-planting firewood species on or around field/farms)	Production of fuel-wood; Production of other products like food, poles, fodder;	India	Subsistence	*Albizia spp.* *Cassia siamea* *Casuarina spp.* *Derris indica* *Emblica officinalis*	Nair (forthcoming) Jambulingam and Fernandes, 1986; AFSD-15; Annex. I.
		Fencing, shade, shelterbelts, etc	Indonesia	Subsistence	*Albizia falcataria* *Calliandra callothyrsus* *Sesbania grandiflora* *Trema orientalis*	

Table 4 page 6

7.	Shelterbelts, windbreaks, soil conservation hedges	Protective roles (shelterbelt wind-break, etc.) Soil conservation; Production of food, fuelwood	India	Subsistence Intermediate	*Casuarina equisetifolia* *Syzygium cuminii*
			Indonesia and other parts of S.E. Asia.	Subsistence Intermediate	*Gliricidia sepium* *Leucaena leucocephala* *Sesbania grandiflora*
1.2	**Silvopastoral Systems (Humid/sub-humid lowlands)**				
1.	Protein bank Multipurpose trees on or around farmlands	Production of fodder/livestock and food crops	India Nepal, Sri Lanka	Mostly-subsistence	*Artocarpus spp.* *Anogeissus latifolia* *Bombax malabaricum* *Cordia dichotoma* *Dalbergia jambolana* *Samanea spp.* *Zizyphus jujuba*
2.	Living fences of fodder trees and shrubs	Service function (fences); Production of tree products	Costa Rica		*Diphysa robinoides*
			Ethiopia	Subsistence	*Gliricidia sepium* *Erythrina abyssinica*
			S.E. Asia	Subsistence	*Sesbania grandiflora*

Table 4 page 7

3. Trees and shrubs on pastures	Production of pasture/ livestock and wood	Brazil	Mostly subsistence	*Acacia spp.* *Anacardium occidentale* *Cedrela odorata* *Cordia alliodora* Various palms	Johnson and Nair, 1984; AFSD-8; Annex. 1.
		Costa Rica	Subsistence	*Enterolobium cyclocarpum* *Erythrina poeppigiana* *Samanea spp.*	Escalante, 1985; AFSD-10; Annex. I.
		India	Subsistence to intermediate	*Derris indica* *Emblica officinalis* *Psidium guajava* *Tamarindus indica*	
1.3. Agrosilvopastoral Systems (Most Ecological Zones)					
1. Home Gardens Tree-crop-livestock mix around homestead	Production of food/fodder/fuel-wood, etc. for home	South and S.E. Asia	Subsistence to intermediate		'Kandyan gardens of Sri Lanka' (Jacob and Alles, 1987; AFSD-23; Annex. I).

Table 4 page 8

	(these dense associations are found in almost all ecological regions and countries; only some examples are given	consumption, and, sometimes, for sale (cash)	Nigeria Latin American countries Tanzania (Highlands)	Mostly subsistence Mostly subsistence Subsistence to intermediate		'Chagga homegardens' (Fernandes et. al. 1984.)AFSD-1; Annex. I).
2.	Woody hedgerows for browse, mulch, green manure and soil	Production of food/fodder/fuelwood; Soil conservation	Indian sub-continent S.E. Asia	Mostly subsistence	*Erythrina spp.* *Leucaena leucocephala* *Sesbania spp.*	'Homestead agroforestry in Bangladesh' (Leuschner and Khalique, 1987; AFSD-25; Annex. I).

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2. (DRY) SEMI-ARID AND ARID REGIONS

2.1. Agrisilvicultural Systems

1. Multipurpose trees and shrubs on farmlands In many places, strips of trees are planted along the edges of contour terraces	(same as in lowlands)	Brazil	Subsistence	*Caesalpinia ferrea* *Prosopis juliflora* *Zizyphus joazeiro*	
		Central African Republic	Subsistence	*Adansonia digitata* *Balanites aegyptiaca* *Borassus aethiopium*	
		India	Subsistence	*Cajanus cajan* *Derris indica* *Prosopis cineraria* *Tamarindus indica*	Shankarnarayan and Harsh, 1987; AFSD-22; Annex. I.
		Kenya	Subsistence	*Acacia spp.* *Balanites aegyptiaca* *Cajanus cajan*	
		Sudan & Sahelian countries	Subsistence	*Faidherbia albida*	Poschen, 1986; AFSD-17, Annex. I. Miehe, 1986; AFSD, 1986; Annex. I.

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			Tanzania	Subsistence	*Acacia spp.* *Combretum spp.*	
2.	AF Fuelwood production	Fuelwood	Chile	Subsistence	*Prosopis tamarugo*	
			India	Subsistence	*Albizia lebbek* *Cassia siamea* *Prosopis spp.*	
			Sahel	Subsistence	*Acacia albida* *A. senegal* *A. tortilis*	
3.	Shelterbelts and Wind-breaks	Protection of agri. fields fields from winds; Production of fuel-wood	India Pakistan	Subsistence, Intermediate	*Azadirachta indica* *Cajanus cajan* *Cassia siamea* *Eucalyptus spp.* *Pithecellobium dulce* *Populus spp.*	Shankarnarayan and Harsh, 1987; AFSD-22; Annex. I.
2.2	**Silvopastoral Systems (Dry Regions)**					
1.	Protein bank	Same as in other regions	India	Subsistence	*Acacia nilotica* *Ailanthus excelsa* *Opuntia ficus* *Prosopis spp.* *Rhus sinuata*	Jambulingam and Fernandes, 1986; AFSD-15; Annex. I.

Table 4 page 11

2.	Living fences	Same as in other regions	East Africa	Subsistence	*Acacia spp.* *Commiphora africana* *Euphorbia tirucalli* *Zizyphus mucronata*
3.	Trees and shrubs on pastures	Same as in other regions	India	Subsistence	*Acacia spp.* *Prosopis spp.* *Tamarindus indica*
			Middle East and Mediterranean	Commercial	*Acacia spp.* *Ceratonia siliqua* *Haloxylon spp.* *Prosopis cineraria* *Tamarix aphylla*

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3. TROPICAL HIGHLANDS

3.1. Agrisilvicultural Systems

1.	Multipurpose trees and shrubs on farmlands	Food production; Soil conservation	India	Subsistence	*Albizia spp.* *Bauhinia variegata* *Dalbergia sissoo* *Ceiba petandra* *Eriobotrya japonica* *Grevillea robusta*	'Hill farming in Nepal' (Fonzen and Oberholzer, 1984; AFSD 4; Annex. I).
			Kenya	Subsistence		
			Nepal	Subsistence	*Bauhinia spp.* *Erythrina spp.* *Ficus spp.* *Litsea polyantha* *Melia azedarach*	
			Paraguay	Subsistence		'Gigante woodlots' (Evans and Rombold, 1984; AFSD-5; Annex. I).
			Tanzania	Subsistence	*Albizia spp.* *Cordia africana* *Croton macrostachys* *Trema guineensis*	

Table 4 page 13

2.	Crop combinations with plantation crops		Brazil	Subsistence, Intermediate	*Alnus acuminata* *Enterolobium contorsiliquum* *Erythrina velutina*	
			Costa Rica	Subsistence, Intermediate	*Alnus acuminata* *Erythrina poeppigiana* *Inga spp.*	
			India	Subsistence	*Albizia spp.*	Bourke, 1984; AFSD-6; Annex. I.
			Sri Lanka		*Grevillea robusta*	
			Kenya	Subsistence	*Grevillea robusta*	
			Papua New Guinea	Subsistence, Intermediate	*Casuarina olygodon*	
			Rwanda	Subsistence	*Albizia spp.*	
			Tanzania	Subsistence	*Cordia africana* *Grevillea robusta* *Trema guineensis*	
3.	AF Fuelwood production	(same as lowlands)	India Nepal	Subsistence	*Albizi stupulata* *Bauhinia spp.* *Grewia spp.*	

Table 4 page 14

4.	Shelterbelts, Windbreaks, Soil conservation Hedges				(same as in lowlands)
3.2. Silvopastoral Systems (Tropical Highlands)					
1.	Protein Bank	Production of fodder/animals and fuelwood; Soil conservation	Indian sub-continent	Mostly Subsistence	*Albizia stipulata* *Bauhinia spp.* *Ficus spp.* *Grewia oppositifolia* *Morus alba*
2.	Living fences	Service roles	Costa Rica	Commercial to subsistence	*Gliricidia sepium*
			Ethiopia	Commercial to subsistence	*Erythrina abyssinica*
			East Africa	Commercial to subsistence	*Dovyalis caffra* *Euphorbia tirucalli* *Iboza multiflora*

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3.	Trees and shrubs on pastures	Fodder/animal production; food production	Brazil	Mostly subsistence	*Desmanthus variegatus* *Desmodium discolor*
			Costa Rica	Mostly subsistence	*Alnus acuminata*
			Indian sub-continent	Mostly subsistence	*Albizia stipulata* *Alnus nepalensis* *Grewia spp.* *Robinia pseudoacacia*

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SECTION 2

Basic principles

- Climate and plant responses: a note on the use of phenological data for the design and management of agroforestry systems. — P.A. Huxley, E. Akunda, A. Repollo
- Crop simulation models and some implications for agroforestry systems. — A.K.S. Huda, C. Ong
- The assessment of stability of agroforestry systems. — J. Riley
- Agroforestry systems : a production/protection land use strategy for steep land in the tropics. — G. de las Salas
- Control of solar radiation climate in agroforestry practice. — W.E. Reifsnyder
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Climate and plant responses: the use of phenological data to help with the choice of woody species for agroforestry systems

P.A. Huxley, E. Akunda and A. Repollo*

International Council for Research in Agroforestry (ICRAF)
P.O. Box 30677, Nairobi, Kenya

Abstract

The value of interpreting a woody plant's behavioural characteristics in relation to environmental changes, both aerial and edaphic, is briefly discussed in relation to understanding species adaptability. Possibilities for managing the external environment and/or the plant itself, so as to synchronize vegetative growth and flowering/fruiting patterns favourably in relation to expected climatic sequences, can also be an outcome of such studies. The methods of investigating phenological behaviour are outlined, and two examples are given from a preliminary branch phenology study carried out at ICRAF's Field Station to illustrate the results of such investigations.

Introduction

Plant phenology is the study of changes in the plant's behavioural characteristics in relation to environment. There is an extensive literature on this subject (e.g., Lieth 1974; Huxley 1983), including many papers relating to the phenology of tropical woody species (e.g., Huxley and Van Eck 1974).

The practical value of understanding the relations between climate and crop growth phases has been discussed, with examples, by Watts Padwick (1979), and the 'heat unit' or day-degree summation approach to predicting crop plant responses has also been extensively reported in the literature (e.g., Iwata 1975). Although many of the comments that follow apply to plants in general, the present paper is specifically concerned with the phenology of woody perennials.

Phenological studies on areas of vegetation can present problems because individual woody plants can sometimes be out of phase with others of the same species, depending on the influences imposed by the site, other external influences and by internal rhythms. Large samples are often required, therefore, for the purpose of describing the behaviour of vegetation complexes (Grouzis and Sicot 1981). However, providing the limitations of the method are recognized, recording behavioural responses and climatic sequences for just a few specimens of any woody species can certainly be informative, as long as the interaction with site characteristics can be clearly defined. Such an activity can provide information on adaptability of woody species, as well as clues

* Professor A. Repollo Jr., DMMMSU, Bacnotan, La Union, The Philippines. Visiting Senior Fellow at ICRAF during 1985-86.

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suitable plant management operations. This type of information can help plan field trials, especially for newly-introduced exotics and/or indigenous species that are being tried in new regions.

This paper first briefly discusses these aspects, then describes the simple methodologies that can be used to obtain phenological information from the field, finishing with two examples of records that have been obtained from a preliminary study at ICRAF's Machakos field station.

Phenology and species adaptability

Plant strategies

Plant species possess a very wide range of strategies to help them establish their place in particular ecological niches (or clines). For well-adapted species the necessary steps in growth and development ('phenophases') have become adjusted and properly sequenced both to seasonal changes in climate, and to influences such as the phenology of associated species competing for a place in the same niche. At the extremes individual species can be found either confined to a highly specific ecological situation or they may traverse a wide range. obviously, the factors underlying the distribution of a plant species in space can be extremely complex.

The ultimate control of morphological and physiological characteristics that enable plants either to be best-suited to a specific niche, or to spread to others, depends upon their genetic 'fitness' or 'flexibility'. However, even species that are restricted locationally will be so confined through some particular set of evolutionary circumstances; yet they may still possess a useful degree of morphological and/or physiological plasticity. This is an underlying feature that needs to be borne in mind in species selection procedures. A comparison of the growth and development patterns as expressed by any woody species in different environments is, clearly, a valuable procedure to provide information on such matters.

Edaphic and climatic requirements

When we say that a woody species is 'adapted' to a particular environmental situation we mean that: (a) the range of soil conditions under which it finds itself is, for each and every soil factor that affects the plant, within the limits that encourage normal growth and development; (b) there are no climatic extremes that will eliminate the species; and (c) the probability of obtaining a suitable length and sequence of climatic conditions for growth and development processes in any one season is high. The absence of other detrimental biotic factors (e.g., pests and diseases organisms) is also important, of course.

Assuming that soil conditions encourage growth, then plants that are adapted to a particular climate will progress through their various phenophases in a regular and unimpeded way (Huxley 1983). Species will vary in these patterns of response, perhaps quite markedly, but each can be expected to behave according to the particular strategy inherent in the pattern originally established at its centre of origin. Thus regulatory controls will be triggered by appropriate climatic conditions to result in leaf initiation, bud development and leaf expansion at an appropriate part of the season; and similarly for flower initiation, anthesis, pollination, fertilization and fruit growth and maturation. Growth cessation, if it occurs, will similarly be brought about by a combination of internal (endogenous) and external (exogenous) factors. The climatic conditions during

each phenophase will also need to be such as to maintain all the different physiologica processes at a balanced rate.

Phenology and ill-adaptation

If a woody species is ill-adapted, then it is usually clear at an early stage that the sequence of phenophases is not properly sequenced or entrained to climatic changes, either (a) because what might be expected from its normal behaviour at its origin does not occur or (b) it behaves in a way that suggests that it will not be able to make good use of the climatic pattern in which it now finds itself. Of course, in the latter case, it may be possible, by using suitable management practices (e.g., lopping or pruning), to adjust the sequence of phenophases to a more suitable entrainment, and the phenological information gained by studying its behaviour in the field will provide information about the best times at which to make such management interventions. In these circumstances, there may be a case for recording the phenological behaviour of the woody species as modified and conditioned by a set or sequence of manipulations (lopping at different parts of the season), or to obtain some clues about this through plant or branch manipulation on individual plants. This is discussed further below.

Plant management and the manipulation of phenophases

Management of the external environment

Management practices which most obviously effect plant phenology are those that impose, or alternatively relieve some degree or another of environmental stress. This is often done by manipulating soil factors.

For example, as with climatic factors, soil conditions can enhance, slow or interrupt the proper sequence of phenophases; in this case by modifying water and/or nutrient supply. In temperate regions the application of nitrogen fertilizers to apple trees in the autumn in order to affect flowering next spring, is an interesting example of this. Additionally, detrimental soil conditions such as toxic effects of excess aluminium/manganese, or heavy metals, or waterlogging markedly affect the phenology of woody species.

With trees/shrubs we are, however, much more limited than with high-value annual crop plants in the ways that we can attempt to modify the soil environment in order to manipulate plant behaviour for production purposes. The most feasible way is through site selection. The choice of soil management practices is often limited although, in agroforestry, we can add or retain plant residues and, perhaps, add some fertilizers. Where soil conditions operate to change the phenological pattern by prolonging the vegetative phase, as when there is added water or nitrogen, such 'surpluses' can sometimes act disavantageously with regard to the objectives for managed systems, particularly when they cause a delay in reaching the flowering/fruiting phase which may reduce yields.

Irrigation can simulate rain and both enhance soil water status and, to some extent, improve aerial humidity profiles. It can thus initiate and/or prolong vegetative growth. There are many examples where 'sequence optimization' of the growth of different agricultural crops is achieved in this way. However, it is usually not feasible to use irrigation with multi-purpose trees in most agroforestry systems.

Manipulation of environmental stress by controlling exposure is another way to modify phenological behaviour. Although subject to the same factors, woody species are

usually used to create the stress-alleviating conditions for lower storey crops (e.g., as windbreaks, shade trees, etc.). Shading will also affect the sequence of phenophases (i.e., prolong the vegetative phase). The most likely situation in agroforestry is an increasing level of shade in the lower parts of a multi-storey canopy, or at a tree/tree interface.

Direct plant manipulation

Most of what has been discussed so far has emphasized the **external** controls over plant behaviour as imposed by either suitable or unsuitable climatic and soil conditions. Internal (endogenous) regulatory processes can be important also, and these can be modified to a greater or lesser extent by various forms of plant management. They are more feasible with trees and shrubs than attempts at climate or soil modification.

For example, by far the most useful management procedure to consider for multipurpose trees is some form of removal of plant parts. This can be by (a) the removal of above-ground vegetative parts by pruning or lopping (the most usual practice); (b) the removal of flowers and fruits (usually done by removing also the vegetative parts on which flowering takes place); and (c) root removal by some form of trenching or other root pruning process. Each of these is briefly discussed below.

Pruning/lopping of aerial parts

Pruning or lopping of aerial parts will affect the annual biomass increment produced (usually by reducing it according to the severity of lopping), and it will affect the subsequent distribution of dry matter. It will also act to modify the initiation, duration and cessation of the subsequent vegetative phenophases. These effects can vary very much both between species, and depending on the time at which the shoots are lopped. They may be promoted to occur sooner than normal, or they may be delayed. This will depend on the condition of the lateral buds, the level of stored materials in the shoot, and the responses engendered by cessation of any hormone supply from the removed shoot apex.

Pruning/lopping is, therefore, a powerful management tool for multipurpose trees. However experiments to test the factors involved (time, intensity and frequency of lopping, type of plant part removed) must be rationally thought out in order to take advantage of the known patterns of climatic change at the experimental site, and their likely effects on the phasing of plant growth. Some preliminary information about the plant's phenological responses in its natural state will enable a much more precise approach to be taken to this form of experimentation which, otherwise, will remain as partial guesswork. Indeed, lopping times for experiments must be defined in terms, not of calender periods but of actual weather patterns and the plant's phenological response if they are to be meaningful.

Removal of flowers and/or fruits

Removing flowers, fruits or vegetative material on which flower initiation is known to occur will have two effects. The first effect is similar to that mentioned above for removing vegetative parts; the second is that of removing a future significant and powerful sink for assimilates and nutrients.

When woody perennials produce fruit, the drain on resources – stored or current – can markedly affect the pattern of subsequent vegetative growth depending on the degree of fruiting experienced in relation to resources available. This, in turn, is affected

by favourable or unfavourable climatic sequences during the fruit maturation period and, perhaps, by the way in which a previous favourable or unfavourable season has affected the plant's levels of stored nutrients and carbohydrate. In some cases biotic factors can also be involved (e.g., damage to the leaf canopy by pest and disease organisms after a fruit load has been established).

It is not uncommon in the tropics to see two plants of the same species at the same site completely out of phase with one another because a prior set of factors brought about a prolific flowering in one but not in the other. The subsequent development of a heavy fruit load on the first specimen was, in these circumstances, sufficient to disrupt its expected sequence of phenophases. This may occur even to the point where it enters a bi-annual or bi-seasonal flowering/fruiting cycle or, in an extreme case, has flowering delayed for several seasons.

The management of flowering in order to adjust fruiting levels is, therefore, another possible tool with which to manipulate climatic 'entrainment'.

Root pruning

Root pruning can modify subsequent phenology. In some cases (e.g., with some temperate fruits) root pruning is used to promote flowering when this is unduely delayed by an extended stage of vegetative growth in the early years. When this occurs it is probably a result of a change in the balance of plant hormones which are produced by roots (e.g., cytokinins and gibberellins) and which regulate growth in other parts of the plant. Removing roots can certainly modify the subsequent extent of nutrient and water removal from the adjacent soil. The practice of root pruning is common in many agroforestry situations because tillage relatively close to trees or hedges can help restrict their competitive influence.

There seems to be relatively little information about how root pruning may affect subsequent within-season phenophases of multipurpose tree species growing in the tropics and sub-tropics, but it could be a useful area to look into as a potentially useful management procedure.

Other practices

Other management practices or situations that can influence the phenology of woody plants in the tropics are those that can **indirectly** affect stress patterns. For example, planting density, choice of site to affect exposure or shelter, aspect, slope (inasmuch as it affects run-off and soil water) and, of course, the association of woody perennials with crops and/or grasses.

With what has been said so far, there seems little doubt that phenology records can usefully be included in all agroforestry field trials in order to establish information about the basic phenological sequences and to compare the effects of different treatments.

Methods

The methods for obtaining phenological records of above-ground sequences of plant behaviour can be extremely simple. It is, therefore, surprising that more use is not made of this approach. Obtaining information about patterns of fine-root growth are more difficult and time-consuming, although they may well be of considerable value.

Phenological methods for above-ground parts

Whenever phenological data are to be collected, concurrent meteorological information must be gathered either from the site itself or nearby. It should be remembered, in this respect, that topographical changes can bring about quite a large difference in local climate in the tropics, especially with regard to night temperature, humidity and dew point (Huxley and Beadle 1964). Such topoclimatic variation (especially night temperature differences) can affect the phenological progress of crop plants, although little is known with respect to tropical trees and shrubs. Bearing these points in mind we can collect phenological information in three ways.

Whole tree phenology

A set of very useful information can be obtained simply by taking weekly or two-weekly sets of observations of whole tree behaviour. This should always be with undisturbed specimens growing in a representative site (the 'control'), but it can be extended to include similar trees in different kinds of sites, or under particular experimental conditions or management practices, if this is of interest. The observations can be made by a trained field assistant and they can be quickly and easily checked. An indication of the intensity of each factor being recorded can be obtained by scoring 1 to 5 (Huxley and Van Eck 1974).

Observations would normally be to identify the periods over which the following occur:

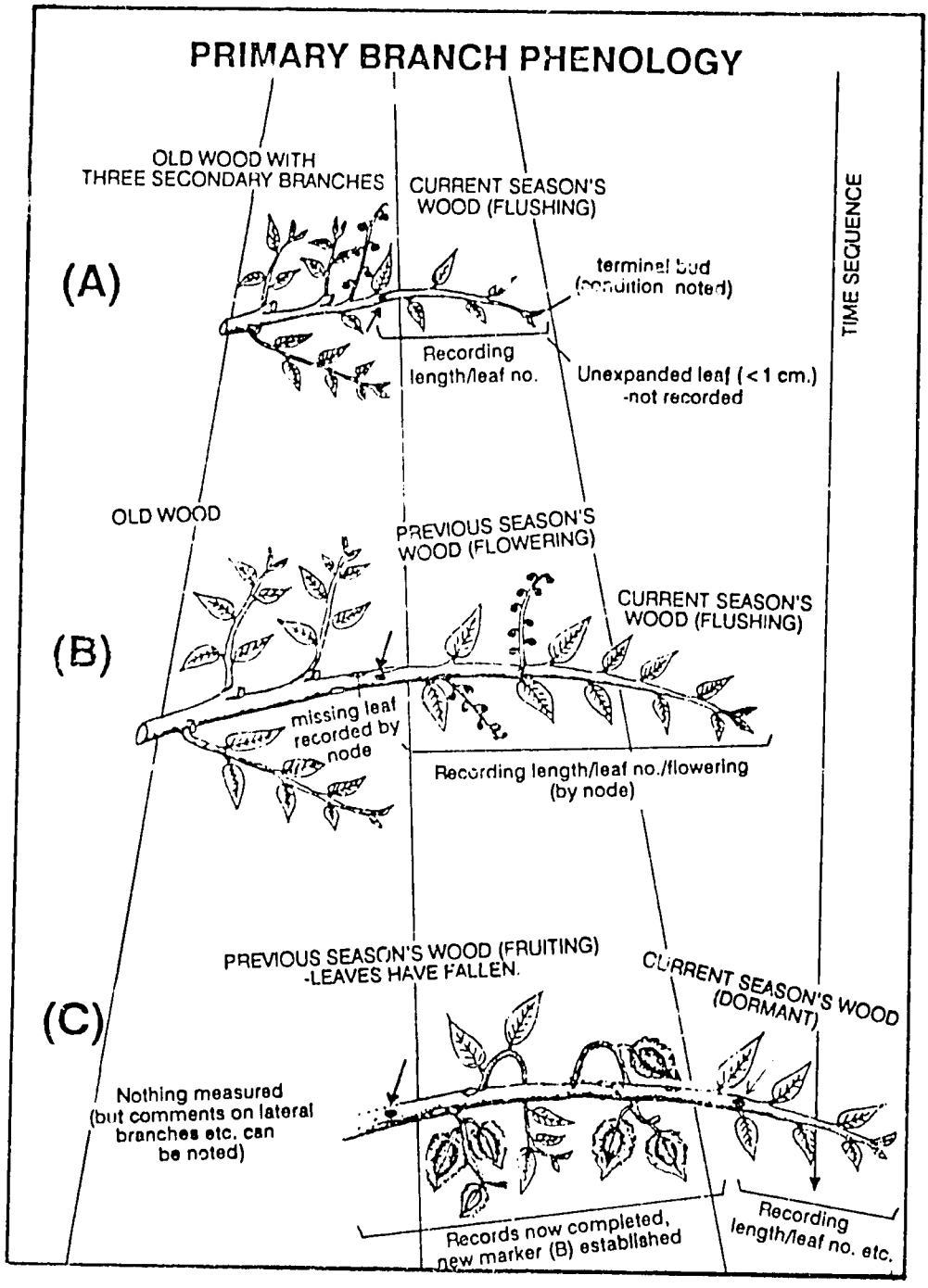
- **Leafy shoot extension** is easily observed as 'flushes', identified by looking to see if new leaves are expanding at the tips of shoots.
- **Leaf fall** can be seen by observing if any senescent leaves are present in the canopy, and by looking under the tree for freshly- fallen leaves.
- **Flowering** is the period from anthesis to petal drop.
- **Fruit growth** will obviously follow flowering. It can be difficult to observe in tall trees. Although the whole period of fruit growth up to final maturation (and fruit fall) is usually easy to see, sampling has to be done if different stages of fruit growth need to be identified.

Branch phenology

A close scrutiny of a branch will often expose details of how it has grown over the past few seasons, as well as providing information about where and what kind of fruiting sites are formed (Figure 1). Making measurements on individual branches can be rather time-consuming so that this exercise has to be carefully thought out. Such a study can include some manipulation which may provide clues relating to tree management by lopping or browsing.

Usually, a number of representative branches are chosen at the start on a random sample of about 3 – 5 trees of the species under investigation that are growing in the selected site conditions. Unless a large amount of replication is possible it will not be possible to make rigorous statistical comparisons, and any replication is just to obtain a better sample mean. If branches on individual trees do not behave similarly this, too, is useful information. Only large differences in phenological patterns will emerge from this kind of investigation, but at least they can be presented as a tabular or graphical record.

Figure 1 Changes in length, leaf number and the occurence of flowering and fruiting on a primary branch of a (hypothetical) woody species. Portions being observed over three seasons (A-C) are indicated. Arrows show original 'base' mark and in C, the new position to which it has been moved.



Branches need to be selected in relation to (a) their position in the tree (as representing, for example, an actively-growing part of the canopy); and (b) their ease of access for subsequent observations. If the canopy is not similarly active in all parts this will necessitate taking replicate samples in each 'zone'; but usually this is unnecessary. It is wise not to chose branches that are too close to the ground, near to a path, or where agricultural operations are being undertaken, because they may inadvertently be removed or damaged.

Once selected, branches are marked with a paint spot at a suitable internode, not too far from the apex but far enough back to be sure that the internode is mature. It is important to use a non- toxic paint, such as a water-soluble plastic emulsion, making certain that it is not placed on green, tender tissue. Usually the mark can be made just below the 7th or 8th node from the shoot apex.

The branch should be labelled to indicate its number and/or location in the tree and any subsequent treatment that is to be imposed, using a label that will persist in a reasonable state over several seasons. The label must be secured in a way that will not damage the shoot. We have found it useful to attach an extra length of coloured string or twine so that each label can be quickly found. The datum spot can be moved after a branch has grown to a point where it involves too much work to count the nodes and/or it exceeds the length of the ruler. It is necessary to note in the records the point to which it has been re-located, and to measure and record both the old and new lengths.

One set of branches should be maintained as a control, with treatments imposed on other sets. For example, the removal of the shoot apex at different parts of the season may provide clues as to the species' potential for re-sprouting at these periods. This approach has to be treated cautiously as the growth regulatory mechanisms of the treated branches may be over-ridden or compensated for by adjacent ones. Thus a positive response of a single shoot to apex removal will indicate that the whole tree or bush is likely to respond in the same way at that part of the seasons. However, a negative response may indicate that growth of the branch still remains suppressed, and a more severe lopping treatment of the whole plant will be needed to test its potential for regrowth. The same applies if flower or fruit-removal is to be tested as a method of changing the plant's phenological entrainment.

Records should be taken at sequential intervals, the actual time being related to periods of climatic change rather than calender dates, as follows:

- **Shoot extension** can be measured with a ruler from the datum spot to the shoot apex in millimeters, expressed later as a rate of growth (cm/standard period).
- **Node number** should also include the presence or absence of leaves at any node. It is best to record only leaves of a size greater than a stated length (e.g., 1 cm) in order to standardize what is being counted as a 'leaf', as and when these are produced from a shoot apex. When lateral buds sprout (i.e., swell observably) from a leaf axil this should be recorded, and it is usually sufficient just to record the subsequent increase in length of each lateral. Otherwise a new set of records for each branch has to be established and this will result in a rapid escalation of the amount of data being collected. The rate of increase in node number and (total) lateral shoot extension per branch with time can be calculated subsequently.

  Flowering should be noted for each identified node at which flowering occurs. Depending on the species this will be as single flowers, inflorescences or short flowering shoots. It may also be necessary to indicate the time at which a shoot apex terminates in a flower, if this is a characteristic of the species. Where flowers are

borne on short shoots (e.g., *Burseraceae*) they can be treated as separate sites to be recorded along with the supporting branch itself.

- **Fruiting** can be added to the record if there are easily identifiable stages of fruit growth (as with many commercial fruits). Otherwise one can merely identify the presence of a fruit (or fruits) until it matures and falls.

There is obviously a limited period during which branch phenological data can be taken before the structure becomes too complicated to record easily. The method is therefore best-suited to investigations that are limited to just a few seasons.

Leaf or flower initiation studies

As the study of an individual woody species progresses it may become necessary to understand more about the way the plant's development sequences relate to climatic and/or management factors, especially the progress of leaf initiation over time (the plastachron), and the appearance of expanding leaves with time (the phyllochron) (Figure 1). These two may or may not be closely correlated depending on whether a period of vegetative bud dormancy occurs; but they are both key stages strongly affected by climatic factors, e.g., by available soil water and atmospheric humidity (or both), and by ambient temperatures. Although results of such a detailed investigation can help with the interpretation of the plant's responses to management, it is essential first to decide whether or not this level of detail is really required. Phyllochron records will be obtained from branch phenology studies (see above), but the plastochron can only be defined by dissection of vegetative apices sequentially with time. This is not difficult and it can be done with a high-powered binocular microscope, taking care to sample representative shoot apices.

Similarly, a knowledge of the time at which flower or inflorescence buds are initiated can be essential to the proper understanding of the way seasonal climatic variations affect subsequent flowering and fruiting. Woody plant species differ considerably in **where** (i.e., on what part of the branch) and **when** flower initiation take places (Huxley 1985). It can be in a previous season, or only just a short time before anthesis (flower opening). If knowledge of the effects of climatic or management factors on flower initiation is required, samples of appropriate buds should be dissected. Buds that have progressed from the vegetative to the developmental stage can nearly always be detected because their morphology changes, and the primordial shoot apex becomes flattened with flowering initials becoming evident. A prior investigation of this formative bud and development process has to precede the main investigation if such morphological changes have not been previously characterized for the species under test. Again, this is not difficult or particularly time-consuming.

Phenological methods for below-ground parts

Methods for studying roots are described in several publications (e.g. Bohm, 1979; Schuurman and Goedewaagen,1971.) All of them are time-consuming and laborious and require special facilities or equipment. For most phenological studies, patterns of below-ground activity may be as important (although much less easily observed) as above-ground activity. Indeed, it is to be expected that tropical woody perennials have as wide range of below-ground root growth strategies (for fine roots, at least) as they do for above-ground leaf production. Furthermore, the ecological success of many tropical woody species may well depend, at least in part, on the differential phasing of root and shoot growth if they are to compete successfully with associated species of one

kind or another (see Huxley and Turk 1975 for an example of root-shoot growth phasing).

It seems likely, therefore, that at some stage many investigators of multipurpose trees will wish need to incorporate a study of what is happening below-ground. Probably the simplest approach that can be suggested at present is to make a succession of observations and/or measurements of topsoil root activity by taking core samples and looking for the the presence of live, actively- extending fine roots. This procedure would initially be purely qualitative; but it can be made quantitive by washing, collecting and measuring the length of different root fractions (Ford and Deans 1977). At the same time the presence or absence of root nodules can be observed, if appropriate. The effectiveness of nodules can be defined quantitatively by estimating potential rates of di-nitrogen fixation, using the ethylene acetylene reduction technique. Such observations may provide useful clues as to whether or not a more detailed below-ground study is needed later.

Examples

We give here two examples from a preliminary branch phenology study on seven woody species that commenced in 1985 at ICRAF's field station at Machakos, Kenya. The objectives were to test the feasibility of this approach and to assess its value for the practical assessment of woody species introduction and management. The methods used were as outlined in the section above and, although sample sizes were very small, the data generally coincide with the observable behaviour of all similar specimens in the plot. The reader is referred to Huxley and Van Eck (1974) for an example of a long-term study of single whole plant phenological observations on a number of woody species at one tropical site.

A comparison of three species

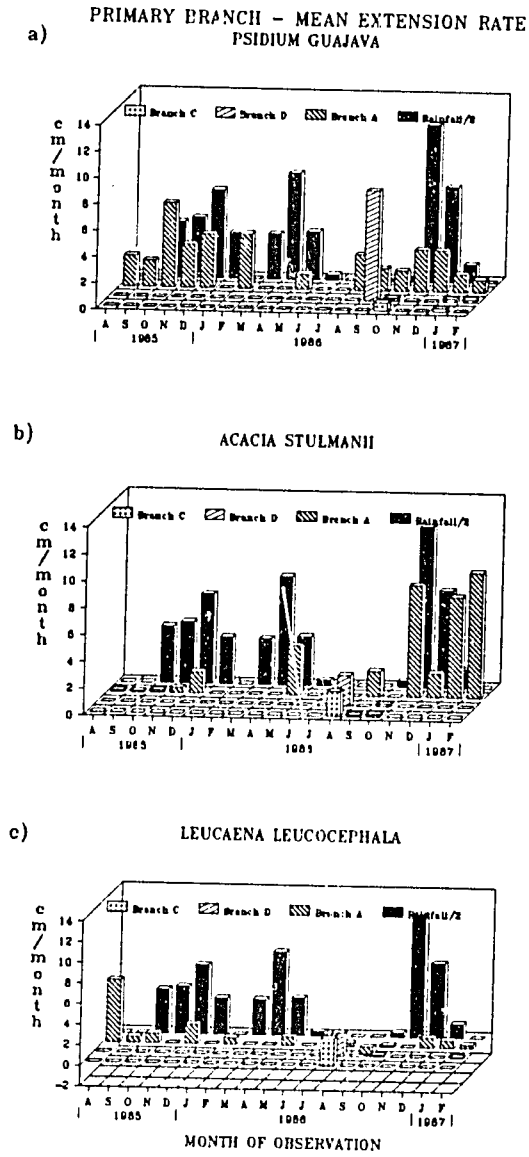
Growth of uncut lateral branches

Figure 2 shows the periods of extension growth of typical primary lateral branches of young trees (4 years from planting out) of *Psidium guajava* (guava), *Acacia stulmannii*, and *Leucaena leucocephala* cv. K.8, over three rainy seasons from August 1985 to February 1987. Monthly rainfall totals are also shown. The first period of rains (short rains) started in October 1985 and continued through January 1986; the second (long rains) was from March to June 1986; and the third (short rains) was from October 1986 to January 1987. Intervening periods were virtually dry seasons. This bimodal pattern is normal in this region. The elongation growth of intact primaries (branch A) is shown as well as the continuation of primary growth by a secondary after removing the apex (branches C & D).

Guava originated in the American tropics but is quite widely spread as a fruit crop through tropical and sub-tropical regions; it has been cultivated in various parts of Kenya for many years. *A. stulmannii* is an indigenous species common to the drier areas of Kenya. Leucaena is native to Central and South America and is usually considered best adapted to higher areas with more than 1000 mm of annual rainfall (Brewbaker 1987).

These three species exhibited quite different growth patterns of uncut primaries. Branches of *A. stulmanii* grew in length mainly during the rainy periods but ceased, as is common with many tropical tree species, prior to the end of the rains. However, in

Figure 2 Seasonal changes in rate of terminal extension growth of typical primary lateral branches of three woody species in relation to rainfall. Some branches were left intact (branch A - means of 6); others had approximately 15 cm of the original apical portion removed either prior to the short rains in August 1985 (branch C, means of 3); or during the short rains in November 1985 (branch D, means of 3). Monthly rainfall totals (cm) are shown at half scale. Flowering times: *Psidium guajava*: November 1985, February 1986, August 1886; *Acacia stulmanii:* September 1985, August 1986; *Leucaena leucocephala*: November 1985, February 1986, August 1986.



C cut Aug 85, D cut Nov 85, A uncut

the short rains of 1986/87, a second phase of growth extended into the dry season. The most vigorous extension growth was in the short rains. A small amount of branch extension also occurred during the dry period in September.

Guava showed a great deal of pre-rains extension growth of primaries in each of the three rainy periods, and extension again ceased (first two seasons), or slowed (last season) before the end of the rains. Branches of leucaena grew vigorously on these young trees well before the short rains started in October 1985 and again, briefly, post-short rains (February 1987). Very little extension growth occurred subsequently. In the last season shown, extension growth began, weakly, in the dry season well before the start of the short rains of 1986/87, and continued, in the same way, into the start of the next dry season (February 1987).

A. stulmanii flowers on the previous season's vegetative flush and, if a period of environmental stress sets in, may or may not set fruit and/or shed young fruits. If not cut back, guava flowers on short lateral shoots arising on maturing parts of a branch and/or on 'spurs' found in the axils of leaves on older wood. Flowering accompanies or follows a period of vegetative growth. Leucaena forms inflorescences on new-shoot, lateral branches arising near the apex of extending primary shoots, i.e., on current season's growth. Its flowering was erratic and badly timed.

The phenological patterns show that both guava and *A. stulmanii* are adapted to the environment at this site. There are no particular soil problems, apart from a generally low level of soil fertility on these Oxisols; and, at least from the three seasons of observations reported here, they could be seen to be suitably entrained to the climatic pattern.

Leucaena presents an entirely different case, however. Flowering occurred only towards the end of the first short rains of 1985 (November). It co-incided with the early start of the long-rains of 1986 (February), but another flowering occurred at the end of these in May, and yet again in the following dry season (August). There appears to be no mechanism whereby leucaena can shed developing fruits, and the depletion of plant reserves during the fairly long fruit growth and maturation periods were not supported by vegetative flushes. A consequence was, eventually, a very weak and intermittent vegetative flush starting early in the pre-short rains of 1986, which continued into the February 1987 start of the dry season. The sequence shows clearly that *Leucaena leucocephala* is not inherently adapted to this site. It can, of course, be forceably entrained by a suitable lopping treatment to be somewhat better suited to it. This has been done at Machakos, so that its non-adaptability is unlikely to be a consequence of unsuitable soil (e.g., low pH) at this site.

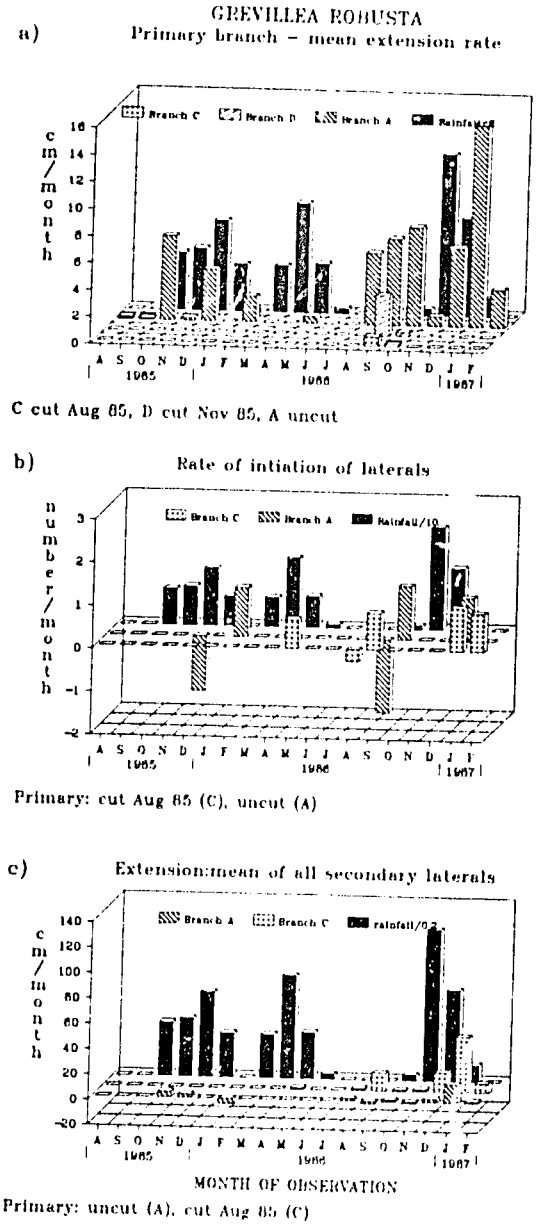
Renewed apical growth on cut branches

In order to obtain some evidence on plant response some branches on each tree had 15cm or so of the apex removed at specific times in the season (see methods sections above). For all three species shown in Figure 2 it took approximately a year before apical growth on the primary was continued (Branches C and D) by a suitable (i.e. proximal) lateral shoot . Nor did it make much difference whether the primary apex had been removed prior to or during the short rains of 1985/86.

Growth of primaries and secondaries in one species

Figure 3 details the initiation and growth of secondary laterals of another well-adapted species, *Grevillea robusta*. The uncut primary lateral branches (branch A) grew vigorously in the first and third rainy seasons (Figure 3a). Primary branch extension almost completely coincided with the start of the short rains in October 1985. Some pre-long

Figure 3 Branch phenology of 3-year-old *Grevillea robusta*.
(a) Rate of terminal growth of typical primary laterals, branch A intact; branches C and D cut prior (August) and during (November) the short rains of 1985. The extension of shoot apex, where shown, is by a replacement proximal lateral shoot. Grevillea did not flower in this period.
(b) Rate of emergence of young lateral shoots, branches A and C treated similarly. Note that, on occasion, some small lateral shoots died back (negative rates).
(c) Rate of extension of all laterals on the recorded portion of the branch (see text), branches A and C treated as before. Scales for rainfall adjusted as necessary.



rains growth occurred in the dry February of 1986 (but there was still probably some soil water storage at depth then). For some reason, there was little extension of primary laterals in the long rains of 1986. Rapid extension started again well before the short rains beginning in November 1986, with another flush towards the end and into the dry season (cf. *A. stuhlmanii*).

As with the other three species, there was a long delay in renewal of terminal growth on primaries once a primary shoot has been cut (branches C & D, Figure 3a).

Counts of secondary lateral buds and their extension growth are also shown in Figure 3. Some young growing laterals (identified when longer than one centimeter) died back on the uncut primaries (branch A) in *Grevillea* in the short rains of 1985/86 (Figure 3b). A few more sprouted when these rains had ceased in January 1986. A similar pattern occurred prior to and at the start of the short rains of 1986/87. The example of a cut primary (e.g., in August 1985 - branch C) showed that nothing happened until April of the following year. There was little dieback of young laterals but some subsequent intermittent sprouting in August 1986, and January and February 1987. These trees were all healthy and very vigorous. The rate of extension of secondary laterals (an expression of their growth 'vigour') is shown in Figure 3c. The few secondary lateral shoots that had been formed grew significantly much later (i.e. in the short rains of 1986), perhaps slightly more vigorously on the cut (branch C) rather than the uncut primary (branch A).

Therefore, although *Grevillea robusta* can form an excellent barrier or decorative hedge, the characteristics shown by these branch phenology observations suggest that it will be somewhat unproductive in terms of biomass production, at least from the sides where these samples branches were chosen.

Conclusion

These few examples illustrate the kind of information that can be obtained by a careful study of the phenology of woody species. A major advantage of branch phenology studies, even on such small samples, is that it forces the researcher to make the kind of combined phenological/morphological observations which, otherwise, would probably be overlooked. Potentially, much more clearly- focussed treatments can be derived if experiments have been preceded by such simple studies or, if they are included in field experimentation, much more useful information can be acquired about the responses to treatments.

What is now needed is the collection of information from larger samples in order to assess the variability in such data sets. Recommendations can then be made on the size of samples needed for analysis by appropriate statistical techniques.

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Crop simulation models and some implications for agroforestry systems

A.K.S. Huda and C.K. Ong

International Crops Research Institute for the Semi-arid Tropics (ICRISAT)
Patancheru P.O., Andhra Pradesh 502 324, India

Abstract

ICRISAT's work on modeling sorghum, pearl millet, and groundnut is summarized, and the implications for agroforestry systems are examined. Trees can improve water infiltration rate and by utilize deeper profile water not accessible to conventional crops. In this paper we have studied how the introduction of tree species in crop systems would affect overall water use and productivity. We have analyzed climatic data of five selected locations in arid and semi-arid India in terms of the distribution and dependability of rainfall and the trend in seasonal rainfall pattern in the recent years.

Probabilities of available soil water are simulated for these locations. Available water holding capacity of the soils are assumed as 25, 50, 100, and 150 mm at each of the selected locations to account soils for ranging from very shallow to medium deep. Grain yields and total dry matter are simulated for these agroclimatic conditions to outline the environments where agroforestry is feasible.

Grain yields and total dry matter of the crops at various levels of shading by the tree-component are simulated. These results are expected to give some insight as to how the tree-management will affect the microclimate and productivity of the crop. Effects of changes in microclimate such as canopy temperature and radiation intercepted (by manipulating row width, plant density canopy growth) on productivity based on information from intercropping and forestry studies are discussed. Simulation results are compared with the experimental data from ICRISAT and elsewhere on appropriate cropping systems under various agroclimatic conditions.

Minimum data sets that need to be collected from specific experiments designed for agroforestry studies are identified.

Introduction

Crop simulation models are useful tools to examine the feasibility of agricultural management systems and can be used to examine the effect of trees within cropping systems. Trees can utilize water in deep layers of the soil profile not accessible to the roots of conventional crops. In this presentation an attempt is made to study how the introduction of tree species into cropping systems is likely to affect the overall use of environmental resources.

This paper has been divided into three parts:

- a comparison of the performance of the two crops, sorghum *Sorghum bicolor* (L.) Moench and pigeonpea *Cajanus cajan* (L.) Millsp., in sole and intercrop systems and relating their performance to agroforestry systems;

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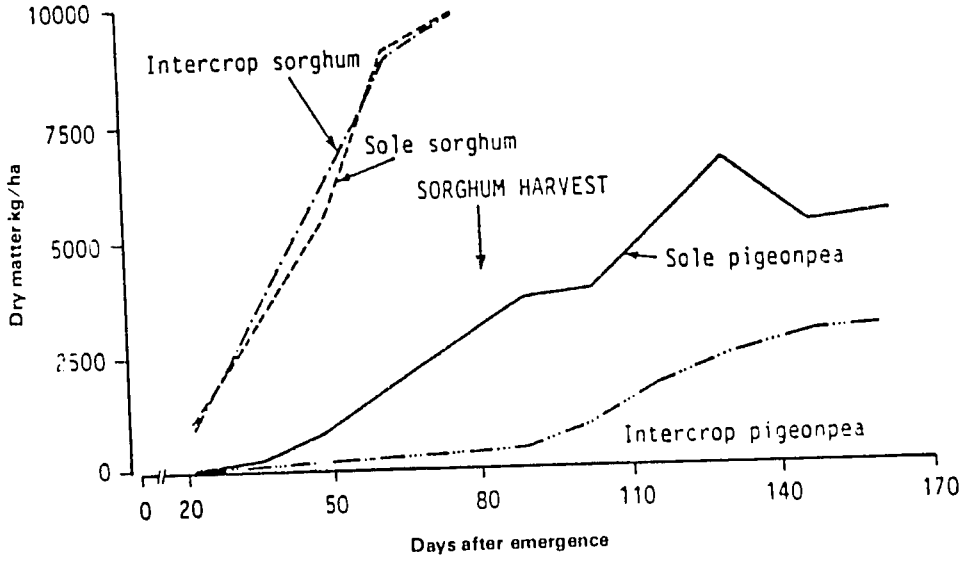
- an analysis of the climatic and soil water data for five selected locations in India to examine where agroforestry systems may be feasible; and
- a simulation using a sorghum crop model and the implications for agroforestry systems.

Intercropping

Many investigations (e.g., Kassam and Stockinger 1973; Willey and Lakhani 1976; Natarajan and Willey 1981; Rao and Morgado 1984; Natarajan and Willey 1985), have shown that intercropping can give rise to substantial increases in yield because the component crops complement each other and make better use of environmental resources than when grown separately. We have used the performance of two crops sorghum and pigeonpea in sole and intercrop systems as a simple model of an agroforestry system.

Figure 1 illustrates the cumulative dry matter per unit area of a sorghum/pigeonpea intercrop during the growing season (Natarajan and Willey 1981). In intercropping, sorghum was the dominant component, and grew at a rate comparable to that of sole sorghum. In contrast, pigeonpea in the intercrop experienced severe competition from sorghum plants which formed a canopy very rapidly.

Figure 1 Dry matter accumulation in sole sorghum and pigeonpea and in sorghum/pigeonpea intercrop on Vertisols in 1977 at ICRISAT Center (after Natarajan and Willey 1981).



At only 30 days after emergence, sorghum intercepted more than 70% of the incident radiation and by about 55 days the peak interception of 84% was achieved (Figure 2). Canopy development in sole pigeonpea was much slower: at 30 days, this crop was intercepting only 10% of the incident light; and at 60-65 days, it had reached a near maximum value of 70% which was more or less maintained until about 110 days.

Figure 3 illustrates the efficiency with which the intercepted energy was converted into dry matter throughout the growing period. Comparing the sole crops, the fitted regression lines show that the sorghum (1.5 g MJ^{-1}) was more efficient than the pigeonpea (0.6 g MJ^{-1}). The intercrop converted the intercepted light energy before sorghum harvest at a rate of 1.7 g MJ^{-1}, which was more efficient than sole sorghum. After the sorghum harvest, the efficiency of conversion of the intercrop pigeonpea reverted to a value virtually identical to that of sole pigeonpea.

Natarajan and Willey (1981) reported that intercropping altered the ratio of transpiration to evaporation from the soil surface. Thus the yield advantages of intercropping were achieved simply by channeling a greater proportion of the water through the crop. These data on sorghum/pigeonpea intercropping were collected from one location (ICRISAT Center, Patancheru). Analysis of agroclimatic data from other locations is a necessary first step to identify areas where the reported success of double cropping is likely to occur.

Figure 2 Light interception by sole sorghum and pigeonpea and sorghum/pigeonpea intercrop on Vertisols in 1977 at ICRISAT Center (after Natarajan and Willey 1981).

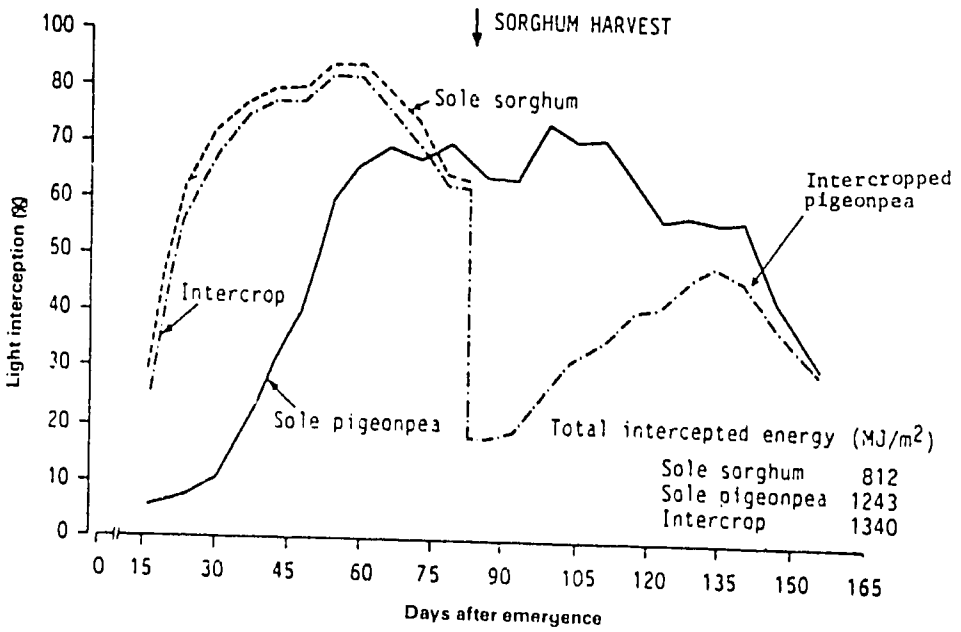
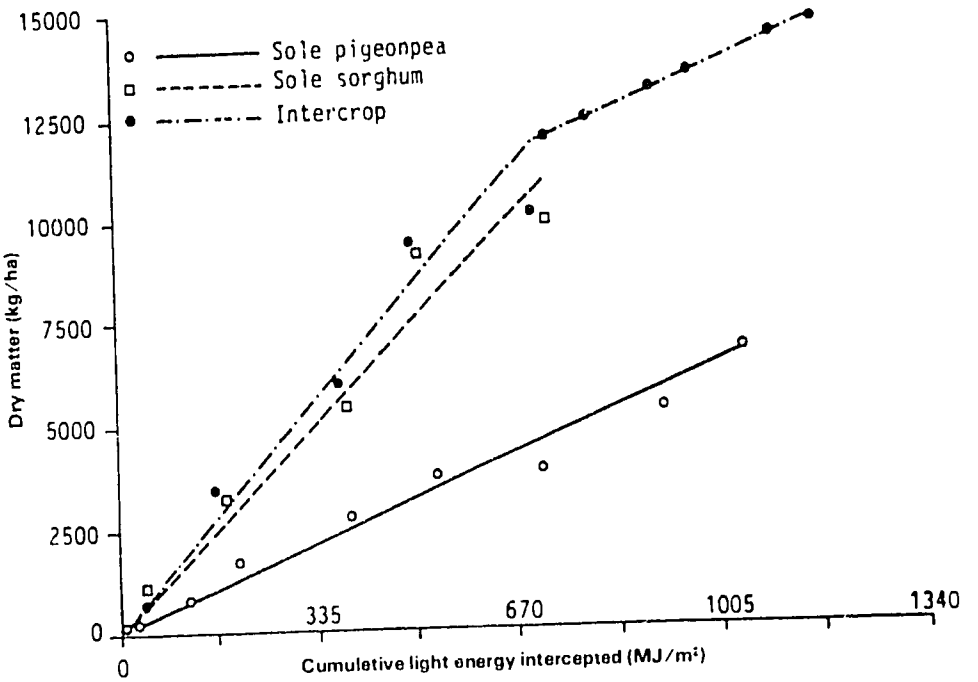


Figure 3 Efficiency of conversion of intercepted light energy into dry matter on Vertisols in 1977 at ICRISAT Center (after Natarajan and Willey 1981).



Climate and soil water

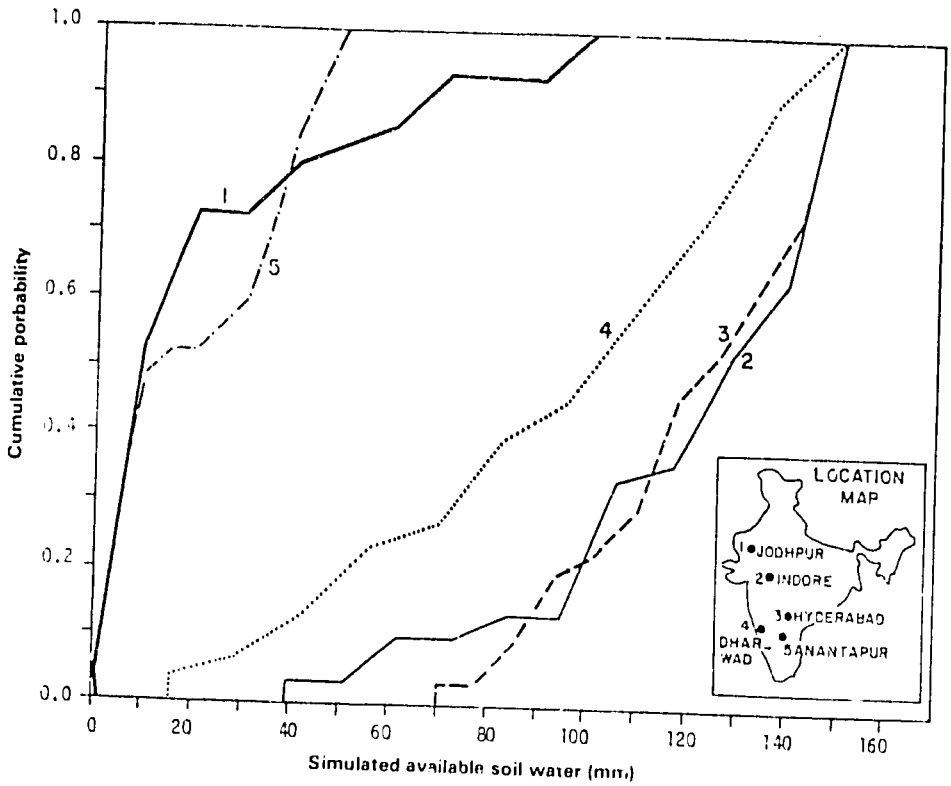
We analyzed climatic data of five selected locations in arid and semi- arid India in terms of the distribution and dependability of rainfall and the trend in seasonal rainfall pattern. Annual rainfall of five locations (Jodhpur, Anantapur, Hyderabad, Dharwad, and Indore) in India, based on data from 1941-70, ranged from 382 mm (Jodhpur) to 1001 mm (Indore); and the coefficients of variation ranged from 20% (Hyderabad) to 42% (Jodhpur).

We examined the mean weekly rainfall distribution and the probability of receiving at least 10 and 20 mm rainfall in each week for these five locations. The number of weeks receiving at least 20 mm rainfall was 11 in Jodhpur, 10 in Anantapur, 16 in Hyderabad, 22 in Dharwad, and 16 in Indore. The continuity of rainfall is important for determining length of growing season. The consecutive weeks receiving at least 20 mm rainfall were 11 in Jodhpur, 5 in Anantapur; 15 in Hyderabad; 15 in Dharwad; and 16 in Indore.

Probabilities of available soil water (ASW) stored in the profile at the beginning of post-rainy seasons were simulated using the Ritchie (1972) soil water model to indicate the possibility of growing a second crop after rainy season cropping.

Soil water was simulated assuming a sorghum crop in the rainy season and using climatic data from 1941 to 1970 (Figure 4). Available water-holding capacities (AWHC) of soils for Anantapur, and Jodhpur were 50 and 100 mm, respectively. For

Figure 4 Probability of (less than a given amount) simulated available soil water at the beginning of postrainy seasons after a rainy season sorghum at five locations in India. Data base is 1941 to 1970.



the other locations, AWHC was 150 mm each. In 70% of the years, the simulated ASW was less than 20 mm in Jodhpur, 35 mm in Anantapur, 120 mm in Dharwad, 140 mm each in Hyderabad and Indore.

Simulation results show that another crop can be grown in the post-rainy season in 70% of the years under residual soil water conditions in Indore, Dharwad, and Hyderabad where 50-75% of the soil profile was charged with available soil water at the beginning of postrainy season. For Jodhpur and Anantapur, the soil was left with a negligible amount of available water at the end of the rainy season crop, and thus growing two crops in a year without irrigation involves high risk. The reasons are not only the amount and distribution of rainfall, but also the poor water-holding capacity of the soils.

Simulation models based on soil, crop, and weather factors are useful to characterize environments quantitatively in terms of production potential and can be used as tools for planning alternate strategies for cropping and land use. No models are yet available for simulating the performance of intercropping and agroforestry systems. However,

we have used in this study a sorghum simulation model developed at Texas A&M University and modified at ICRISAT for use in the semi-arid tropics.

Modeling

The sorghum simulation model, SORGF, developed by Arkin et al. (1976) and modified by Huda (1987) was used in this study. The SORGF model requires daily rainfall, maximum and minimum air temperatures, and solar radiation as weather input data, and latitude of the location. The plant and soil information needed includes date of sowing, depth of sowing, row spacing, plant density, potential number of leaves and their maximum size, water-holding capacity of the soils and available soil water at sowing.

The model calculates the daily growth and development of a standard grain sorghum plant under adequate management, sufficient plant protection, and recommended doses of nutrients in a field stand. It accounts for the physical and physiological processes such as phenology, leaf area development, light interception, and water use which are independently computed and used as sub-models. The potential dry matter is calculated from radiation intercepted and the net dry matter is calculated accounting for water and temperature stress. Partitioning of dry matter into different plant parts is based upon the stage of development of the plant. The final biomass and grain yield per unit area are calculated by multiplying plant density with the biomass and grain weight per plant at physiological maturity, respectively.

Because our analysis deals with soil water availability and the feasibility studies of agroforestry systems, it is pertinent to describe briefly the soil water balance sub-routine of the SORGF model. Daily soil water is simulated in the model using the data on rainfall and irrigation, initial water content in the soil profile, and the available water-holding capacity of the soil, following the approach of Ritchie (1972; 1973). Evaporation and transpiration are calculated separately to obtain evapotranspiration. Evaporation is primarily dependent upon the potential evapotranspiration (PET) and the number of days since the last significant rainfall/irrigation event. Potential evaporation below a plant canopy (EOS) is calculated after simulating the potential evaporation from bare soil (EO) and relating it to the leaf area index (LAI) values. EO is calculated in the model using net radiation as input data. Net radiation is calculated from albedo, maximum solar radiation reaching the soil surface, and sky emissivity. Ritchie (1973) reported that transpiration is dependent upon PET and the relative soil water level, RSW, defined as the ratio of available water on any day to the maximum available water holding capacity of the rooted profile. Arkin et al. (1976) defined the water-stress coefficient as 1.0 (suggesting no drought-stress) if RSW is above 0.4, the coefficient decreasing linearly from there to 0 when RSW is 0.

The SORGF model was used to simulate total biomass production of sorghum at ICRISAT Center. Climatic data from 1974 to 1986 were used. Simulations were made for three soil types.

Available water-holding capacity of these soils was taken as 50 mm (Shallow Alfisols), 150 mm (Vertic Inceptisols), and 250 mm (Vertisols). Simulations were made for three periods in a year (June to September, October to January, and February to May). June to September is the rainy season; October to January is the post-rainy season, and February to May is the summer season. Because of insufficient available water in the soil profile, it was difficult to support a second crop on the Alfisol in all the years and a third crop on all the soils in almost all the years except during 1983/84. However we assumed an established stand (trees) in the beginning of the second (for Alfisol) and third seasons (for all soils).

Huda (1987) used a simple relationship of 3.0 g of dry matter accumulation for each megajoule (MJ) of radiation interception. This coefficient was derived from an irrigated sorghum grown during post-rainy season. The coefficients for dry matter accumulation efficiency used in the simulation study were 25% higher for the rainy season, when saturation vapour pressure deficit is usually less than 1 kPa; and 25% lower in the summer season, when saturation vapour pressure deficit is usually greater than 2 kPa (Monteith 1986), as compared to the values used for the post-rainy season. The introduction of separate light use efficiency coefficients in the SORGF model for rainy, post-rainy and summer seasons needs further investigations.

Figure 5 shows available soil water simulated for three soil types at the beginning of each crop season for three periods at ICRISAT Center. It is apparent that in Shallow Alfisols there is very little soil water available for crop use over extended drought periods. In Vertic Inceptisols and in Vertisols, there is fairly good degree of storage for a longer time. Results show that in 70% of the years simulated soil water at the beginning of postrainy (after rainy season sorghum) was nearly full in all three soils. At the beginning of summer season the simulated soil water was zero in the shallow Alfisol in all years and was less than 15 mm in Vertic Inceptisol and less than 95 mm in Vertisol in 70% of the years, respectively.

Figure 5 Probability of (less than a given amount) simulated available soil water at the beginning of each of three periods in three soils having different available water holding capacity (AWHC) at ICRISAT Center. Climatic data from 1974 to 1986 were used.

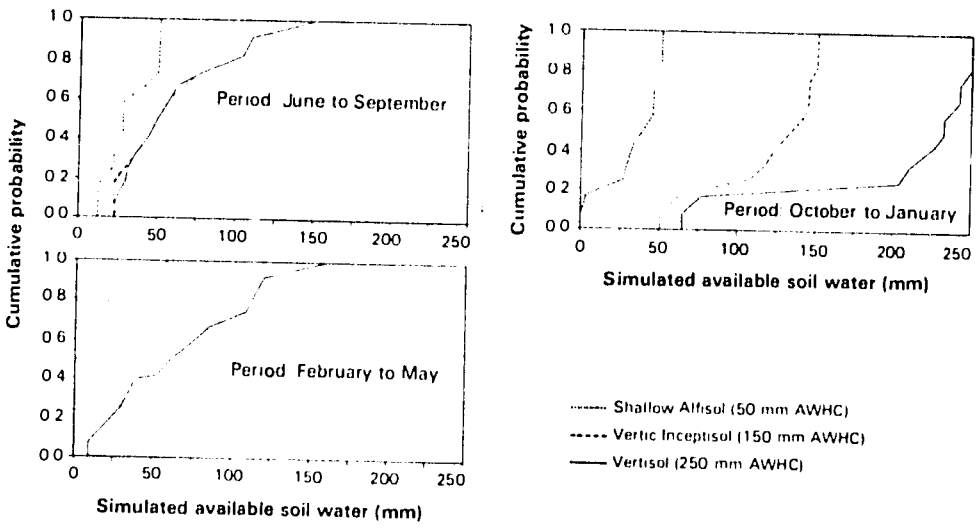
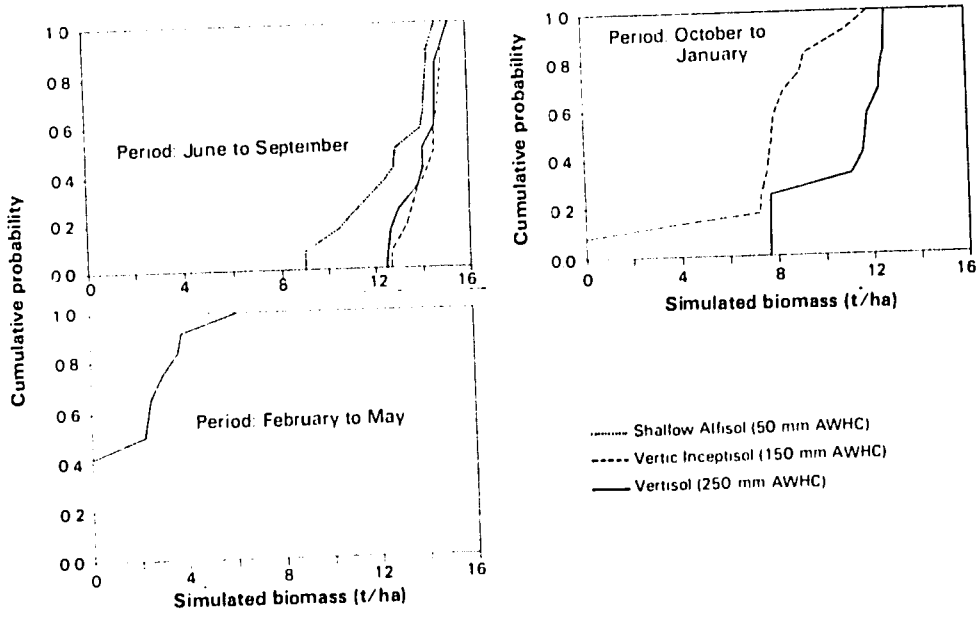


Figure 6 shows the simulated biomass of sorghum in three periods in three soils at ICRISAT Center. The range and variability in biomass across three seasons and three soils are noticeable. In Vertisols, for example, simulated biomass production decreased from the rainy to the post-rainy season; and in the summer season simulated biomass was zero in 42% of the years. In the rainy season there was no difference between

Vertisol and Vertic Inceptisol, but in Vertic Inceptisol simulated sorghum biomass was considerably lower in the postrainy season and zero in the summer season. Simulated sorghum biomass in the Alfisol was lower and more variable than in the other two soils in the rainy season and was zero in the postrainy and summer seasons. Zero biomass simulation of sorghum resulted from an extended period of drought when simulated available soil water in the profile was virtually zero for more than 15 days and the model assumed the complete senescence of the crop.

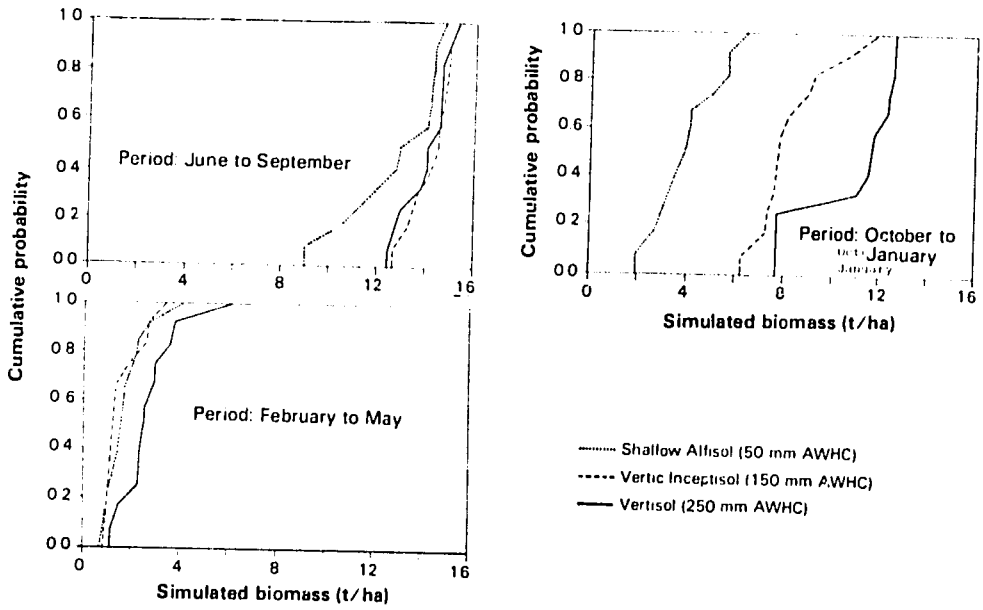
Figure 6 Probability of (less than a given amount) simulated biomass using a sorghum simulation model, SORGF for three periods in three soils having different available water holding capapcity (AWHC) at ICRISAT Center. Climatic data from 1974 to 1986 were used.



Considering an established stand (tree) in an Alfisol during the post-rainy and the summer seasons, and in a Vertic Inceptisol during the summer season, we report the corresponding simulated biomass of sorghum in Figure 7. These were simulated biomass values of sorghum at the time when the soil in the crop root zone became completely dry. Complete senescence of sorghum occurred when zero soil water continued for more than 15 days. Under such circumstances we made assumptions that the model allowed sorghum crop to senesce but permitted trees to use water from deeper layers in the soil profile for their sustenance. We made these assumptions based on our experience with sorghum. However, further research is needed to understand how a tree species behaves in a situation when zero soil water continues in crop rooting zone for a number of days. The mean biomass (tree) in a Shallow Alfisol was 13, 4, and 2 t ha^{-1} in rainy, postrainy, and summer seasons, respectively. Mean biomass in a

Vertic Inceptisol was 14, 8, and 2 t ha^{-1} in rainy, post-rainy, and summer seasons, respectively (Fig. 7). Mean biomass in a Vertisol was 14, 11, and 3 t ha^{-1} in rainy, post-rainy, and summer seasons, respectively. Thus, trees could provide some biomass during the summer season which could be used as fuel and fodder, unlike sorghum which stopped growing.

Figure 7 Probability of (less than a given amount) simulated biomass of tree using a sorghum simulation model, SORGF for three periods in three soils having different available water holding capacity (AWHC) at ICRISAT Center. Climatic data from 1974 to 1986 were used.



Simulation results using a sorghum model showed some promise to generate first hand approximation information about the alternate land use systems for three soil types in one location. Such studies need to be extended to other locations. However, validation of the simulation results in respect to agroforestry systems is an essential step for extending this work further.

Validation

The validity of this simulation will be examined by comparing actual values being collected on *Leucaena* based systems at ICRISAT. Important values to be considered are the depth of water uptake by trees, the competition for moisture between trees and crops, the rate of canopy formation of trees following pruning and the efficiency in which intercepted energy is converted into biomass.

Acknowledgement

The authors express their sincere thanks to Dr. J.L. Monteith for making valuable comments to improve this manuscript. Thanks are also due to Mr. D. Midya for his assistance in analysing the data; Mr. K.S. Prasad and Mr. M. Ashok Reddy for cartographic assistance; and Mr. K.P.C.S. Raju for typing the manuscript.

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The assessment of the stability of agroforestry systems

J. Riley

O.D.A. Biometrics Liaison Officer
Rothamsted Experimental Station
Harpenden, Herts AL5 2JQ, UK

Abstract

Environmental data can provide useful information in a statistical analysis but only if the information is collected at meaningful time intervals. A statistical method to assess the stability of mixed species systems is described and its modification for use with perennial crops is considered.

Introduction

The stability of intercropping systems has been considered by a number of research workers although published work on this subject is rare. A useful paper is by Rao and Willey (1980); a statistical paper reviewing the available assessment techniques and presenting a new approach is Mead et al. (1986). In this paper, I shall present and examine the concepts of this recent work and consider its extension for use with agroforestry systems.

Most work that has involved the statistical assessment of stability has used variation, dependence upon environment, or risk to describe the degree of stability. The use of measures of variability such as the coefficient of variation assumes that 'stable' means unchanging or constant in return. This need not be so, for a farmer will surely not object to a large increase in yield provided his yields do not fall below a desirable minimum. However, the main fault with such an approach is that the structure of the data in terms of temporal or spatial differences is usually ignored which may give rise to spurious results.

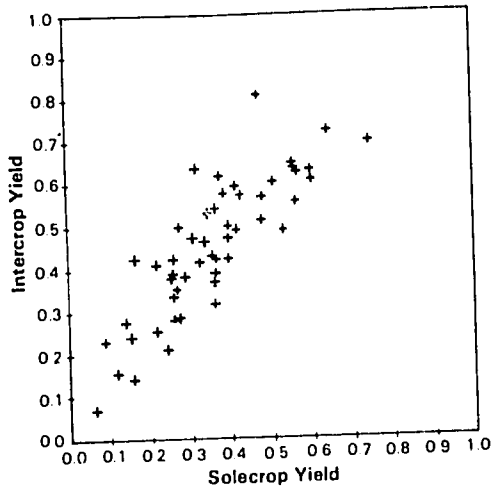
The idea of dependence upon environment rests upon the technique developed by Finlay and Wilkinson (1963). The success of this method depends largely upon the choice of the environmental index on which to regress the yields. In monocropping situations, the index is usually taken to be the mean yield of all the genotypes at that environment. In intercropping however, this means that the index is composed of the intercrop yield, and its two corresponding sole crop yields all of which are interdependent; any comparison of regressions based upon such indices will not be valid since the regressions will be interdependent.

The risk approach to the assessment of stability has been used by Rao and Willey (1980) who examined sorghum and pigeonpea returns from different farming systems at a range of environments and related them to the minimum required levels of return thus producing estimates of risk. Although this method ignores the structure of the data it is well-defined and permits the idea of stability to be seen in a more realistic way.

A new approach

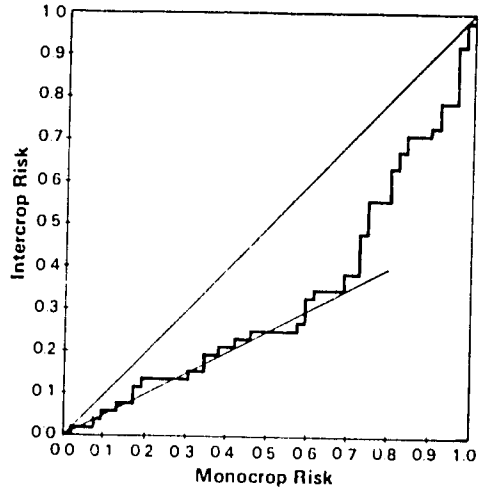
Mead et al. (1986) develop this risk approach allowing for the possibility of temporal and spatial components of variability in the data. Using a set of data consisting of sorghum/pigeonpea intercrop returns and sole sorghum returns, each from one of 51 site x year combinations, they examine the variation from site to site and from year to year for the 51 pairs of values, using bivariate analysis of variance. The patterns of variation for the site year and interaction effects appear consistent so the data set is used as a whole. Still relying upon the idea of 'bivariates' the intercrop returns are plotted against the sole crop returns, as in Figure 1, and the overall scatter is considered in terms of a bivariate probability distribution.

Figure 1 Intercrop returns plotted against sole crop returns for 51 sorghum/pigeonpea combinations.



To examine the size of risk for the two farming systems over the same range of site x year combinations the empirical relative risk is calculated for any possible minimum level of return. The range of values obtained for each farming system are plotted against each other, giving the stepped risk curve in Figure 2. Clearly, the risk for intercropping is only half that for the sole crop system for risks up to 50%. The calculation of this empirical curve is useful but dependent upon large data sets. If the data can be described in terms of a fitted bivariate distribution then the probabilities of falling below any pre-determined minimum level can be calculated and plotted against each other to give a smooth, not stepped, relative risk curve. If the method is appropriate for large samples it may well be applicable to smaller samples.

Figure 2 Empirical relative risk curve.



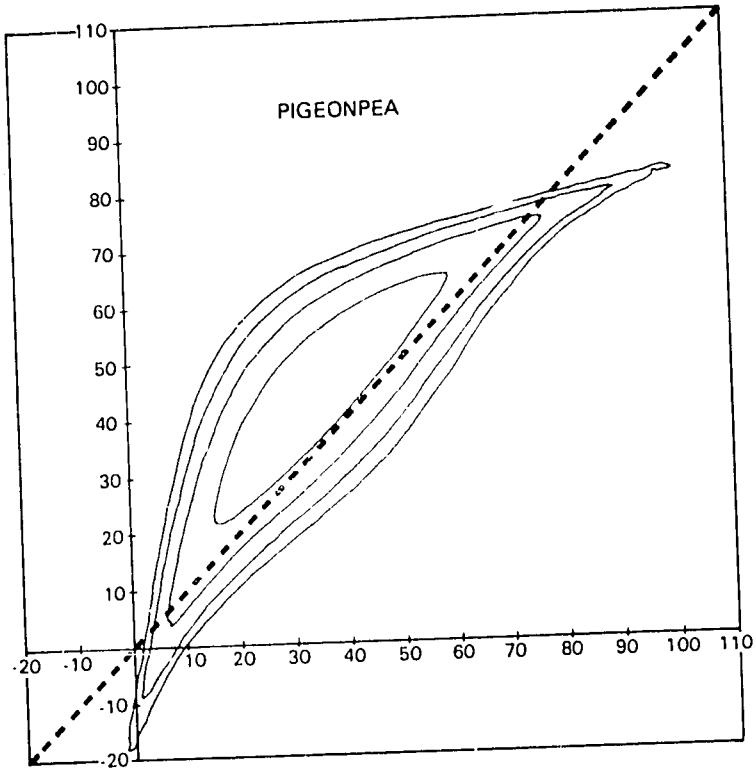
Statistical model fitting

A bivariate distribution is fitted to the data in Figure 1 by considering the marginal and conditional distributions of functions (sum and difference) of the two return variates, intercrop and sole crop. Using a sophisticated computer package (GENSTAT (Alvey et al. 1983), although GLIM (Baker and Nelder 1978) will serve equally well), normal distributions are fitted to the sum of the two return variates and to the difference of the two variates. Suitable integration then provides the bivariate distribution of the two original variates. The contour plot for the fitted bivariate distribution is in Figure 3. Using this distribution the probability of the return for each system falling below any value can be calculated; these two sets of probabilities when plotted against each other give a smooth relative risk curve as in Figure 4. Note the similarities between Figures 1 and 3 and between Figures 2 and 4. This exercise, when repeated for intercrops of sorghum with cowpea, greengram, groundnut and soybean, showed for each crop that the intercrop was less risky than the sole crop system and that a good fit was obtained in the choice of bivariate distribution.

Adjustments for environmental differences

In the initial stages of data assessment it may be deduced that large variability exists from site to site or from year to year or from both sources. This will prohibit the use of the data set as a whole but can be dealt with in one or more of the following ways. The choice of sites, which may be a subset of the total number, should be made for the area for which recommendations are needed and only those sites included, provided the site-to-site variability is acceptable. Abnormal patterns of variability will be reflected in the residuals from the bivariate analysis of variance; adjustments to the data can be made on the basis of these residuals. Collection of environmental data such as altitude and

Figure 3 Contour plot for fitted bivariate distribution.



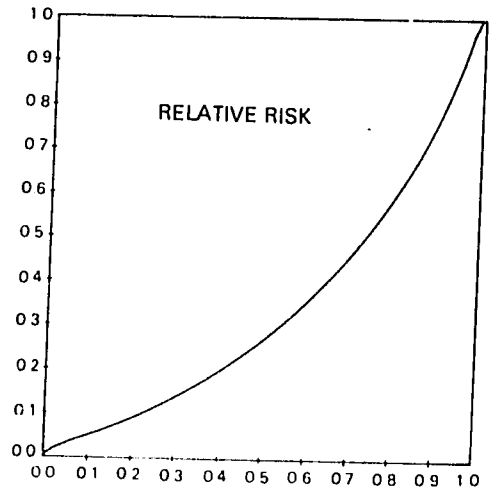
soil type and climatic data such as rainfall and temperature can provide a possible - explanation for the variability and can also be used to adjust the data.

Applicability to agroforestry systems.

Agroforestry systems differ from intercropping with two (or more) annual species since the perennial component may exist for many years before providing the farmer with any return. The method can be used, however, for the following data sets:

1. For final returns from the tree component (e.g., timber) and accumulated returns from the crops species, over a range of sites;
2. For intermediate returns from the tree component (e.g. fodder) and crop returns up to or at that time, over a range of sites;
3. For returns from the tree component and from the crop components for a rotation system at the end of the time period in terms of final yields for different sites or plots;
4. As in 3, but with intermediate yields not correlated within species or adjusted for previous bearing patterns; and

Figure 4 Estimated relative risk curve.



5. As in 3, but with response curves fitted to the pattern of growth over time and parameters of these curves used for different plots (or sites) as one return variate and the crop returns as the other.

Other situations can be identified for use of the method which can be tested for suitability by close examination of the data.

Acknowledgements

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Agroforestry systems: a production/protection land use strategy for steep land in the tropics

G. de las Salas

Consultant on Agroforestry
Apartado aereo 12803, Bogota, Colombia

Abstract

This paper deals with the suitability of agroforestry systems as a protective/productive land-use alternative for some regions of the tropics.
To support this statement the following considerations are briefly drawn:

- *the fragility of tropical soils*
- *the expansion of agriculture at expense of forest land*
- *the improvement of productivity and preservation of environmental conditions of mis-used cropland.*

Both economic and social role of forest trees and crops in combination (spatial and/or sequential) for the production of the rural poor is pointed out.

Special attention is drawn to the environmental conditions for determining the potentials and limitations of agroforestry systems, notably: soil, climate, and microclimate, vegetation, pests and diseases.

Perspectives of the use of agroforestry systems in soil conservation programs are analyzed.

Introduction

Factors influencing the agricultural production systems like the agroclimatic conditions (distribution and amounts of rains, soil fertility, soil drainage, slope, microclimate among others), land tenancy, crops sequence and culture practices, must be sufficiently known.

In the tropics the different systems of agricultural production and cattle raising predominant in each ecological region, are strictly related with the type of soils and the social pressure on the land.

In tropical Latin America, on soils of high fertility, dominant production systems are perennial cultures like palm, coffee, cacao, sugar, cotton, banana and grasses for livestock. All these are stable systems which need renovation only after 15 or 20 years.

On poor soils, the small farmer produces basic grains for his subsistence, utilizing shifting agriculture. This was efficient in the past when the population density was low and the requirements of the people were also low. The interval between seedings was long enough to permit restoration of the soil.

Under ever-higher demographic pressures and the growing need to produce crops at a commercial scale, it was forgotten that basic grain agriculture on poor soils and steep land is stable only when it is part of a system that provides soil restoration. Such a system is one that simulates the various storeys of a natural forest. Agroforestry systems appear to approach this condition and therefore have been favored by various research and donor institutions to demonstrate their efficiency in rural environments as a protective/productive land use strategy.

The problematic of land use in the tropics

Fragility of Soils

Many soils of the humid tropics are characterized by high acidity, aluminium toxicity, and low levels of available phosphorus, potassium and organic matter, all properties which indicates low fertility and limited potential for crop growth. Many of the nutrients utilized in traditional agriculture are naturally available from burning and from decomposition of organic matter rather than stored in the soil.

Nutrient cycling mechanisms are located in the above ground living biomass and in the top roots. Under continuous vegetation cover or permanent cropping systems, very few nutrients are lost due to the closed system of bioelement recycling. However, as above ground biomass decomposes or is continuously disturbed the nutrient level is reduced due to leaching, soil erosion and nutrient export by crop harvest. Therefore, most soils of the humid tropics do not support continuous cropping under natural conditions. If crop yields are to be maintained, then fertilizer inputs, crop rotations and adaptive cropping systems will be required, such as: sustained annual crop production, pastures, plantation crops, forestry, alley cropping and the like.

Expansion of agriculture at expense of forestland

There is widespread agreement concerning the scarcity of high quality agricultural land in developing tropical countries. Generally speaking, agricultural production will be able to keep up with population growth in the next decade provided it can grow by at least 2.5 - 3 percent per year without putting more – and not always suitable – land into crop and livestock production.

The pressure to expand and intensify the crop land in the humid tropics has resulted in increasing demands on forest land. Sommer (1976) estimates the deforestation rate of the humid tropics at 110,000 km^2 / year while Myers (1980) in a study for the National Academy of Sciences of the United States estimates high conversion rates from forest to agriculture in almost all the tropical countries studied, notably Brazil (400,000 km^2 in few years); Colombia (2000 km^2 / year); Peru (300,000 km^2 by the end of the century); and Ivory Coast (35,800 km^2 converted in 10 years).

Forest areas will continue to be exploited and converted for agriculture and cattle raising as a result of foreign or internal pressures. This procedure has the following effects:

1. The progressive destruction of natural forests;
2. The replacement of balanced ecosystems and ecologically adapted farming methods (i.e. agroforestry, nomadic animal husbandry, native shifting cultivation with long fallow periods, etc.);

3. A decrease in soil productivity as a result of soil erosion on one hand and of decline in soil fertility on the other hand;
4. Loss of germplasm;
5. Loss of the capacity of self regulation; and
6. Presence of poor farmers without capacity to improve their incomes and their quality of life.

Forest Plantations

The general picture in tropical America and perhaps in some parts of Africa is that afforestation is largely out of proportion with deforestation. Arguments for improving high-yield forest plantations intensively managed on suitable land, have never been more justified than now. Known examples are those from Venezuela (200,000 ha of *Pinus caribaea* on lowland) and Brazil (more than 2 million ha of eucalyptus managed for pulp production), both on savannah landscapes. In mountainous land, however, the situation has not always been satisfactory and has even been disappointing. Private owners have reafforested large areas mainly with conifers thinking in terms of income rather than in improving the environment. On volcanic soils the yields of these plantations have been satisfactory but the costs of exploitation (harvesting and transportation) are onerous so that there exists a 'bottle neck' to industrialize such plantations.

The growing demand for wood in the tropics, along with intensifying competitive land use pressures, calls for a revision of land use planning in order to concentrate wood production on the most appropriate sites.

Forest trees and crops in land use planning

Trees and crops to do the job

Selection of trees and/or crops to improve soil productivity while preventing soil erosion, requires careful consideration. Planting unsuitable species or tree/crop combinations can result in wasted effort and money and possible loss of time, if failures are slow to appear.

There is no point in trying to put trees or crops in nearly soil-less sites because the growth and crop production will be poor. In such cases grasses would preferably be combined with an efficient legume like *Cajanus cajan* (pigeon pea) to ameliorate the physical condition of soil and to enrich it with nitrogen and organic matter.

The selection of trees and crops as a land use strategy on steep land is largely a matter of assessing their adaptability to prevailing site conditions, their acceptance by the farmers, the farmers' needs for fire wood, poles, timber, food, etc. and the rentability of the system rather than its efficiency in preventing soil erosion. In fact, the first priority may be to obtain these by-products, if conservation is to have local acceptance.

In Panama for example, *Byrsonima crassifolia* is tended by the farmer since its fruit is largely utilized in the preparation of juice locally named *chicha de nance*. In the watershed of Paute River, Ecuador, where erosion control has become a great problem, farmers accept technical assistance in increasing their crop production by means of measures that include planting fruit trees and other trees known in the region for centuries (e. g., *Eucalyptus globulus, Prunus capuli*) rather than to plant 'miracle' trees in their farms.

E. deglupta is used in Costa Rica at the age of 1 year as training poles for banana trees. Okigbo (cited by Kunkle 1978) reports that in south-eastern Nigeria, cashew trees (*Anacardium occidentale*) were first planted as an anti-erosion measure, but now the fruits and seeds are also important by-products used for both food and commercial purposes.

Augmentation of productivity and preservation of environmental conditions

Changes in farming methods and land use – brought about in great measure by modern agricultural policies in developing countries – have resulted in increases in soil productivity (e. g., coffee, rice, cotton). But these changes also have originated a series of environmental problems that include soil erosion and appearance of pests not previously known. As important factors contributing to the erosion problem, the following deserve mention:

1. Government policies to support the intensification of crop production, notably coffee. The loans afforded by the state to the coffee grower encouraged him to cut the tree storey of a traditional 'multi-strata system', (to plant up to 10,000 coffee trees/ha) severely diminished the protection against soil erosion. This was the case in a coffee country like Colombia (with 1 million ha of productive land for coffee). Now the small farmer is coming back to his traditional system.
2. Indiscriminant use of biocides in intensive crop culture (e. g., cotton, rice) has caused contamination of soil and water. Even so dramatic is the situation in the livestock sector all over the humid tropics, at least in Latin America. The steep land has been mismanaged for centuries almost always in the following pattern:

   (a) Slash and burn agriculture – grassland for cattle raising;
   (b) No use of fertilizer;
   (c) No rotation of grazing land;
   (d) Annual burning of grasses to induce fresh growth of palatable young shoots.

This form of range management has led to various types of erosion, among which the so called 'cattle step' is the most widespread in mountainous landscapes. The damage done to forest and watersheds by this type of cattle management exceeds by far the poor returns from meat production if one takes into account the low carrying capacity of many tropical areas (mostly one animal per 5 or more hectares).

Fortunately acid savannah landscapes are being successfully managed by grass varieties adapted to these edaphic characteristics (Hecht 1979). Some parts of the humid Amazon area are under experimentation with grass-legume combinations to increase cattle production. Various scientists (see Sanchez 1976, 1979; Hecht 1979; Toledo and Morales 1979; among others) are optimistic over the experimental results while others (Deurojeanni 1982; Goodland and Irwing 1975; Shubart 1977; Fearnside 1978) are pessimistic and foresee devastating erosion and they doubt the applicability of the experimentation to large areas. Although this subject is not the matter of this paper, its importance is unquestioned. Much research is needed to obtain an accurate appraisal of soil erosion problems.

Environmental conditions to determine potentials and limitations of agroforestry systems

Soils

As pointed out previously, many of the soils of the humid tropics have low fertility, especially lowland soils. There are, however, areas occupied by fertile soils (Andosols, Nitosols, Vertisols, Inceptisols). Although notably smaller in extent, the majority of them are under coffee. On the other hand, foothills with relatively high fertility due to a large amount of organic matter and to a fertile parent material, are already occupied by vegetables, pastures and other land uses (e. g., cacao, cassava). Poor and partially steep soils remain under 'clean crops' like maize, onion and rice, among others, all of them subsistence crops. **Unfertility of soils and steep landscapes are two strong limitations to bringing agroforestry techniques to the small farmer successfully.** Furthermore, the small size of the farms makes it difficult for the farmer to plant part of the terrain with woody species, being the crop production essential for the farmer (at least in simultaneous tree/crop models).

Some of the poorest soils tend to produce yields that decrease continuously for 8 to 10 years and then stabilize. The main problem here is that their management is still in its experimental phase and it is risky to extrapolate research results. However, there are a few successful examples. In fact, in the 'Sierra peruana', soil conservation measures (terraces, mulching, green manure) accounted for 60% of the improvement of the crop production of the small farmer using a crop/tree spatial model on treated slopes. A second example is that of the 'selva alta', also in Peru, where the German Agency for Development successfully experimented with woody species in private small farms.

Ecologically, the problems in Andosols, Fluvents (alluvials) and Ultisols are minor, as organic matter could be increased, soil protective is feasible and the proper combination of chemical, organic and green fertilizers could be established, if the economic profit supports it. Most difficult is the management of Alfisols, Vertisols and even some Andosols that are abundant in mountainous landscapes in tropical America and perhaps also in Africa. In such soil types, the shallow depth (generally 30 to 40 cm), the presence of expansible clay and the erodibility of the top soil, respectively, make difficult the application of efficient cultural practices.

Summarizing, crop/tree production – both spatial or sequential on small farmer's land of the tropics – is based more on economic than on ecological factors.

Climate and macroclimate

Moisture, temperature, and rain distribution are normally considered to be important factors in field crop production. Of these, moisture relationships (especially seasonal variation of evapotranspiration) determine the more intricate ecological relationships and therefore have been considered as the most important determining factor in crop ecology. In the humid tropics the chances of having abundant water supply in critical periods are higher than in the regions of less – and more variable – precipitation. The adoption of resistant varieties and crops more adaptable to different climates has been a long-term answer to the problem. Agroforestry systems are more difficult to evaluate since the interactions among plants of different size and root systems cause changes in at least the following factors:

1. Soil moisture;
2. Temperature of air within the system;
3. Evapotranspiration;
4. Wind;
5. Incident light;
6. Decomposition rates of organic matter and nutrient dynamics;
7. Ground temperature;
8. Photosynthetic activity;
9. Nodulation (in some shade trees like *Erythrina spp*);
10. Daylength;

Failures in identifying and monitoring these microclimatic factors can lead to losses in crop production. In general, however, farmers have, by trial and error, adopted the best practices to manage their crops.

Pests and diseases

This aspect constitutes an important matter of study to derive the limitations and potentials of agroforestry systems in tropical environments. It is well known that the more primitive (and consequently diversified) an ecosystem, the more resistant it is to pests and diseases.

The incidence of diseases and pests is of utmost importance in the humid tropics. Attacks of insects, fungi, viruses, nematodes and other parasites affect the growing crop, and thus the final product. On the other hand, the indiscriminate use of pesticides has led to many failures. Ecological guidelines have to take into consideration besides the economic implications. A necessary prerequisite is a background of biological information.

The control of diseases with chemicals has severe effects on the ecological complex, but these are not so serious as those caused by insecticides. The use of pesticides is, especially in tropical areas, spreading rapidly. At the same time, farmers and research workers feel an urgent need to develop effective alternative approaches, e.g., integrated pest management (IPM).

Perspectives

Agroforestry systems: where to implement them?

Here we are concerned with the application of agrometeorological research to the changes in both macro- and microclimate. The results must be transferred to the rural poor in an intelligent and easy way, so that they can take advantage of the improvements in farm management methods.

The combination of livestock with trees planted for fuel, helter and shade, fodder, or fence posts, can be very satisfactory in flat land. Successful examples exist in various countries of the American tropics. In hilly land, however, this kind of combination has to be practiced carefully since the lack of ground cover under tree plantations can lead to severe soil erosion. Pereira (1979) reports examples of such damage under eucalyptus in East Africa and Ethiopia and the same can be seen in the Andean countries of South America.

Notwithstanding this fact, successful case studies deserve mention. Budowski (1981) comments that for at least 80 years, a local alder species, (*Alnus acuminata*), has been successfully planted at elevations between 1300 and 2500 m asl with high rainfall (2000 - 3000 mm) on good soils in the dairy region of Costa Rica. The presence of alder trees is said by farmers to increase fodder production. The trees are planted at wide spacings within pastures that are grazed (*Pennisetum clandestinum*) or cut (*Pennisetum purpureum* and *Axonopus scoparius*). Most alder trees found in pastures are regularly pruned. This species fixes nitrogen through large nodules. Some initial measurements indicate a mean annual increment in diameter of 2-3 cm with harvesting after 15-20 years. The wood is easily workable for multiple purposes. In Colombia, a 16-year-old stand of alder is being harvested by a match industry.

Another example in the same country is the silvopastoral enterprise in more than 500 hectares in the highlands (1800 - 2200 m asl) near the city of Manizales in which *Pinus patula, Cupressus lusitanica* and *Alnus acuminata* stands are being grazed without diet supplements (except mineralized salt).

The taungya system – as a part of a strategy to change land use or to protect watersheds – is well known. Pereira (1979) reports that the taungya ('shamba') system (pines planted between vegetables) in Kenya successfully avoided both significant soil erosion and loss of streamflow regulation. Today, with the pines approximately 30 years old and ready for harvesting, water use of the two species remains equal. The Forest Department is continuing with the plantation program in which agroforestry plays an integral part.

In tropical America and the Caribbean, taungya has a successful history. In Costa Rica, tree species of a high commercial value like *Cordia alliodora, Gmelina arborea, Eucalyptus deglupta* and *Terminalia ivorensis* associated with maize, beans, cowpeas and string beans have demonstrated at an experimental level how to convert large areas of degraded lands into valuable tree plantations. Haiti is reafforesting thousands of hectares of steep eroded land. Thousands of farmers are expected to be involved in the programs which allow them to combine field crops with fuelwood trees (such as the excellent *Azadirachta indica* named locally as 'neem'). The rising prices of firewood posts and timber and the possibility of eventually obtaining cheap and large sources of fodder and biomass on marginal agricultural lands have generated great interest among funding agencies.

The use of agroforestry systems in soil conservation programs

Soil protection under tree crops.

Afforestation is normally an acceptable method to reduce erosion and help control flooding while at the same time providing timber and/or firewood. However, this statement must be regarded with caution, since on steep land with fragile parent material (e.g., saturated and decomposed ash under shale), afforestation could be the worst land use alternative. In such landscapes, big natural landslides occur frequently and the risk of a failure is very high. On stable soils afforestation can fulfil not only a protection objective but also a production one: getting products of direct value to rural people such as fruit, fodder, fence posts, timber, since these by-products can be as important as the protection itself.

The most important function of tree or shrub vegetation for soil protection is to protect against the splash erosion caused by raindrops. Kunkle (1978) cites an experiment in Africa in which the 10-year average soil loss from bare soil was 126.6 ton/ha; but when the soil was protected from the raindrops with a fine wire gauze, the rate of loss was reduced to only 0.9 tons/ha. In upstream afforestation programmes in the Cauca Valley in Colombia, bamboo trees have been selected not only for soil conservation but also to yield benefits for farmers. For steep land, FAO (1976) has developed some useful conservation techniques.

The following is a list of desirable characteristics of tree species for soil conservation programmes (Kunkle 1978):

1. Good survival and fast growth on impoverished sites;
2. Ability to produce a large amount of litter;
3. Strong and wide-spreading root systems with numerous fibrous roots;
4. Ease of establishment and need for little maintenance;
5. Ability to reproduce vegetatively
6. Capacity to form a dense crown and to retain foliage year-round or at least through the rainy season;
7. Resistance to insects, diseases, and browsing;
8. Soil improvement (nitrification by legumes); and
9. Provision of some economic returns, preferable on a short-term basis, such as fruits, nuts, fodder or beverage products.

Soil stability and crop/tree production

In Honduras and Guatemala, burning the bush to prepare the soil for corn and beans is very widespread. This has led to a strong selection of fodder trees. In fact, there exists a traditional silvopastoral system, having an enormous potential and requiring only low inputs. Leguminous species like *Gliricidia sepium* and *Leucaena spp* have been associated with corn and beans since pre-Colombian time, a system attributable to the Maya culture. The cultivator traditionally leaves and tends the naturally-regenerated trees of laurel (*Cordia alliodora*) on the 'milpas' (abandoned bush fallow). This kind of land management deserves more attention and improvement, since it fulfils two goals at the same time: soil stabilization and crop or tree production.

In humid environments, the tending of the natural regeneration in the native forest for fuel, forage and other products, permits a great opportunity to improve the land use of small watersheds. This opportunity is followed by the 'agroforestry chance' to introduce trees into the crop and livestock areas with the main objective of leaving seed-bearing trees to regenerate the pine (*Pinus oocarpa*) forest after the agriculture or cattle raising has been abandoned. It goes without saying that the involvement of the local community in the support of agroforestry and conservation programs is extremely important. In this respect, the FAO Conservation Guides 12 (FAO 1985) and 14 (FAO 1986) deserve careful reading.

Final remarks

Technical data and site-selection criteria as well as measurements on stream flow and discharges in agroforestry experiments in small watersheds vs. other land uses, should be worked out by hydrologists.

Investigations of kinetic energy of raindrops in relation to soil erosion should be carried out.

The Universal Soil Loss Equation (USLE) should be tested in agroforestry systems (and in monocultures as well) in order to evaluate the soil loss rate over a reasonable period of time.

Small watersheds with various land uses including agroforestry systems (e.g., coffee with and without shade), should be accurately instrumented in order to record:

1. The efficiency of agroforestry methods to reduce erosion rates;
2. The recovery of nutrients with agroforestry systems vis-a-vis other land use practices; and
3. The long-term productivity of land for crops, wood and livestock under agroforestry systems.

Foresters, agronomists and land - use planners should be realistic when stating the benefits derived from associated trees and crops on steep lands. The introduction of agroforestry systems alone does not necessarily result in reduced flood damage, reduced drought, increased rainfall or the control of erosion and sedimentation. There is a need for 'enlightened land-use techniques' for conserving soil while maintaining high productivity on critical steep mountain areas. Greater supervision and control of upland use, including grazing and logging, must be accomplished soon.

A long-term strategy to control human and livestock populations in the uplands in addition to developing systems of producing trees and crops when appropriate, deserves high attention by land-use planners and decision-makers in tropical countries. In addition, the development of community organizations to restore wasted lands and non-destructive forest management practices should be encouraged.

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Control of solar radiation in agroforestry practice

W.E. Reifsnyder

Yale University School of Forestry and Environmental Studies
New Haven, Connecticut, USA

Abstract

One of the major controls of microclimate and growth in agroforestry practice is solar radiation. It is also one that is subject to considerable control by man. This chapter reviews basic principles of solar radiation and discusses the ways solar radiation climate in a tree/crop combination can be controlled and/or modified.

These ways relate primarily to the tree component which is the relatively stable and continuing part of the system. Interactions between the trees and solar geometry produce the particular solar climate of a tree/crop system. These interactions and effects include: interception of radiation by tree stands of various densities; effect of canopy structure; effect of row orientation and spacing; effect of latitude and time of year on solar paths; shade from single tree crowns; and spectral quality of sunlight under partial shade.

Implications for agroforestry practice are discussed briefly.

Introduction

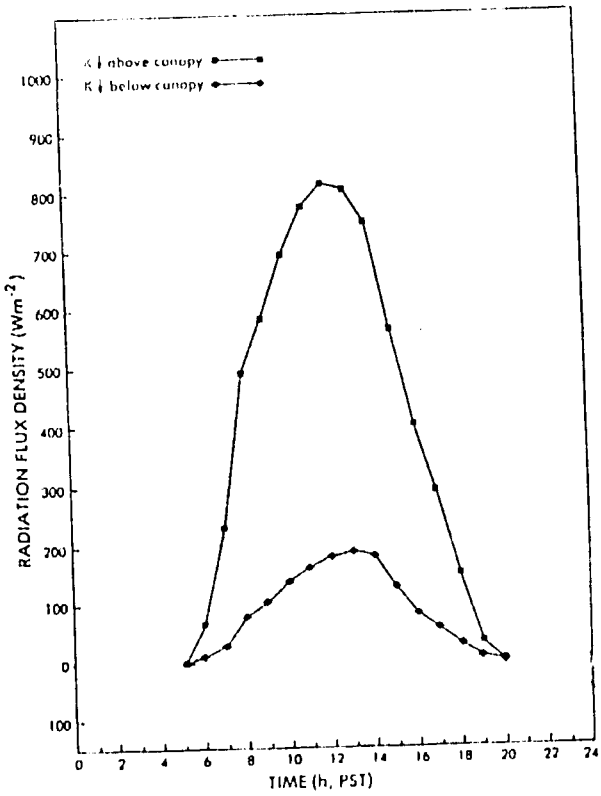
In the early days of agriculture, trees must have primarily been a nuisance: clearing away large trees to prepare an area for the planting of a crop was certainly a difficult and never-ending task. However, in some parts of the world where sunshine was abundant, perhaps over-abundant, the value of the shade provided by an overarching tree must have become apparent. And so by repeated experience, systems of food and fiber production were developed that involved some combination of tree and crop (King 1987).

At one time, tobacco grown in Sumatra under partial tree shade was highly prized for its qualities as a wrapper for fine cigars. Connecticut tobacco growers successfully mimicked the shade of the Sumatra trees by covering their fields with acres of cheesecloth, producing the thin, smooth leaf that was similar to the Sumatra leaf. In a study of the microclimate inside a tobacco shade tent, Waggoner, Pack and Reifsnyder (1959) found that solar radiation, evaporation and wind were all reduced substantially as compared with conditions outside. They concluded that the major effect of the tent was in the reduction of solar radiation, mimicking the reduction of solar radiation by the Sumatra trees. Thus an agroforestry system developed indigenously was transferred to another region through artificial control of the microclimate.

A similar use of artificial shade is reported by Stathers and Bailey (1986), in the growing of ginseng (*Panax quinquefolium*). This perennial herbaceous plant normally grows in the shade of deciduous trees in eastern North America. Commercial growers simulate the radiation climate with wooden lath or woven black polypropylene cloth. Measurements of downcoming solar radiation above and below a canopy of the cloth showed that the radiation was reduced to approximately 25% of the above-canopy value

(Figure 1). The absorption of much of the radiation by the canopy produced a double maximum of temperature at the canopy at the canopy and soil surface (Figure 2). Other microclimatic modifications at plant level included a higher average air temperature; higher relative humidity; higher dewpoint temperature, decreased wind speed; and decreased evapotranspiration. These modifications permit successful growing of ginseng in the arid interior of British Columbia, Canada.

Figure 1 Solar radiation above and below a canopy of black polypropylene cloth, after Stathers and Bailey (1986).



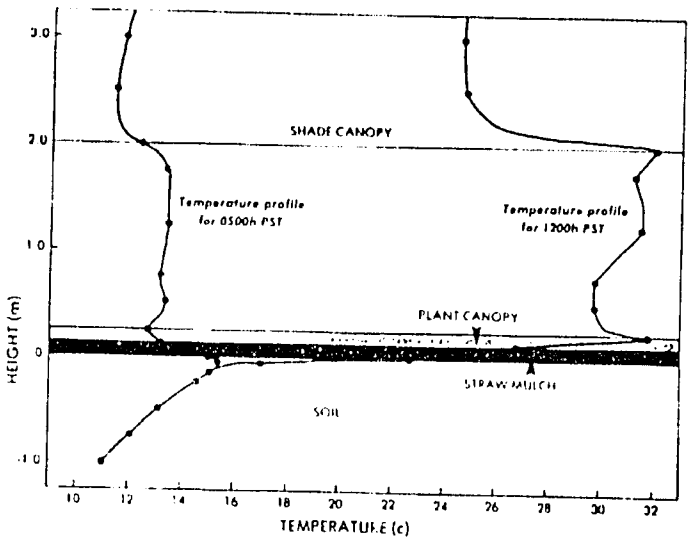
Conklin (1953) has pointed out that the Hanunoo of the Philippines practiced a complicated agroforestry system in which clearing for rice cultivation involved the leaving of selected trees to provide a partial canopy of foliage to prevent excessive exposure to sunlight. The trees were not only utilized for their protective value but also for the production of wood, medicines, cosmetics and other products.

Despite the historical and, indeed, obvious role of trees in controlling the radiation climate in agroforestry systems, relatively little specific research has been undertaken, especially in the tropics where agroforestry is often the dominant cropping system. It seems likely that the main reason for this is that research in crop microclimate developed largely in temperate regions where large-scale agriculture has been dominant. In the past hundred years, much has been learned about forest and plant microclimate (Geiger

1957; Yoshino 1975). Much of this information may be transferable to agroforestry systems and practices, at least for a first approximation.

The objective of this chapter is to survey what is known about solar-radiation climate and its conscious control by vegetation manipulation. I hope that this information will suggest ways that knowledge of radiation climate might be used in agroforestry practice; and indicate gaps in our knowledge that can be filled by appropriate research.

Figure 2 Temperature profiles above and below shade canopy, clear summer day (Stathers and Bailey 1986).



Solar radiation

The amount and spectral distribution of sunlight reaching the earth's surface is dependent primarily on 'obstructions' that remove or modify the solar beam in some manner. Thus extraterrestrial sunlight shining through clear sky is reduced in total amount and selectively reduced by various molecules and aerosols (Figure 3; Gates 1980). Most of this selective reduction is in the near-infrared region. Light scattered by 'pure air' molecules is rich in short wavelengths; thus the sky appears blue while the solar beam is depleted in these wavelengths. Light transmitted and scattered by the water droplets in clouds spans the visible spectrum and thus appears white.

By contrast, light under a plant canopy is rich in near- infrared wavelengths (Figure 3). This enhancement of infrared light is the result of the spectral properties of green leaves which transmit and reflect highly in the near-infrared region (Figure 4; Ross 1975). In the far-infrared region (beyond about 3000 nanometers), leaves are nearly complete absorbers, but there is very little of this radiation in sunlight.

Figure 3 Solar irradiance, cloud light, sky light and shortwave radiation beneath vegetative canopy (from Gates 1980).

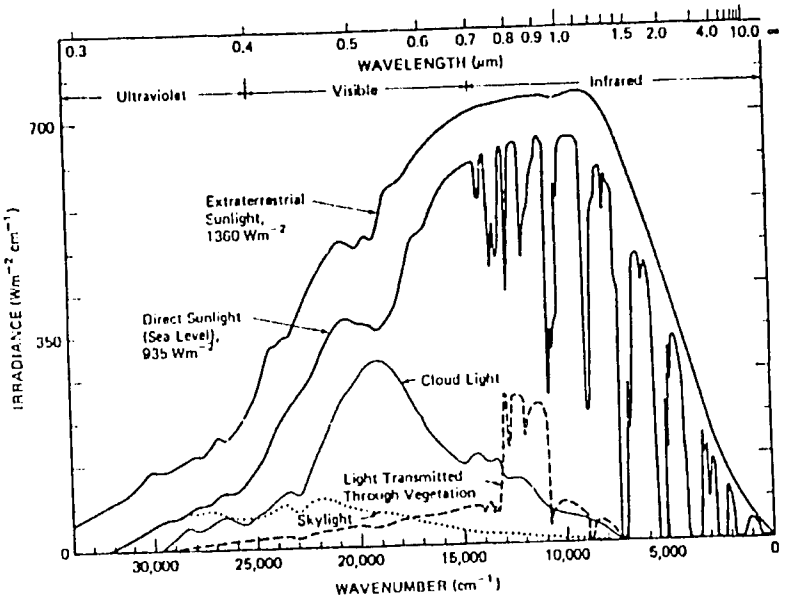
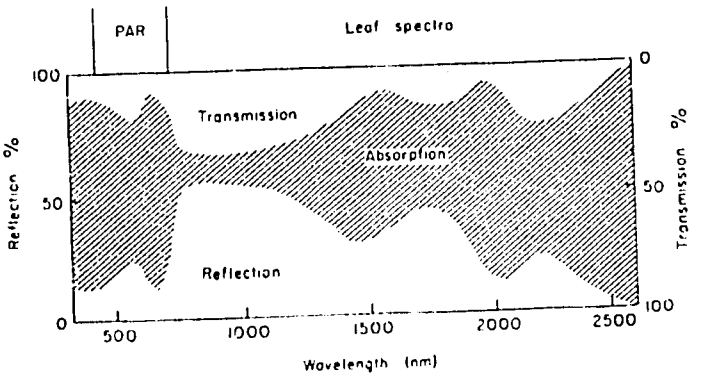


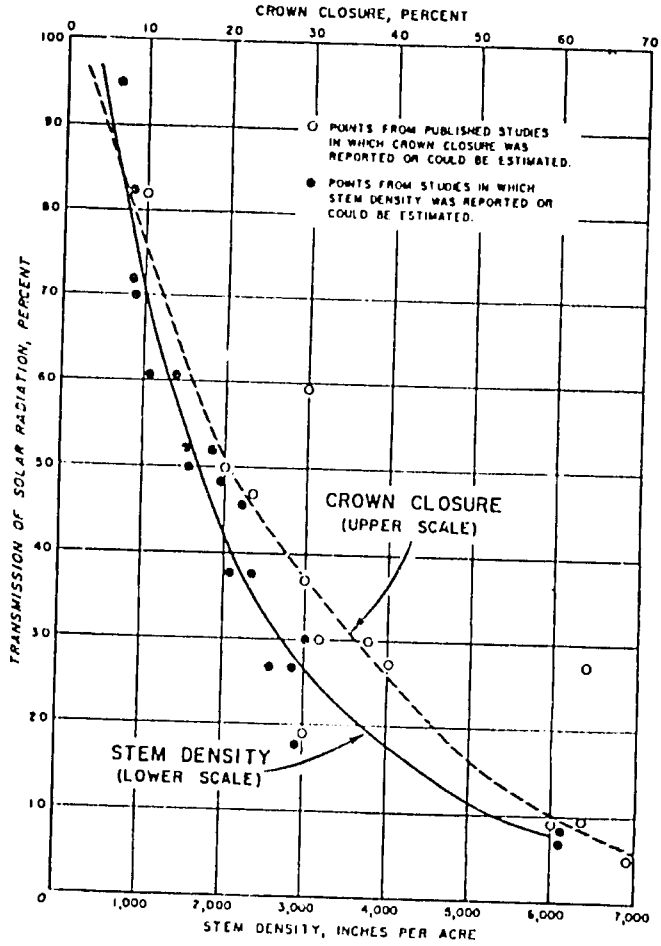
Figure 4 Shortwave transmissivity, absorptivity and reflectivity of green leaf (Ross 1975).



Radiation profiles in a forest stand

Transmission of solar radiation through a forest canopy depends on stand density; but the relationship is not linear (Reifsnyder and Lull 1965). This relationship can be looked at as function of crown closure or of stem density (Figure 5; Miller 1959). THus a stand with 50% crown closure will transmit less than 20% of the incident solar radiation. With

Figure 5 Transmissivity of tree stands as a function of crown closure and stem density (Miller 1959).

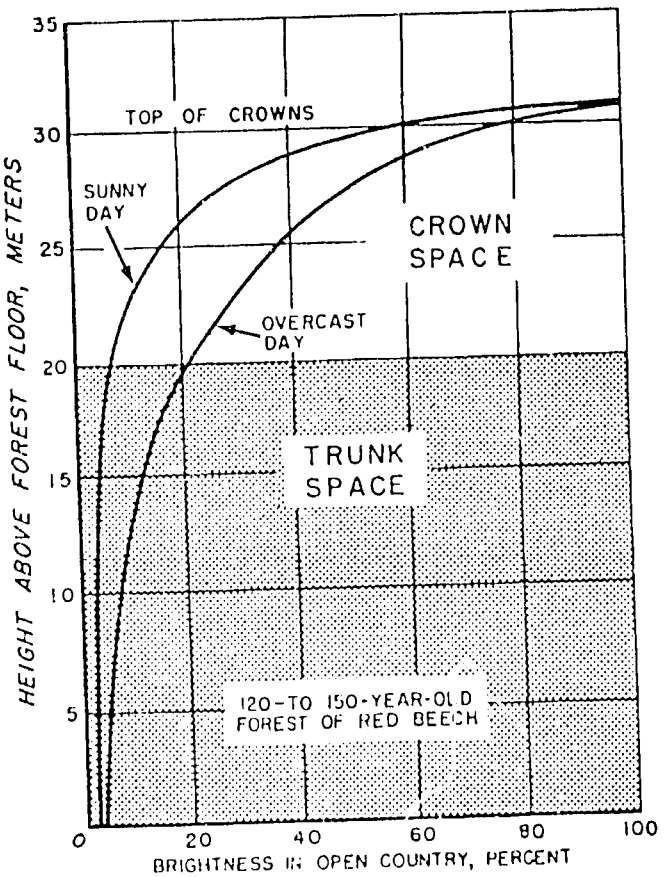


only 10% crown closure, certainly a rather open stand, radiation reaching the ground is reduced by about 25%. Thus it might be expected that even sparse stands would offer considerable protection from excessive radiation loads. On the other hand, a crown closure of only 1/3, a rather open stand, would reduce the solar radiation beneath by two-thirds, which might result in too little radiation for some crops.

However, it should be noted that most of the data on which Figure 5 was based come from mid-latitudes where even at noon, the sun is far from the zenith. I would expect that in the tropics where the sun is close to the zenith at noon, the relationship between transmission and crown closure would be closer to linear. This would especially be true for broad-leaved stands in which the upper canopy is more-or-less like a single layer of horizontal leaves.

The foregoing data are for direct and diffuse solar radiation from a clear sky. On cloudy days, when only diffuse radiation is present at the top of the canopy, transmission is greater than on clear days (Trapp 1938). That is, the diffuse light from the sky can find many more holes to come through than can the direct beam of sunlight. As Figure 6 shows, at every level in crown and trunk space of a dense broadleaf stand, the percentage of transmitted light was greater on an overcast day as compared with a clear day.

Figure 6 Vertical profiles of light in a beech stand on sunny and overcast days (Trapp 1938).



Effect of canopy structure

The amount and spectral distribution of sunlight reaching the ground beneath a tree canopy depends not only on the crown closure (as indicated in the previous section), but also on the way that the canopy is structured. Young provides an illustrative example of this (Section 1), showing how a 25% tree cover can be arranged in different ways. Thus a plot of land can have the trees in a block, encircling the plot along its boundaries;

as wide strips; as more numerous narrow strips (both of which may be oriented differently with respect to the sun's path); as small trees randomly distributed; or as fewer large trees also randomly distributed. Perhaps the most obvious effect of such distributions is in the control of the solar radiation at the ground. Unfortunately, relatively little information is available on these effects; and what there is, is scattered widely in the literature.

Single-layered canopy vs deep canopy

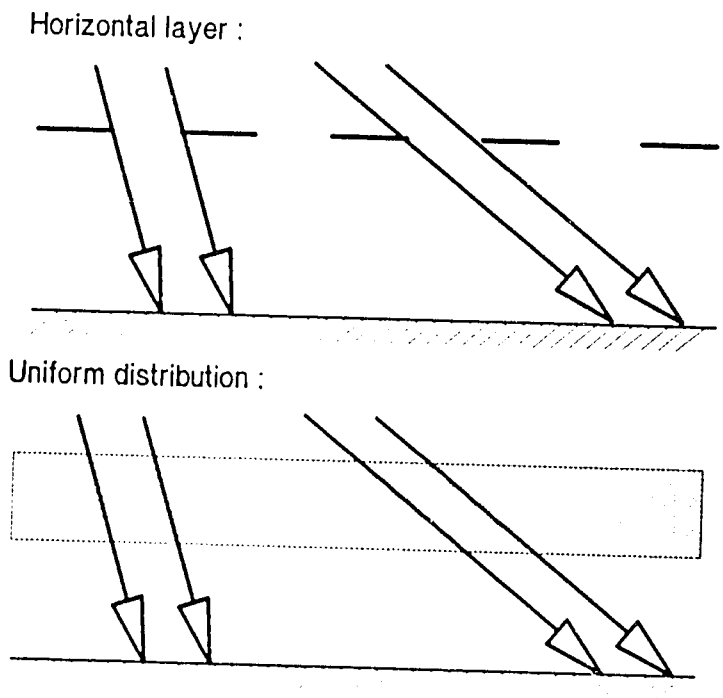
A deep canopy with more-or-less uniform distribution of vegetation elements has often been characterized (with respect to the attenuation of direct-beam radiation) as a uniformly scattering medium (Figure 7). In this case, the solar beam is attenuated according to the negative exponential equation:

$$I(\text{below}) / I(\text{above}) = \exp(-kx)$$

where x is the path length through the medium and k is an attenuation coefficient, a constant for a particular medium. If the canopy consists of a single layer of horizontal leaves, the solar beam is not attenuated, and the same proportion of direct-beam sunlight is transmitted at all solar angles:

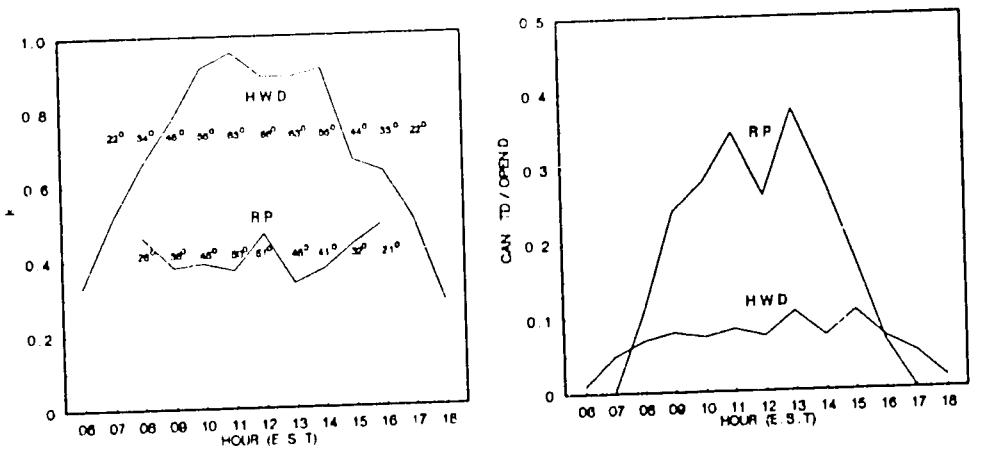
$$I(\text{below}) / I(\text{above}) = \text{constant}$$

Figure 7 Direct-beam solar radiation penetrating single-layer canopy (upper diagram) and canopy composed of uniformly-scattering vegetation elements.



These relationships can be tested in canopies that approximate the two conditions. Reifsnyder, Furnival and Horowitz (1971/72) compared the direct-beam radiation above and below canopies of two kinds: a conifer canopy representing a uniform scattering medium; and a broad-leaved canopy representing a single, horizontal layer of leaves (Figure 8). In the conifer stand, the extinction coefficient should be constant throughout the day (Figure 8a); in the broadleaf stand, the ratio of direct beam radiation below to that above should be constant (Figure 8b). The fall-off of the ratio at the beginning and end of the solar day can be attributed to the presence of tree trunks and other vegetation that destroys the single-layer assumption at low solar angles.

Figure 8 Direct-beam radiation above and below forest canopies of two types: a broadleaf stand (HWD) and a conifer stand (RP); a) extinction coefficient; b) ratio of direct beam radiation below the canopy (CAN TD) to that above (OPEN D). Numbers at each hour indicate the solar altitude at the time of observation (Reifsnyder, Furnival and Horowitz 1971/72).



Clumped vs dispersed crowns

As pointed out by Young (this volume, Section 1), the nature of clumping of tree crowns (few large crowns vs many small crowns) will affect the microclimate beneath. One effect of such clumping will be to control the pattern of light and shade on the ground beneath. Underneath a broadleaf canopy with many scattered vegetation elements and many gaps in the canopy, one should expect many small, short- duration sunflecks. A canopy in which the vegetation elements are clumped, the sunflecks should be larger and illuminate a particular ground spot for a longer time. Measurements in the two stands referred to above confirm this assumption (Reifsnyder and Furnival 1970). Figure 9 shows that there were many more short-duration sunflecks beneath the broadleaf canopy than under the conifer canopy even though the overall canopy density was similar in the two stands.

How does the sunfleck distribution affect the total direct-beam radiant energy received for a day? At least for the two stands studied, it appears that there is not much difference in the daily totals (Table 1). Furthermore, most of the energy in both stands was in long-duration sunflecks. Very little of the total energy was contained in the more numerous sunflecks under the broadleaf canopy.

Figure 9 Number of sunflecks beneath conifer and hardwood stands, in terms of their duration at fixed sensor location (Reifsnyder and Furnival 1970).

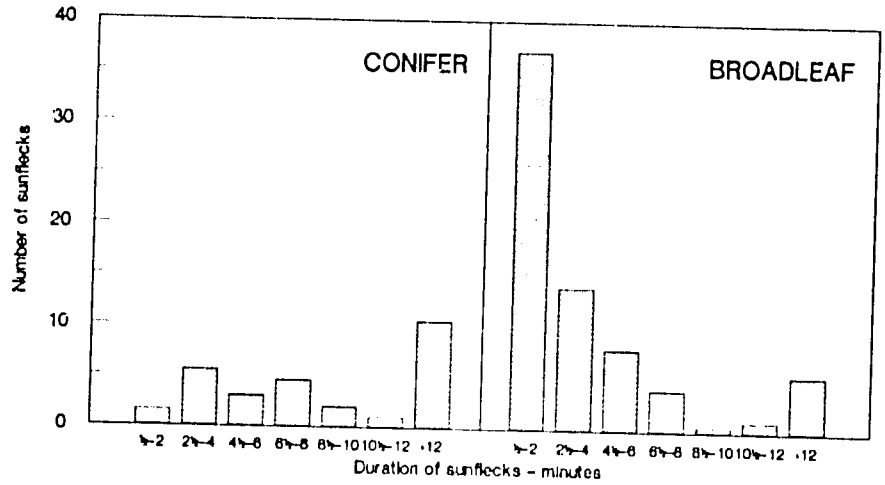


Table 1 Distribution of direct-beam energy in sunflecks, as percentage of total in all sunflecks.

Duration of sunflecks (minutes)	Broadleaf				Conifer	
	Location 1		Location2		Location1	Location2
	AM	PM	AM	PM	all day	all day
10	90	74	81	91	87	91
3-10	8	13	12	7	12	8
<3	2	13	7	2	1	1
Total (MJ m^{-2})	16.26	3.34	6.23	10.66	12.25	15.68

Source: Reifsnyder and Furnival 1970.

Effect of row orientation and spacing

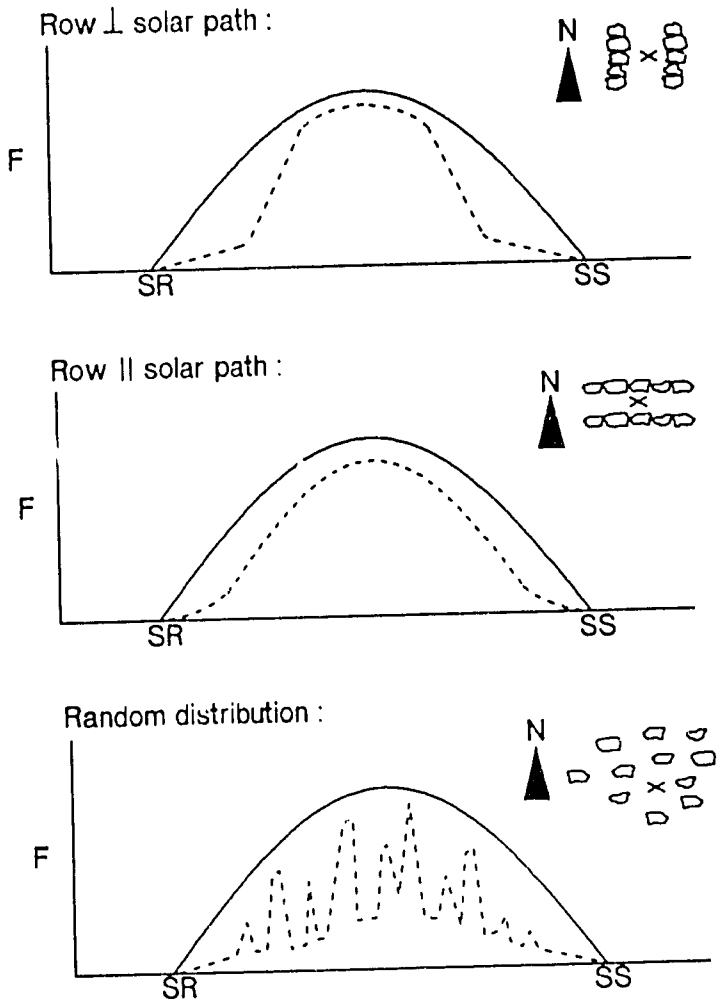
Consider next an agroforestry system in which low-crop areas are separated by rows of trees, with the width of the open space nearly equal to the width of the tree crowns. In an area near the equator, the solar radiation reaching the center of the open row will depend on the orientation of the rows. Figure 10 shows diagrammatically the total solar radiation expected with N-S and E-W row orientations and with a random tree distribution of the same crown density.

With the N-S rows, the center of the open space will receive direct-beam sunlight for a period in the middle of the day, the exact duration depending on the ratio of the tree height to the width of the rows. With E-W rows, the center spot will typically be exposed to nearly full sunlight throughout the day, missing only the skylight obscured by the

nearby trees. By contrast, a random orientation of tree crowns will result in an irregular pattern of sunfleck and shade, as shown in the last part of Figure 10.

Of course, rows can be oriented in any direction, can be on a slope of any inclination and azimuth, and can vary in the ratio of strip width to tree height, all of which will change the course of solar radiation received by a particular spot.

Figure 10 Diagrammatic representation of solar flux (F) above (solid line) and below (broken line) three types of canopies, for sun passing close to zenith.
Top, tree rows oriented north-south;
middle, tree rows oriented east-west;
bottom, trees oriented randomly.



Effect of latitude and time of year

Thus the actual pattern of sun and shade will depend on the complex relationships of the solar path to the specific plot. This in turn depends on the latitude and time of year. Sun-path diagrams showing these relationships graphically are available in the Smithsonian Meteorological Tables (List 1958), for latitudes ranging from the equator to the poles. These relationships can be interpreted in terms of the solar radiation reaching the surface.

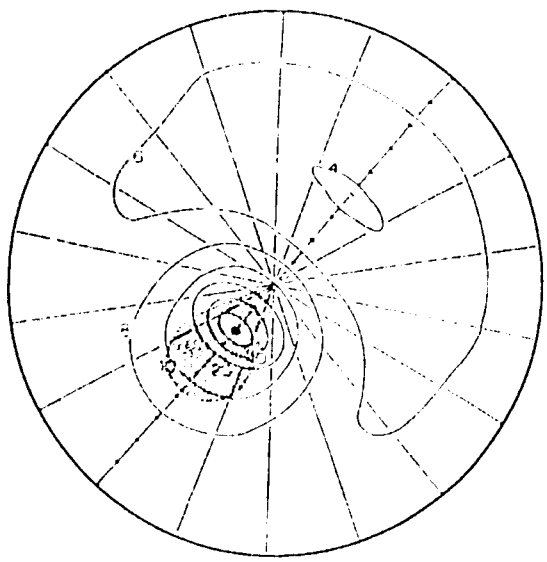
Harrington (1984) describes a computer algorithm that calculates the solar radiation in an open strip between trees for any strip orientation, slope inclination and azimuth, day of year, and latitude. The algorithm also permits the inclusion of elevation, atmospheric turbidity, cloud amount and cloud type to provide an estimate of daily total solar radiation as a function of position across the strip.

Shade from a single tree crown

Not all agroforestry practices involve strips; some involve growing crops under more-or-less-isolated trees. In contrast to the sunfleck that courses over a shaded floor, the isolated tree casts a shadow that moves over a sunny ground. Halverson and Smith (1974) list a FORTRAN program that will calculate the length of the shadow cast by a tree on any slope and azimuth. Quesada, Somarriba and Vargas (this volume, Section 2) describe a program that will plot the distribution of shadows from a specified plot of trees.

Figure 11 (Grant 1985) illustrates the radiance distribution of a clear sky with the shadow of a spherical crown superimposed. With a clear sky, the maximum sky radiance is centered on the sun; the minimum at right angles to the sun. Thus a tree blocks the

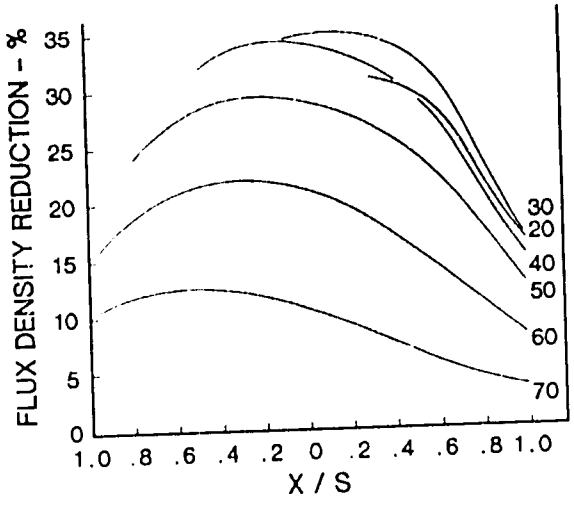
Figure 11 Simulated clear-sky radiance with superimposed shadow from an isolated spherical-crowned tree (Grant 1985).



brightest part of the sky. The percentage of blocked sky radiation (i.e., not including direct-beam radiation) is shown in Figure 12 for a range of zenith angles. Here, X/S is the relative distance from the center of the shadow to its edge. Although the overhead sun is not shown, it would be close to the top three curves. The percent reduction at the center of the shadow ranges from about ten percent for the shadow cast by a low sun, to about 35% for the sun near the zenith.

With a cloudy sky, the reductions are less than ten percent because of the nearly uniform radiance of the overcast sky.

Figure 12 Reduction of flux density in shadow of crown, for various solar zenith angles (z), as a function of the ratio of distance from center of shadow (X) to the half-width (S) of the shadow (Grant 1985).



Spectral quality of sunlight under partial shade

Shortwave radiation reaching the ground surface beneath a partial canopy consists of at least four components: direct beam radiation coming through gaps in the canopy; diffuse radiation from the reflection and transmission of the direct beam by leaves and other vegetation elements; sky radiation transmitted through canopy gaps; and radiation reflected off vegetation elements (Figure 13; Reifsnyder, Furnival and Horowitz 1971/72). In this scheme, multiple reflections between canopy and ground surface are ignored; for most canopies these components are small.

In addition to reducing the amount of energy received by a sunny spot, the canopy changes the spectral distribution in sunfleck and shade because of the unique spectral properties of vegetation. In full shade under a broadleaf canopy, light is enriched in the near infrared regions (because of the high reflectivity of leaves in this spectral region); and diminished in the blue and red regions, as compared with green wavelengths (Figure 14; Horowitz 1975). Light in sunflecks is enriched in the red, and reduced slightly in the blue region of the spectrum, relative to green wavelengths.

Figure 13 Model of penetration of solar radiation through a canopy. OPEN TOT is the total solar irradiance at top of canopy, consisting partly of direct beam radiation (OPEN D) and partly of diffuse radiation (OPEN I); CAN PD is the penetrating direct-beam component; CAN RD is the component reflected and transmitted by leaves; CAN PI is the diffuse radiation penetrating canopy gaps; and CAN RI is the diffuse radiation reflected and transmitted by leaves (Reifsnyder, Furnival and Horowitz 1971/72).

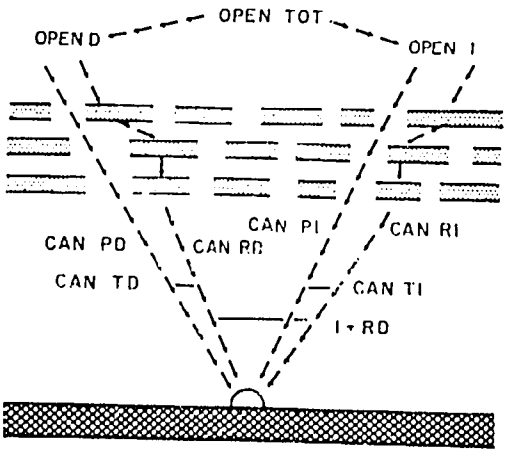
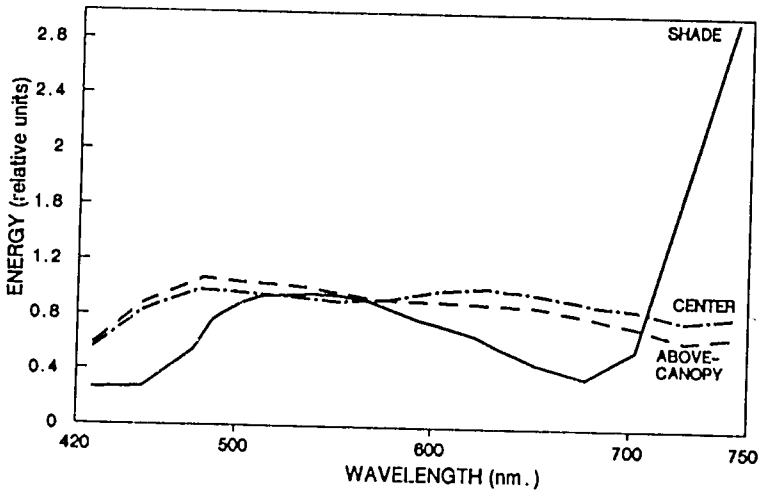
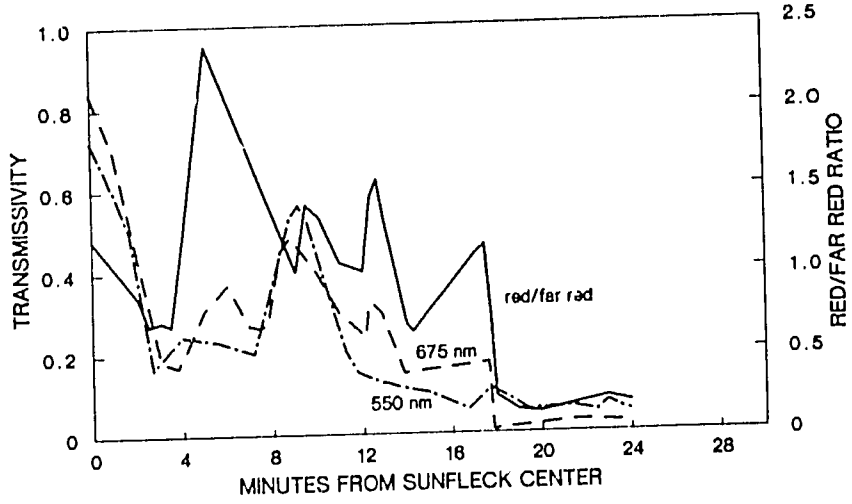


Figure 14 Spectral distribution of light above a temperate-zone broadleaf forest, in the center of a sunfleck, and in full shade beyond the edge of the sunfleck (Horowitz 1975). Canopy in full leaf, clear sky.



Of course, sunflecks do not have a hard edge, largely because the sun is not a point source of radiation. There is thus a penumbra effect which produces not only a gradual change in the energy from the center of the fleck to full shade; but also a change in the spectral distribution of that energy. Figure 15 (Horowitz 1975) shows the change in canopy transmissivity of green light (550 nm) and red light (675 nm) from the center of a large sunfleck to full shade (indicated by the time elapsed as the sunfleck coursed over the radiometer). Although the curves are not smooth because the canopy gap producing the sunfleck had various vegetation elements in it, the trend is clearly from a red-rich center to a green-rich shade. The red/far-red ratio beneath the canopy also changes from relatively high values in the sunfleck to low values in full shade.

Figure 15 Transmissivity (calculated as the ratio of light of indicated wavelength incident above stand to that at ground level, as function of distance from center of sunfleck; and the red/far-red ratio at ground level, also as function of distance from sun-fleck center (Horowitz 1975).



Implications for agroforestry

It must be admitted that there is very little 'hard' information on control of solar radiation in agroforestry practice. Most of the available information concerns the extensive field or extensive forest; edge and transition conditions have been little studied. Yet these transition zones are at the heart of much agroforestry practice, certainly in alley-cropping and similar methods.

Because of the geometric niceties of solar radiation, it is relatively easy (especially in these days of microcomputers) to estimate radiation conditions resulting from various cultural practices. Predicting the effects of such radiation control on microclimate and consequent crop (and tree) growth is nevertheless still problematic. The bottom line, of course, is how well do plants A and B grow under particular radiation regimes and the microclimate produced by the plant configuration. We might try to perform field

trials using all possible combinations, but such would soon become prohibitively expensive and difficult if not impossible to interpret.

An alternative might be to determine the radiation requirements of plants currently used in various agroforestry systems. Then with our knowledge of feasible radiation manipulation, we could plan field trials to test what seem to be the most likely combinations. Of course, radiation manipulation is only part of this: microclimate and soil moisture, as well as various cultural practices must be included in the experimental design.

It may also be necessary and appropriate to look at the problem in the reverse sense: given a radiation regime proscribed by solar geometry and certain cultural practices that may be difficult to modify drastically, what plant combinations are likely to succeed?

In both situations, the information most likely to be missing is that relating to specific radiation requirements of the plants. A first step might be to assemble, analyze and interpret known information on radiation requirements of plants currently used in agroforestry systems. This would point out the gaps in our knowledge and would form the basis for appropriate growth chamber and field experimentation.

In the meantime, agroforestry field experiments should certainly include careful consideration of the radiation climate – both by calculation and, where possible, by concomitant radiation measurements and visual observations.

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Simulation of tree shadows in agroforestry systems

F. Quesada, E. Somarriba, E. Vargas

CATIE
Av. 7, c.15 y 17, Casa 1561, San Jose, Costa Rica

Abstract

The understanding of how tree canopies intercept light is of prime interest for several disciplines. For instance, regeneration success of valuable tree species in a forest opening depends to a great extent on the illumination patterns at the forest floor. In agroforestry, it could help in the design of the planting arrays that most favourably influence the associated crop, and in the selection of appropriate experimental and sampling designs that take into account the fact that the associated crop is influenced by a neighbourhood of trees that may extend far beyond the nearest three or four neighbours.

Several attempts have been made to model light interception and shade projection by tree canopies. These studies have dealt with: 1) determining the ground area under shade in relation to stand density, and 2) the orientation and length of shadows cast by trees at different latitudes, days and hours, etc. These studies provide some insights into appropriate planting patterns of trees and associated crops; but to be useful in selecting appropriate experimental and sampling designs, they should accurately keep track of shade movement on a coordinate grid system conveniently placed on the study plot. The model herein presented tackles this problem.

We developed a model which allows the calculation of the number of hours of both absolute shade, and overlaps cast at each coordinate point in the study plot over a number of days specified by the user. The plot can be a horizontal or tilted plane with a maximum size of 1 ha, and located at any latitude. The plot can be a lattice with a minimum size of 0.5 X 0.5 m. Any number of trees can be 'planted' on this plot following any spatial arrangement, but crown shapes have to be one of the following types: spherical, hemispherical, ellipsoidal, hemi-ellipsoidal, and conical. Solar movement can be simulated at any daily and hourly interval depending on the accuracy needed and on computer time available. A computer programme was written in BASIC to be run in microcomputers with a minimum RAM memory configuration of 256 Kb. In this presentation an overview of model development is presented. Emphasis is placed on describing the geometric strategies adopt and in the presentation of the critical angles studied. An application of the model is presented.

Introduction

Tree shadows on an arbitrary plane are a function of tree parameters (tree height, tree coordinates, etc.), the position of the sun at any latitude and day of the year, and the orientation and slope of the plane. We describe an algorithm and computer programme that calculates the total hours of shadow in each small square of a plot over a given period of time which can be selected by the user. An optional subroutine provides the totals of shadow overlaps in each square over the period of time selected.

Shadow equations for a horizontal plane

We consider only trees with crowns of the following types: spherical, hemispherical, ellipsoidal, hemi-ellipsoidal and conical. The equations of the crown shadows are obtained with respect to a universal reference frame (an ordinary cartesian system of coordinates). The introduction of some intermediary cartesian systems is necessary before the equations are referred to the universal frame previously mentioned. These systems have their origins either at the center of the shadow (when the shadow is a symmetric figure and has a center) or at the base of the tree trunk.

The data that determine the tree shadow are: tree coordinates (with respect to the universal reference frame), trunk height (distance from the ground to the beginning of crown), crown height and crown diameter. Required positional data are latitude, day of the year and hour of the day. We assume that tree crowns are opaque; sun rays are parallel; that no corrections due to refraction of sun light in the atmosphere are necessary; and that there is no difuse radiation; that trunk width can be neglected so the only shadow that the tree produces is due to the crown.

Shadow equations for a tilted plane

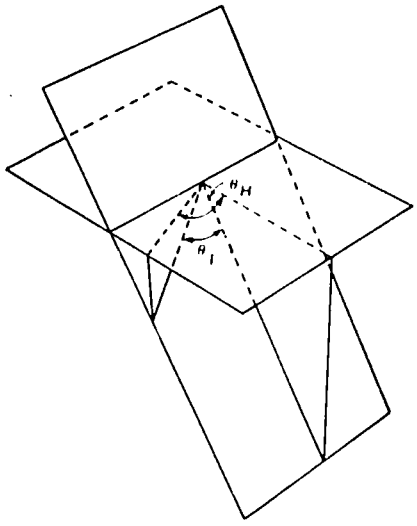
A general strategy for describing shadows on tilted planes has been developed, based on the concepts of a virtual shadow and a generalized change of coordinates. A virtual shadow is the one that the crown would project on any imaginary plane. When we deal with a tilted plane we can consider the virtual shadow over an imaginary horizontal plane. If this virtual shadow is thought of as a real opaque plane object capable of obstructing light rays, then it should also be capable of projecting a shadow coinciding with the real shadow of the crown.

If one considers now two reference frames, one in the real tilted plane and the other in the virtual horizontal plane, a generalized change of coordinates can be defined as a function which assigns to every point in the virtual plane its shadow in the tilted plane. This change of coordinates can be applied to the equations of shadows in the horizontal plane to render the corresponding equations in the tilted plane. One advantage of this method is that it is no longer necessary to compute the equations for the tilted plane case by case. One further advantage is that as soon as one has need for computing new equations for shadow types not included hitherto, it is sufficient to compute them for the horizontal case only.

The generalized coordinate transformation developed depends on the slope of the plot; and on its orientation with respect to north, defined as the angle between the north axis and the horizontal projection of the line of maximum slope in the plot. The generalized change of coordinates has been performed by means of simple trigonometric calculations. In order to make these calculations clear we have simultaneously considered four basic planes attached to each tree: the real tilted plane where the tree is located; a virtual horizontal plane which passes through the basis of the trunk; a vertical plane containing the trunk and which is parallel to the lines of maximum slope of the tilted plane (this plane is called 'gradient' plane); and finally a vertical plane which contains the trunk and which is parallel to the sun rays (referred to as 'solar' plane) (Figure 1).

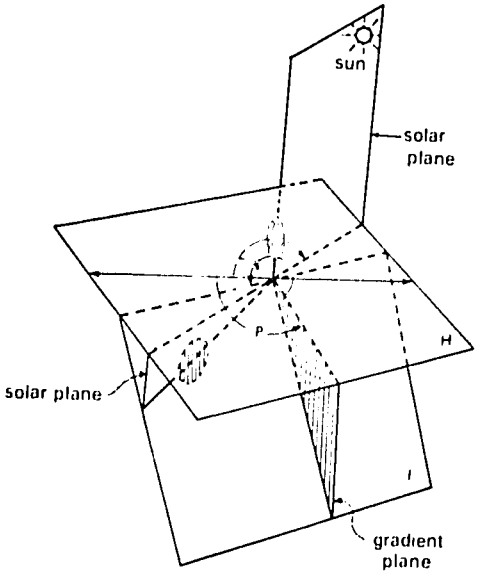
The transformation shows that when crowns are projected in a tilted plane they undergo an amplification-contraction effect as well as a 'twisting' effect: the line containing the shadow of the trunk is no longer a symmetry axis for the shadow (Figure 2). This 'twisting' effect is not equivalent to a rotation of the shadow. The general transformation is linear and so it can be expressed in matrix form.

Figure 1 Geometry of tree shadow on a tilted plane.



Details of the mathematical development are presented in Quesada, Somarriba and Vargas (1987).

Figure 2 Relationship between virtual shadow and the real shadow on a tilted plane.



Development of computer programme

We now describe a programme that can be run on a personal computer of about 256K RAM memory. A detailed discussion of the algorithm as well as a list of the programme is given in Quesada, Somarriba and Vargas (1987). The programme is written in Microsoft BASIC in module form and has a size of 34 kb.

Input data required by the programme are the geographical characteristics of the plot, the type of crowns and the tree distribution on the plot. Other input data are selected by the user and concern the degree of accuracy desired in the output. If the programme is operated in the interactive mode (an option for operating it in batch form is offered), then it asks the user for the latitude, maximum slope of terrain, orientation of slope with respect to north, and the time interval for which the position of the sun should be recalculated (a multiple of five minutes).

The size of the plot is now required, the present version of the program allows a square plot of at most 150 meters on a side. The size of the squares into which the plot is going to be subdivided (minimum of 0.5 m) is required.

The next data to be entered are the coordinates of each tree with the description of crown shape and size. Next, the user specifies the dates for the beginning and end of the period. Finally the user is asked if he wants to receive as output the amount of shadow overlap in each square of the plot.

The output contains the coordinates of the center of each of the squares of the plot; the total hours of shadow received by the corresponding square (in hours) during the period of simulation (e.g., 30 of March to 20 of November); and the total hours of shadow overlap during the simulation period.

A brief description of the algorithm

The plot is represented in the computer memory as a matrix. If shadow overlaps are required, an extra matrix of the same size is needed. The program proceeds 'tree by tree', instead of 'square by square'.

The programme considers sequentially the moments of time which conform the period of simulation. When moment 'm' is being scanned and tree number 'n' is being considered, the programme first locates the center of the crown shadow. The programme then enters a 'sweeping' subroutine which determines which of the neighbouring squares of the center are shaded at the scanned moment of time. At this point, analytic expressions for the shadow are required; the coordinates of the center of each square are tested against the set of inequalities which represent the shadow at this given moment. If shadow inequalities are not satisfied, the next square in the sweeping subroutine is considered. The shaded squares are then registered in the matrix, a 1 being added to those entries of the matrix which correspond to the shaded squares. When this process is finished for tree 'n', the program jumps to tree 'n + 1' and so on until it finishes with all trees in the plot. At this time, scanning of moment 'm + 1' starts and tree number 1 is the first to be considered.

The programme could also be used to have the exact position of shadows at any given time during the year. This could be achieved by entering the same date and hour for the beginning and end of the simulation period.

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Tree and crop selection and management to optimize overall system productivity, especially light utilization, in agroforestry

J.E. Jackson

Institute of Horticultural Research
East Malling, Maidstone, Kent ME19 6BJ, UK

Abstract

Optimizing management of agroforestry systems necessitates maximizing the efficiency of use of light resources. This involves recognition of the light requirements of the trees and crops involved and the factors influencing light interception by the trees and penetration to the ground crop.

There are four main types of crop light response:

A Yield is a linear function of light intensity. With ground cover crops of this type the amount of shade is important but the pattern of shade relatively unimportant.
B Yield increases linearly with light intensity up to a certain level and then plateaus. With such crops the distribution of light over the crop surface can have a big effect on average yield.
C Economic yield is only produced at high levels of irradiance and the crop or tree cannot effectively use low-intensity light.
D Exposure to high light levels is harmful and some degree of shade is needed.

Where shade is required (Type D) then sparsely foliated trees giving uniform shade over most of the ground may be needed and such a shading pattern may also be advantageous with Type B ground crops. In general, however, the most important requirement of the tree crop is that it maximizes the yield of economic product per unit of cast shade. Fruit trees tend to be of Type C and their density and volume of canopy can often be reduced with little or no loss of yield and, by so doing, let more light to the ground crop.

This can be achieved either genetically, in particular by selecting for columnar types, or by the pruning techniques used. Forest tree genotypes with a high ratio of timber production to total tree volume, hence cast shadow, are also available and would be particularly useful in agroforestry.

Where fuelwood or fodder trees are grown in agroforestry blocks under subsistence farming or smallholder circumstances a key objective must be to sustain production. Harvesting methods which have only a minimal effect on light interception are the key to this. Removing lower branches will have little adverse effect on subsequent light interception and canopy productivity. Reducing canopy dimensions, especially by harvesting outer rows, will have a much greater adverse effect on productivity per unit of fuel or fodder harvested. Removal of individual trees throughout the block will have effects part-way between those of branch removal and those of reducing the dimensions of the wooded area.

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Introduction

Agroforestry systems incorporating a range of tree and crop species offer much more scope for useful management of light interception and distribution than do monoculture forests and agricultural crops. The potential benefit as a result of combining field crops with trees is obvious from consideration of the waste of light resources experienced in orchards and tree-crop plantations.

Trees are commonly planted at spacings appropriate to their size at maturity. This inevitably leads to under-use of available light in the early years after planting. Even modern, productive apple orchards can intercept as little as 30% of the available light at five years of age (Jackson 1980). A coconut plantation that intercepted 90 percent of the available light at maturity intercepted 50% when three years old and 70% when five years old (Nelliat et al. 1974; reported by Nair 1983).

Even at maturity many tree crops transmit a high proportion of the available light because experience has shown that it is not beneficial to have the trees denser or more closely spaced. Apple orchards seldom intercept more than 70% of the available light, those which do so being too dense and shaded for profitable fruit production (Jackson 1980). Twenty-year-old tall coconut palms in the Russell Islands were found to transmit 40-70% of the available light, depending on planting density (Smith and Whiteman 1983) and a dense dwarf palm plantation transmitted 20%.

Okigbo and Greenland (1976) and Okigbo (1980) identified more efficient use of light resources by plants of different heights and canopy structures as one of the advantages to be gained by growing crops in mixed stands. The way in which this is achieved in one traditional agroforestry system, the village-forest-garden system of Indonesia, was described by Michon (1983). In these forest-gardens, the cultivated crop species, from small herbs to taller emergent trees, form a layered structure giving a gradient in light and humidity exploited by plants according to their ecological requirements.

It is reasonable to suppose that successful systems of tropical agroforestry evolved along the lines described by Bunting (1980) for tropical mixed cropping in general. As soon as a gap appears in the mixture the farmer, or his wife, puts something in it. A body of knowledge is thus built up as to the combinations of available plants which most nearly meet the farmer's requirements.

The effective application of the much more rapid and powerful modern scientific methods of improving agricultural productivity to these mixed crop systems depends on understanding the crop interactions, particularly in relation to use of light, water and nutrient resources and developing appropriate management strategies. This paper concentrates on light utilization in agroforestry systems and the ways in which this can be optimized.

The general theory of light penetration and shading in agroforestry systems

The characteristics feature of light interception and penetration in discontinuous canopies such as those in agroforestry is that it **cannot** be calculated as a simple function of vertically-summed leaf area index (L) and a light extinction coefficient (K) by the usual equation:

$$I / I_o = e^{-KL} \tag{1}$$

where I is light intensity beneath an LAI of L and I_o is light intensity above the canopy.

Instead the transmission through the (discontinuous) tree canopy must include a component representing light which misses the trees altogether by penetrating directly to the ground crop through gaps between the trees or rows of trees. If such transmission is designated T_f then the total light transmitted to the ground or field crop surface (T) expressed as a decimal fraction of light above the trees is as shown in Equation (2) (Jackson and Palmer 1979; Jackson 1983):

$$T = T_f + (1 - T_f)\, e^{-KL'} \tag{2}$$

In this equation T_f represents the fraction of the ground surface which would still receive light if the trees were 'solid' or non-transmitting to light and the second term represents light actually transmitted to the ground through the tree canopy with L' being $L / (1 - T_f)$.

The corresponding equation for fractional interception by the trees (F) is:

$$F = F_{max} - F_{max}\, e^{-KL'} \tag{3}$$

where F_{max} is the decimal fraction of the available light which would be intercepted if the trees were 'solid'.

From these equations it can be seen that:

1. The partitioning of light between the trees and the crop is a function of tree LAI and also of tree dimensions and arrangements which (together with latitude, time of day and time of year) determine the cast-shadow area for direct light (F_{max} for direct light) and the corresponding interception of diffused light.
2. Addition of a unit amount of tree leaf area will result in interception of more additional light if it is done in such a way as to reduce T_f by increasing F_{max} (e.g., by placing additional trees in gaps or increasing tree dimensions so as to increase the proportion of the ground which is shaded) than by increasing leaf area within the same canopy volume. In the extreme case, with widely scattered blocks of trees, doubling tree leaf area by placing extra trees in gaps could almost double light interception. Doubling the leaf area within the existing trees would increase light interception to a much smaller extent and hardly at all if L' in Equations (2) and (3) was already high. This conclusion, which is obvious, is borne out by the simulation studies of Rook et al. (1985).

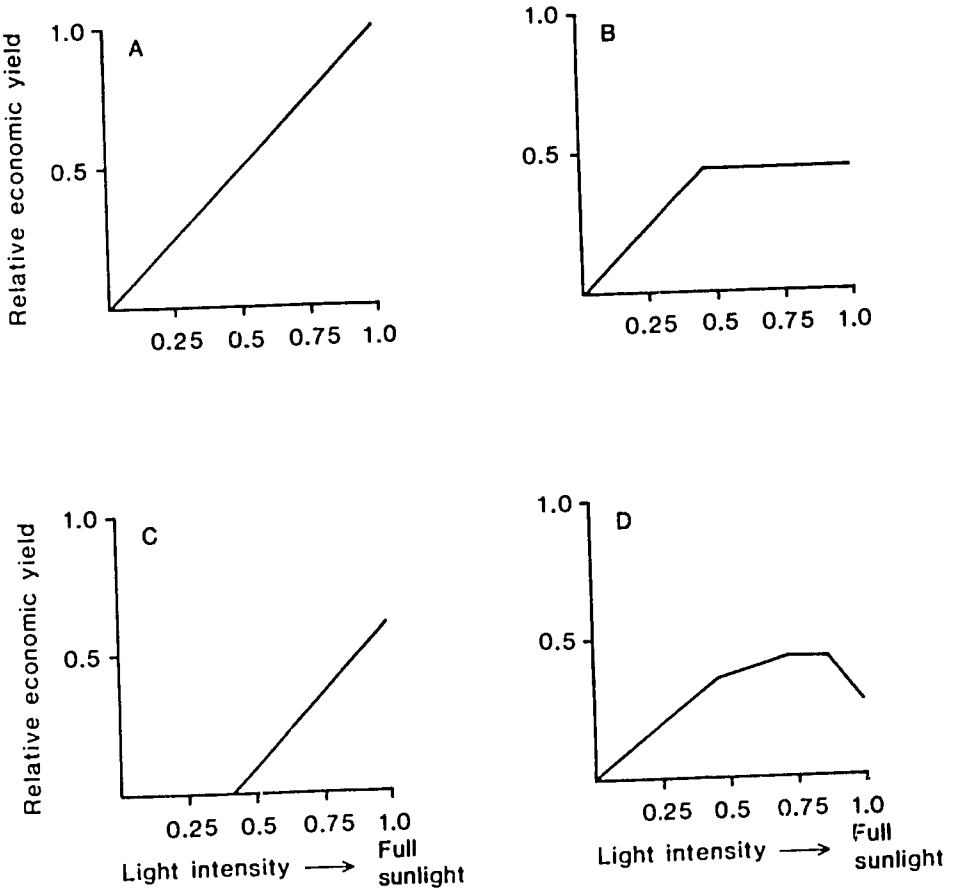
Using a modified Norman and Welles (1983) radiation interception model they calculated that under a particular set of conditions for Pinus radiata in New Zealand increasing the crown height to give a 77% increase in crown volume, with a correspondingly reduced foliage density, increased photosynthate production per tree and per unit ground area by 12%.

Light requirements and responses in agroforestry

The light requirements and responses of tree and crop plants can be categorized into four types as shown in Fig.1. In the first type (A) there is a linear relationship between intercepted light or light intensity with the regression line going through the origin.

There are many examples of dry matter production by crop plants being proportional to intercepted radiation, particularly early in the season (Biscoe and Gallagher 1977; Monteith 1977a). This does not necessarily imply a linear relationship between canopy productivity and light intensity because at least some of the variation in radiant energy interception in the data used was a consequence of variations in percentage effective ground cover (percentage of available light intercepted) rather than in light intensity. There is, however, also direct evidence that net canopy photosynthesis can be as linearly dependent on irradiance changes during a day (Biscoe and Gallagher 1977).

Figure 1 The relationship between economic yield and light intensity for four different plant types showing linear dependence (A), a degree of shade tolerance with low light saturation (B), shade intolerance (C) and shade requirement (D).



Observational studies have also shown an approximately linear relationship between the dry matter production of grass and weeds in coconut plots planted at different densities and the degree of shade. Smith and Whiteman (1983) found the mean above-ground dry matter yields of sown grasses and weeds under natural shade levels of 69, 54, 43 and 17% full sunlight (PAR) were 56, 49, 33 and 20% of those obtained from unshaded control sites.

Monteith (1972) cites crops such as maize, bulrush millet and tropical grasses in general as having this type of non-saturated light response. Subsequently Monteith (1977b) attributed this to C_4 plants in general.

The second characteristic type of crop x light relationship (B) is that in which crop canopies show light saturation at less than full sunlight intensity. In this case net photosynthesis or crop growth increases with light intensity up to a certain level and then stays at this plateau rate irrespective of further increases in irradiation (Biscoe and Gallagher 1977; Sale 1974). Mott and Popenoe (1977) show this response curve as typical of tropical legumes and Monteith (1972) shows a rather less flattened one for tropical species such as cassava and beans.

The third type of relationship (C) is one in which there is little or no economic yield at below a threshold level of light intensity although yield can be a linear function of light intensity above this point.

Cannell (1983) suggested that fruit and seed-yielding crops in general are intolerant of shade. It seems that the processes involved in flower and fruit bud formation, fruit set, fruit growth and the development of economically important visual attributes such as red skin pigmentation (anthocyanin formation) require levels of insolation much higher than those needed for vegetative growth. This was shown by within-canopy studies and artificial shading experiments on apple in which progressive increases in shade which had little effect on vegetative growth had dramatic effects on fruit yield and quality (Jackson and Palmer 1977a, 1977b; Jackson et al. 1977). From this and other work it was concluded that canopy zones receiving less than 50% of full daylight were effectively incapable of producing good quality apples and studies on peach planting systems suggest that fruit formation in this stone-fruit crop is at least as shade intolerant.

The final category (D) includes trees and crops which actually benefit from shading. Huxley (1967) showed by direct experimentation that Robusta and Arabica coffee seedlings increased in dry weight more rapidly when grown under 27, 38 or 54% full daylight than when grown in the open. This phenomenon appears widespread among tree seedlings. A rather more surprising result, in view of the generally adverse effects of shade on fruiting, was the increase in yield of top quality fruits of peppers in Israel which Rylski (1986) achieved by artificial shading. When imposed in summer, low levels of shade (12 and 26%) gave yield improvements of more than 62% over the unshaded controls while reducing light by 47% gave 30% more yield than control.

Management of agroforestry systems to maximize productivity through optimizing light utilization

Selection and management of 'high light requirement' fruit tree crops

There is ample evidence that seed and fruit producing trees are often of Type C as defined above. They cannot produce their crop in the more shaded parts of the trees and consequently there has been a pronounced move towards using very dwarfed trees giving shallow, well-illuminated cropping canopies in the commodities which have had

the greatest research input. The change in apple production has been particularly dramatic with large trees replaced by more productive shallow cropping canopies of little more than a metre in depth and with orchard LAIs of around 2 or less (Jackson 1980; Jackson and Middleton 1987) compared with old style large tree orchards with LAIs of 5 or more. The productivity gain in the sole crop orchard is a result of better illumination of the fruiting wood, easier and cheaper management as a result of the reduced tree size (Jackson 1985) and a lower respiratory load in relation to photosynthetic productivity. In the agroforestry situation there would be a tremendous additional advantage of eliminating the non-productive zones of fruit- and seed-producing trees in that this would enable light currently intercepted unprofitably by the lower and inner parts of such trees to be available for growing understorey crops.

The simplest approach to meeting the specific agroforestry objective is to produce vertical columnar trees capable of producing fruits all the way down to ground level and so contained in their lateral growth that they bear fruits right back to the tree trunk, i.e. there is no unproductive inner zone. Such trees would minimize F_{max} for any given level of fruit production, minimize light interception per unit of tree LAI, and maximize availability to the inter-crop at ground level. There are two ways of achieving such tree form, by selection and breeding; and by pruning.

Selection and breeding for columnar fruit tree form

Variation in branching habit and tree form is commonplace within both coniferous and deciduous tree species, arising by mutation, but it is only recently that this variation has been exploited in a systematic way other than for purely ornamental purposes. Two common mutant forms, those generally referred to as 'pendula' and 'columnaris' can have the narrow-crowned habit which minimizes their cast shadow areas. 'Spur-types' with the main branches clothed in fruiting spurs rather than long lateral branches are also commonly found, e.g., in apple and in peach, an outstanding example being Red Delicious apple of which spur-types predominate. Such trees are, by and large, of conventional form even though the ratio of fruit yield to tree cast shadow area is obviously greatly increased.

A much greater potential for radical change in tree form has come with the identification of the gene for compact, columnar, non- branching habit and its use in breeding programmes (Tobutt 1985). Trees of this type are essentially upright poles covered with fruiting spurs without any lateral vegetative branches. The first varieties from these programmes are just now becoming commercially available. A rather similar habit is available within *Prunus*, although so far only exploited in the ornamental cherry Amanagawa. There are also prospects of compact types of a number of other fruit species (Alston and Spiegel-Roy 1985).

Pruning to produce fruit trees with a maximum ratio of fruit yield to cast shadow

Depending on natural tree branching and fruiting patterns two methods suggest themselves. Where the fruit trees crop on young wood, e.g., one-, two- and three-year-old wood, they can be pruned to produce a vertical axis with cropping laterals which are removed by cutting back to the trunk as soon as they surpass the desired maximum age. This is the basis of the 'pillar' and the 'slender spindle bush' (Wertheim 1978) and also of the 'axe' which is being used for both apples and peaches in France (Lespinasse and Delort 1986).

The major weakness exhibited by 'pillar' systems in the United Kingdom and 'axe' systems in France is that, where the trees are planted relatively close together in hedgerows only a few metres apart and growth is vigorous, the lower parts of the trees become excessively shaded by the adjacent hedgerows, are unable to produce good quality fruits and may even fail to regenerate lateral branches after pruning back to the trunk. Control of the vigour of growth of the top of the trees by careful pruning is essential to prevent this happening if vigour is not naturally controlled by genotype (scion and rootstock) or soil. In the agroforestry situation this problem is much less likely to occur because the trees or hedgerows can be spaced so widely apart that even the lowest parts of the tree receive ample sunlight for production of good quality fruits and for branch regeneration.

Where the fruit trees crop best on older spurs then either:

1. A columnar tree shape around a 'centre-leader' vertical axis can be maintained by using the 'North Holland' type of pruning system with shortening back or removal of extension shoots in both summer and winter. In this approach the lateral branches are not allowed to extend more than about a metre from the trunk.
2. As an alternative, trees of a spreading-branched form can be spur pruned so that all the fruits are borne on spurs on main scaffold limbs with gaps between these limbs for light penetration. This is, however, a much more difficult tree form to manage than are the centre-leader, vertical axis forms described earlier.

Selection and management of other tree crops in agroforestry situations

Some forest trees as well as fruit trees are shade-intolerant (Perry 1985) and Assmann (1970) concluded that mixing shade-tolerant and shade-intolerant trees led to increased productivity compared with growing intolerants alone. For example, the yield of *Pinus sylvestris - Fagus sylvatica* mixtures was up to 24% greater than that of pure *P. sylvestris*. Shade-intolerant timber trees can be regarded as ideal partners for understorey crops in the same way as fruit trees and palms and the same design requirements are relevant.

Even when the trees are Type A in their light response it is clearly advantageous in an interspersed agroforestry situation for the timber trees to have a maximum ratio of economic yield (trunk) to tree volume and cast-shadow area (F_{max}). Essentially to achieve this we need trees with strong genetically determined apical dominance (or apical control). This tree type has been sought for very different reasons in the Finnish forest tree breeding programme. In this the ideotype for conifers has stems which are straight, have small taper, thin bark, good quality timber and rapid height and diameter growth, and branches which are slow growing, are consequently small in length and diameter and subtend angles at about 90 degrees with the stems (Karki and Tigerstedt 1985). Such trees could be very suitable for row and alley cropping (see below).

The Finnish selection and breeding programmes have produced narrow crowned trees with a high, and highly heritable, ratio of standing stemwood to total above-ground fresh weight. Among the species with narrow crown forms are *Picea abies, Pinus sylvestris* and *Betula pendula*. It is noteworthy that narrow-crowned clones occurred naturally as did the Wijcik mutant of McIntosh which is the source material for compact apple tree breeding. There seems every possibility that a systematic search for narrow-crowned or columnar types of relevant tree species for agroforestry would result in the rapid identification of suitable clones.

This argument is probably relevant in all agroforestry situations where timber is an important product. It is likely to be most difficult to put into effect where the ground

crops is of Type D with a specific shading requirement. In general it is much easier to ensure an even low level of irradiation in the understorey if the trees have high F_{max} and low leaf area per unit canopy volume, grown as flat-headed (umbrella-like) trees or as very tall thin hedgerows, than if they are dense and columnar with low F_{max} and high density of shading although this can be achieved in row and alley systems with appropriate dimensions and row orientations (Jackson and Palmer 1988). The ideal understorey crop or alley crop to combine with dense columnar spaced trees is one with an Type A light response so that it can make use both of very high irradiances in unshaded areas and low irradiances close to the trees.

Fuelwood and fodder trees in an agroforestry situation

It is assumed that these have a Type A light response, with some economic product, in the form of branches and leaves, being produced even in shaded situations and trunk thickening and upward growth being a function of total light interception. There is not likely to be any intrinsic advantage from growing such trees in close, intercropping association with crops. Indeed their yield of vegetative dry matter per unit ground area may well be higher if they are grown in solid blocks with a degree of 'density stress' (Cannell 1983). If the trees are grown in such blocks, or at least in multi-rows, their productivity will be influenced by the following:

1. The upper limit to potential yield will be determined by F_{max} and reduction in this will, other things being equal, be accompanied by loss of yield.
2. Increases in leaf area index of a closed canopy or of leaf area within a given tree volume will not necessarily lead to increases in net photosynthate production. Above a certain leaf area index, which varies with the light extinction coefficient, surplus production is reduced as respiratory losses more than counterbalance photosynthetic gains (Saeki 1960; Kira and Kumura 1983).
3. As a consequence of 1 and 2 reduction in the dimensions of a fuel or fodder tree block, especially reduction in the horizontal dimension of ground area covered, will reduce its productivity to a much greater extent than will removing branches from individual trees or removing individual trees from within the stand as long as these do not leave large gaps.

In general, the techniques of clear-felling of forest trees and even of coppicing are largely determined by the specification of the end product, e.g., in terms of sawnwood potential, pole characteristics, etc., and by the economics of harvesting on a large scale. In the small-scale agroforestry situation it may well be possible to treat fodder and fuelwood as regular crops from the trees while maintaining them as photosynthetically efficient canopies. In this context it is worth noting that fruit trees, once mature, are capable of putting 70% of their dry matter increment into harvested fruit each year (Jackson 1985) and data presented by Barlow and Smith (1971) shows up to 77.5% of the total annual increment going into harvested fruit and deciduous leaves with only 22.5% going into root and trunk and branch tissues. If such a ratio of consumable to structural product could be obtained in fodder trees by appropriate selection and management then sustained annual harvesting of only that production which is surplus to the trees' maintenance needs could well replace the longer term cycles of production (Cannell 1983) which are currently common.

Effect of the light requirements of the ground crop on system design and management

Although it is possible to think of available radiant energy being partitioned up between the tree crop and the ground crop the proportionate partitioning will only have a corresponding effect on ground crop yields if this crop is Type A in its light responses. In all other cases the pattern of shade distribution over the ground could be of critical importance.

Jackson and Palmer (this volume, Section 5) show that row and alley systems can result either in relatively uniform shade across the alley or in a combination of dense shade near the trees and little shade in the alley centre or adjacent to a south-facing row (if north of the equator). Moreover, the shade pattern can change with time of year. The uniformity of shade cast by scattered or evenly distributed trees will depend on the height of their foliage above the ground as well as on its LAI. Under these circumstances the efficiency with which a crop can utilize the light which is not intercepted by the trees will depend on the combination of crop requirements and light intensity pattern over space and over time.

In order to assess the magnitude of these effects it will be necessary to obtain data on shade responses under the appropriate environmental conditions. An indication of the likely crop-specificity can be obtained from the work of Willey and Holliday (1971a, 1971b). They showed the yield of barley to be reduced by shading during the ear development phase but not by shading during the subsequent grain-filling period; whereas the yield of wheat was reduced by shading at either of those times. Yoshida and Parao (1976), in experiments involving shading to 25, 50 and 75% of full daylight, found the vegetative growth of rice to be almost unaffected by shade but the reproduction and ripening phases to show a linear dependence of yield on light intensity. Where shade is of positive benefit, as in protecting peppers from sunscald, it is unlikely that a combination of exposure to full sunlight for part of the day coupled with deep shade for another part of the day – as is achieved with some row and alley systems – will be of equal value to an equivalent average reduction in light as a result of a virtually continuous sparse overhead canopy. A combination of shade trials and computer modelling of light interception and distribution could be very valuable as a supplement and a guide to direct experimentation to optimize agroforestry design and management and the selection of appropriate trees and crops.

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SECTION 3

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The continental oases of southern Tunisia and the agrometeorological network of Nefzaoua Project

P. Sarfatti and L. Ongaro

Istituto Agronomico per l'Oltremare
Ministero Affari Esteri
Via A. Cocchi 4, 50131 Firenze, Italy

Abstract

The Nefzaoua Region represents the final phase in the transition from the mediterranean climate to the warm desert climate. We examine the 'agrometeorological efficiency' of the traditional oasis system and illustrate certain trends in oasis management. Finally we describe the agrometeorological network of the Nefzaoua Project.

Introduction

The Nefzaoua Project managed by the Istituto Agronomico per l'Oltremare of Florence (IAO) and the Institut des Regions Arides of Medenine (IRA), is a cooperative project between Italy and Tunisia. Its aim is to combat desertification and to improve the traditional management of the oasis.

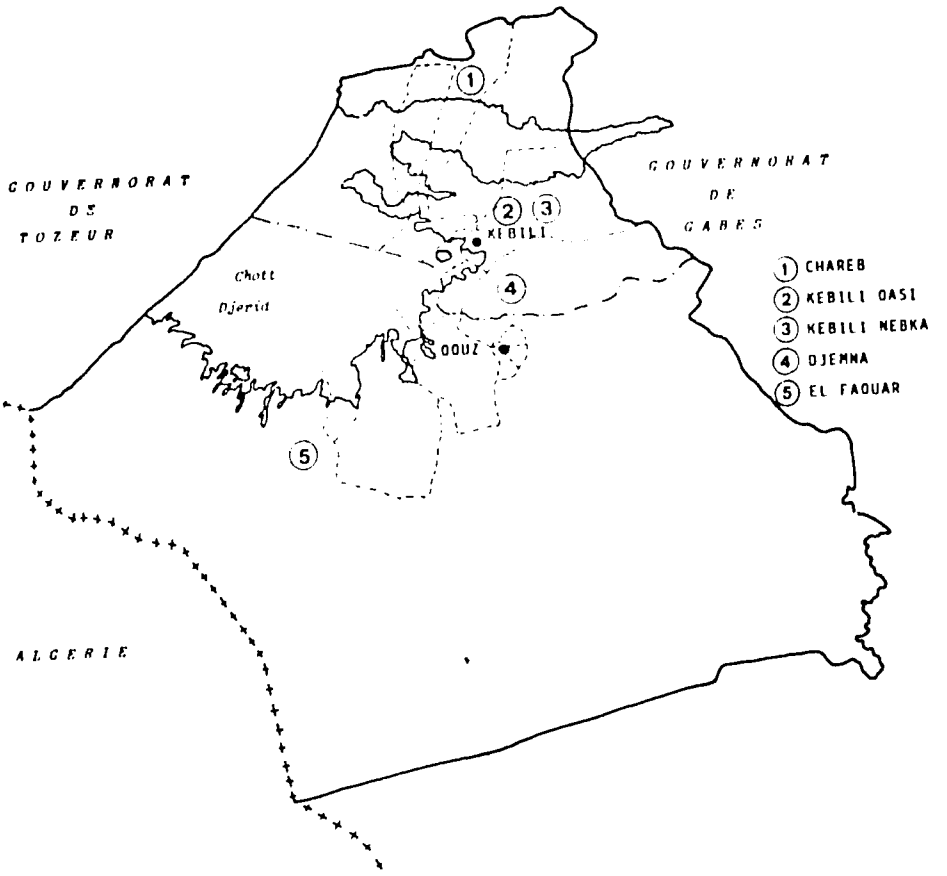
Though agroforestry has been developed in the humid tropics with completely different plants, nevertheless its principles and techniques might also help to deal with efficient use of light and water in complex multi-strata vegetation structures in arid climates, such as the continental oases of the Nefzaoua.

The region of Nefzaoua

The region of Nefzaoua in southern Tunisia lies to the south of the Chott El Fedjedj, and to the east of the Chott El Djerid, two vast salty depressions that range in elevation between +23 and -20 m asl. Eastwards are the Matmata mountains and southwards is the Sahara desert (Figure 1).

A recent survey of the geomorphology, soils and vegetation of the area has been conducted by the Istituto Agronomico per l'Oltremare (Ongaro 1986) and a land units map has been drawn. The region has a tropical arid climate (T_{ave} = 21 °C) with outbreaks of cold air from the Mediterranean sea; occasionally it is reached by the edges of the frontal depression systems crossing the upper latitudes. Throughout the entire zone the scanty and variable rainfall (90 mm per year) coincides with the period of lowest temperatures.

Figure 1 Agrometeorological network of Nefzaoua (1:1,500,000).



The Nefzaoua represents the final phase in the transition from the mediterranean climate to the warm desert climate dominated by tropical highs.

The oasis

Agriculture is practiced exclusively in the oasis; the surrounding steppes are grazed by camels, goats and sheep. Traditionally vegetation in the oasis is structured on three levels: 1st level, date palms; 2nd level, fruit trees (olives, figs, pomegranates, almonds and apricots); 3rd level, fodder plants (alfalfa and barley) and vegetables.

Fields are small and surrounded by hedges of palm leaves; the irrigation and drainage network is very close and plants are irrigated by submersion. The soils have a great percentage of sand and silt and, by consequence, have a very low cation exchange capacity. Therefore the manure used to maintain their fertility is a very important factor and also

contributes to increased soil available water capacity. Commonly the oasis is protected from the outside by one to three shelterbelts of non-living barriers.

The components of the whole system (vegetation structure, irrigation and drainage, hedges and shelterbelts, manure) contribute to create the 'oasis effect' leading to a reversal in the ratio between turbulent latent heat flux density and net all-wave radiation flux density (Flohn 1971; Oke 1978). The traditional management of the oasis has created a very complex system with the integration of agriculture and rangelands that cope quite well with the extreme environmental conditions.

The present situation

Recently a decline in the productivity of many oases has led to a change of the system. Certain trends can be discerned:

1) abolition of fruit trees and, in some cases, of fodder plants with the consequent loss of manure;
2) new irrigation methods using closed pipes instead of the traditional open air network; and
3) larger fields of date palms with decreased plant density.

All these management modifications affect many agrometeorological parameters inside the oasis (temperature, global and net radiation, wind speed, potential evapotranspiration, etc).

On the other hand desertification in the surrounding steppes has been accelerated by climatic factors as well as by overgrazing with the consequence of increased heat advection from the areas in which the oases are embedded. Thus the traditional agroecosystem is being replaced by a more 'simple' but probably more unstable one, the long term validity of which has yet to be shown.

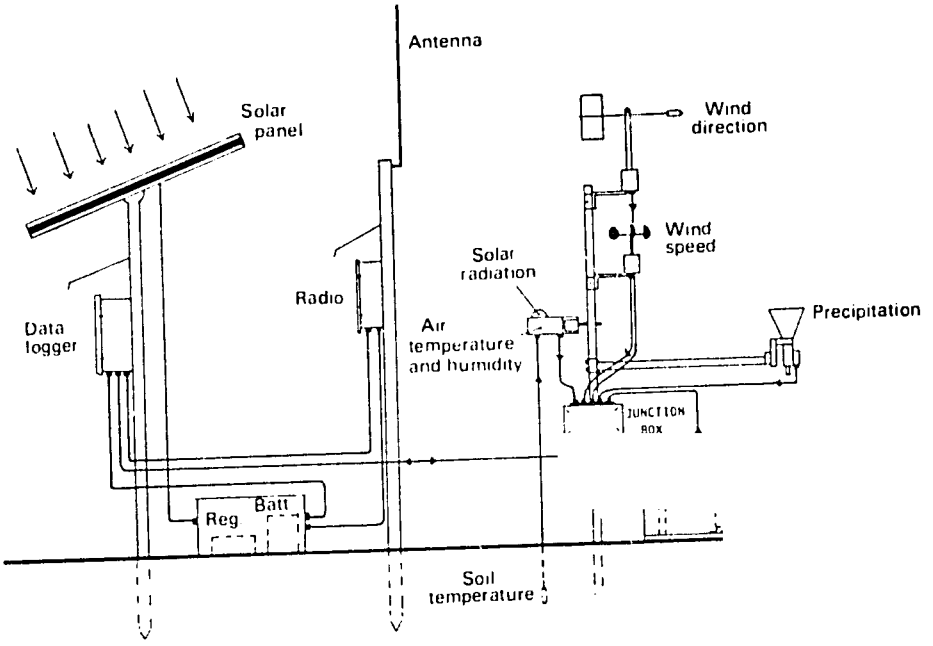
The agrometeorological network

To monitor the present situation and to assess the validity of possible new proposals, an agrometeorological network will be implemented during 1987, as a part of the Nefzaoua Project. The network will be composed of five peripheral stations and a central unit in Kebili for data processing and storage. The meteorological variables to be measured include: precipitation, air temperature and humidity, solar radiation, wind speed and direction, evaporation and soil temperature (Figure 2). Data will be sampled every two minutes, pre-processed and transmitted automatically by radio to a personal computer. Data will also be stored at the local stations on solid state memory modules with a thirty-day data capacity. Solid state modules will be interchangeable and connectable to the computer by an interface. All the peripheral components will have a working range from -50 °C to + 125 °C. The stations that don't 'see' Kebili will be connected by two radio repeaters.

The network has been designed to be reliable and user-friendly (Benincasa et al. 1984; Sarfatti 1986).

The network will also provide 'ground-truth' for a long-term remote-sensing experiment that will be conducted after 1988 by IAO .nd by the Italian National Research Council (CNR) to monitor desertification processes and oasis 'health' utilizing Landsat TM and TIROS AVHRR images.

Figure 2 Peripheral agrometeorological station (1:30).



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The need for meteorological information to plan agroforestry on steep slopes in Ethiopia

M. Negash

Land Use Planning Department, Ministry of Agriculture
P.O. Box 5580, Addis Ababa, Ethiopia

Abstract

Ethiopia is characterized by land features of mountains, hills, plateaus, valleys and gorges. In general, the land above 1500 m elevation is classified as highlands. The country covers 124 million hectares of land comprising 42 million people. Agriculture is the dominant sector of the economy. It contributes to 90% of the exports and an employment of more than 80% of the labour force.

On the other hand, 95% of the cultivated lands are situated in the highlands where 88% of the human population and two thirds of the livestock are found. The highlands are rugged and steep. As a result of their steepness, overgrazing, overcultivation and wanton deforestation, the highlands suffer from environmental degradation.

The traditional climatic zones prevailing in the country are:

- *Kolla (arid & semi-arid)*
- *Woina Dega (semi-humid)*
- *Dega (cool and humid)*
- *Wurch (cold and moist)*

In these zones, 12 major land use and cover types were identified from satellite imagery interpretation and limited field checks.

The cropland occupies 14.8%; grazing and browsing land 51%; forests 3.6%; and currently unutilizable land 18.7%; of the country.

In the history of Ethiopian agricultural land use, agroforestry is closely related to intercropping of perennial and annual crops. It is widely practiced in the south, southwestern and eastern parts of the country. Agroforestry has also recently been recognized as impoerant soil and moisture conservation.

At present, the productivity of the highlands is declining below the food requirements of the people and the livestock. The reasons are severe soil erosion and decline in the fertility of the soils resulting from poor land management practices.

In order to reverse the situation, scientifically designed and planned agroforestry farming systems are urgently needed on steep slopes. The systems should itegrate resource - conservation - based production of crops, livestock, woods and conservation of nature. However, these require basic information on climate, soils and slope classes. In Ethiopia, 6 rainfall pattern regions, 10 thermal zones, 15 length-of-growing periods, 18 major soil types, 380 land systems and 5 slope classes were identified at exploratory levels of studies.

Introduction

Ethiopia is situated between 3° and 18° north latitude and 48° east longitude (i.e., in East Africa). It is mainly characterized by land features of mountains, hills, plateaux, valleys and gorges. In general, the land above 1500 m asl is considered rugged highlands. The country has a total land area of about 124 million hectares and comprises 42 million people (FAO 1986a).

Agriculture is the dominant sector of the economy. It contributes to 90% of the exports and an employment of 88% of the labour force. The farm families organized into peasant association are about seven million and the annual population growth is about 2.9% according to the 1984 national census. Ninety-five per cent of the cultivated lands are in the highlands. They contain 88% of the country's human population, two-thirds of its livestock and over 90% of its economic activity. However, the highlands suffer from environmental degradation as a result of overgrazing, overcultivation, excessive deforestation, and slashing-and-burning of the natural vegetation cover. The destruction of forests according to recent estimates is 200,000 ha per year which is over the potential capability of the existing 3.6% forest land. The sensitive arid and semi-arid vegetation of the lowlands is badly threatened by overgrazing. The present estimate of the annual country-wide soil loss rate is 2 billion cubic meters. The highlands are seriously threatened by sheet, rill and gully erosion. Sheet and rill erosion attack mainly cultivated lands and grazing lands. For these reasons, the fertility and productivity of the highlands is declining rapidly.

The traditional agroclimatic zones and slope classes

The four traditional agroclimatic zones of Ethiopia are distinguished by the linked factors of altitude, annual rainfall and temperature (Table 1).

Table 1 Traditional agroclimatic zones.

Agroclimatic zone	Climate	Altitude m asl	Average annual rainfall, mm	Area km^2
Kolla	arid & semi-arid	< 1500	< 800	702,755
Woina-Dega	semi-humid	1500 < 2400	800 < 1200	398,811
Dega	cool & humid	2400 < 3200	1200 < 220 0	127,954
Wurch	cold and moist	≥ 3200	≥ 2200	14,280

However, rainfall is related to geographical position as well as altitude. At a given altitude, a site in Tigre or Eritrea, or in the south-eastern region towards the frontiers of Somalia or Kenya, is likely to receive less than a site in Shewa, Keffa, Elubabor or Wellega.

In order to understand in detail the agroclimatic conditions of the country, the four agroclimatic zones are sub-divided into 11 sub- agroclimatic zones based upon the distributions of the average annual total of rainfall (Table 2).

Table 2 Sub-division of agroclimatic zones.

Agroclimatic sub-zones	Climate	Altitude m asl	Annual rainfall mm
Bercha	arid	<500	<200
Dry Kolla	semi-arid	500-1500	200< 800
Moist Kolla	warm-semi-humid	500-1500	800-1400
Dry Woina Dega	semi-humid	1500-2400	<900
Moist Woina Dega	semi-humid	1500-2400	900-1400
Wet Woina Dega	humid	1500-2400	>1400
Moist Dega	cool & humid	2400-3200	900-1400
Wet Dega	cool & wet	2400-3200	>1400
Moist Wurch	cold & humid	3200-3700	900-1400
Wet Wurch	cold & wet	3200-3700	>1400
High Wurch	extreme cold & wet	>3700	>1400

The five slope classes distinguished in Ethiopia are: 0-10%, 11- 25%, 26-35%, 36-50% and more than 50%. Slope class 0-10% occupies mainly the lowlands below 1500 m elevation (about 703,000 km^2) and the flat highland plateau and valley bottoms. The other classes are found mainly in the highlands. Slopes greater than 50% occupy a large area compared to the other classes.

Present land use and cover types

Land use refers to the uses to which the land resources are put by man to derive the maximum benefits in order to satisfy his social and human needs. These are food, clothing, shelter, firewood and other materials such as wood for furniture (FAO 1986b). Land use involves the physical interaction between the resources and the powers of man and animal required to produce the necessary commodities. However, land cover types reflect only the natural and physical features of the resources from which man can benefit. These resources are vegetation, soils, water, cultivated land areas, salt flats and the rocks. Vegetation by itself comprises forests, woods, bushes, shrubs and grass at various levels of cover density.

In Ethiopia, a land-use/land-cover study was carried out by interpretation of Landsat imagery (1972-1979) and limited field checks (FAO 1984a). The study distinguished 12 major land cover types:

1. Urban and built-up land
2. Cultivated land
3. Afro-Alpine and sub-Afro-Alpine vegetation
4. Forest land
5. Woodland

6. Riparian woodland or bushland
7. Bushland
8. Shrubland
9. Grassland
10. Wetland
11. Bare land
12. Water bodies

The 12 major cover types were further subdivided into two to five sub-units. A further classification was made, based on main land use and main crops. Finally, the distribution of land under the major kinds of land uses were summarized as shown in Table 3.

Table 3 Classification based on land use and main crops.

Use	Area (ha)	Percent
Crop land	16,413,140	13.1
Annual crops	2,074,050	1.7
Perennial crops	63,725,700	51.0
Grazing and browsing land		
Forest, woodland, bush and shrub	4,473,520	3.6
Forest	10,135,470	8.1
Other	4,719,740	3.8
Currently unproductive land	23,292,380	18.7
Currently unutilizable land	124,834,000	100.0
Total		

The history of agroforestry in Ethiopia

In the history of Ethiopian agriculture, intercropping is a common practice especially in the south, south-western and eastern parts of the highlands. At present, it is remarkably considered as an old agroforestry practice in the perennial crop growing areas. Among the perennial crops, coffee, ensete and chat (*Chata edulis*) could be mentioned as common examples.

The history of the traditional agroforestry farming systems in Ethiopia goes back to the beginning of coffee production in the country. In general, coffee grows wild as well as cultivated in the south and south-western highlands. However, it is cultivated in pure stands in the eastern and central highlands. Wild coffee grows naturally as bushy strata under tall forest trees, while cultivated coffee is common to homesteads under the shade of irregularly scattered trees. The common shade tree genera are *Albizia, Acacia* and *Corida*. All of these have flat and wide umbrella-shaped canopies. However, the canopies allow an optimum amount of light rays to penetrate and reach the coffee bushes.

On the other hand, since the shade trees and the coffee bushes are scattered, there is enough space to plant other crops in between. Farmers in the south till the coffee fields in the rainy season with hoes and intercrop them either with cereals such as maize

and sorghum; pulses; or root crops such as taro, potatoes and cassava. Some farmers intercrop coffee with perennial crops such as ensete, lemons, oranges, limes and hops. In some other perennial crop areas, where coffee is not commonly grown, ensete and cabbage are grown in the shade of scattered trees. And in the central Ethiopian highlands, acacia trees are scattered in the cereal and pulse fields. Chat bushes in the eastern (Hararghe) and central highlands are intercropped with cabbages, sweet potatoes, shallot or onions during the growing season.

As a result, farmers derive multiple uses from their intercropping. They produce coffee, beans, seeds, vegetables, loppable browse for their cattle and firewood from the branches of the trees. Therefore the system does not very much affect or change the natural ecological balance of these areas, because the canopies of the trees and the branches of the bushy perennial crops intercept the erosive heavy rain drops. On the other hand, the root systems allow free infiltration of water by retarding surface run-off and bind the soil *in situ*. Added to that, litter from leaves and bark add organic matter, increases fertility of the soil and improve its structure and its workability.

These ecological interactions not only conserve the soil but keep the moisture and nutrient balance of the soil intact to make it reliable for crop production. Today, farmers need to produce enough for themselves and if possible a surplus to insure food and export securities for their nations. This should also be done without causing serious and irreversible damage to the resources.

In Ethiopia, cultivable land is scarce and vulnerable to degradation. Therefore, an understanding of the traditional agroforestry farming system invites us to think more scientifically about its advantages and to design scientifically-tested systems to protect our environment. This requires identification of the quality and distribution of various environments, the crops to be grown, their optimum environmental requirements, and the trees and shrubs to be integrated within the system.

It also involves the selection and breeding techniques of high yielding plant and/or crop species, proper management and conservation techniques and designs. However, identification of techniques should rely upon research findings and recommendations in order to arrive at conservation-based multiple productivity of the resources.

The need for agroforestry planning in Ethiopia

For many centuries subsistence mixed agriculture has been practiced, mainly in the highlands of Ethiopia. It integrates both livestock- rearing and the production of rainfed cereals, pulses, perennial crops, fibre crops and oil crops. Oxen and man were and still are the main sources of farm power. Cows are reared to produce oxen and some milk products. Goats and sheep are kept mainly for meat and as a source of cash in the peasant economy. Horses fulfil the need for transportation of humans and goods. However, for many centuries, land has been ploughed and grazed without thinking of soil and water conservation measures. As a result of human and livestock pressure on the land, cultivated and grazing lands are expanding at the expense of the natural vegetation. Therefore, erosion in the highlands is aggravated as a result of misuse of land and wanton destruction of the natural vegetation. Drought is a common and recurrent phenomenon, especially in the north and north-eastern parts of the country.

The environment of the Ethiopian highland is fragile because of its rugged and steep terrains. It requires wise and scientific uses for its sustained productivity. For instance, if one compares the north with the south and south-western regions of the highlands, the latter are better protected than the former because of considerable cover by vegetation and old practices of agroforestry-oriented farming. In the south and south-western

regions, perennial crops (e.g., ensete and coffee) and their associated tree canopies intercept the rainfall thereby protecting the soil from its erosive power. On the other hand, soils in the northern, north-eastern and central highlands are heavily washed and the environment is degraded. Crop failures and significant yield decreases are common phenomena in these areas. The causes are serious droughts and bareness of the ground. Therefore, people and livestock are suffering from shortages of food and feed in those areas.

In order to reverse the degradation of the environment and halt the ongoing soil loss, scientifically-based agroforestry systems planning is badly needed on the steep highlands of Ethiopia. In such a system, the major concern of planning should be efficient soil- and water-conservation practices and sustained production of cereals, pulses, oil crops, fruit, fodder (browse and herbs), firewood and wood products.

Availability and quality of climatic data

In Ethiopia there are more than 506 climatic stations. All operate under the authorization of the National Meteorological Service Agency (NMSA), which is responsible for the collection, analysis and distribution of the climatic data.

Of these, 213 record precipitation; 192 stations record precipitation and temperature; 52 stations precipitation, temperature and relative humidity; four stations precipitation, temperature, relative humidity and solar radiation; 18 stations precipitation, temperature relative humidity, solar radiation, and sunshine duration; 27 stations precipitation, temperature, relative humidity, solar radiation, sunshine duration and windspeed. Many of the stations have records of more than 5 years. However, only a few stations, such as Gore and Addis Ababa, have records of more than 35 years.

The shortcomings of the climatic data in Ethiopia are the short periods of observations; the poor quality of the data due to inconsistency of records; and the relatively few stations that make comprehensive agroclimatic measurements.

Rainfall patterns and distribution

The Land Use Planning and Regulatory Department (LUPRD) of the Ministry of Agriculture studied the climatic patterns of Ethiopia sources (FAO 1984b). Six major rainfall pattern regions were distinguished.

Rainfall pattern region 'A' encompases the north-eastern and south-western parts of the country. The region receives rain in summer (i.e., in June, July, August and September). In the highland areas, precipitation exceeds one-half potential evapotranspiration (PET) at the beginning and end of the rainy season; and full PET in the middle of the rainy period. However, in the lowlands of north-eastern areas the rainfall exceeds $^1/_2$ PET only in July and August and is always below full PET. Therefore, the lowland areas suffer from shortage and insufficiency of rains.

Region 'B' encompasses the southern and south-western parts of the country. The region receives tremendous amounts of precipitation from March to early December in highland areas; and from mid-April to November in the lowland humid savanna areas. Precipitation always exceeds full PET for most of the rainy season. The region is characterized by rains occurring from spring to autumn and is ecologically stable with vigorous vegetation growth and cultivated perennial crops such as coffee, ensete and rootcrops.

Region 'C' receives rain in spring, summer and autumn. The region covers the eastern and south-eastern plateaux and escarpments. The rainfall occurs from February to November in highland areas and from March to November in the low-lying areas. In most of the regions, precipitation during the rainy season is more than $^1/_2$ PET.

Except for some low-lying areas, the region does not suffer from an insufficiency of moisture for the growth of natural vegetation.

Region 'D' covers the north-eastern Red Sea coastal areas. It enjoys rains throughout the year. However, summer rain is small compared with the other three seasons. In most of the areas, precipitation is below $^1/_2$ PET. Therefore, growth of natural vegetation is highly affected by the short and zero length of the growing period. Therefore, the region is considered not climatically suitable for cultivation of crops and livestock rearing.

Region 'E' covers the whole of the Ethiopian rift valley and the eastern, central and south-eastern highlands. It receives rains from March to the beginning of October i.e. small rains in spring and big rains in summer merging together. However, there prevails a very short dry spell in May which has little effect on crops and the growth of natural vegetation. In most of the highland areas precipitation is higher than potential evapotranspiration. But in the lowlands, like in 'Dire Dawa', precipitation is always between half and full PET.

Region 'F' covers the southern and south-eastern frontiers with Kenya and Somalia. It has a bi-modal rainfall distribution, with spring rainfall considerably greater than the autumn rainfall. The significant rainy months are April to the end of May and from September to November. The rains bordering region 'C' of this zone are more reliable than rains in the south-west and south-east. In the highland areas near region 'C', precipitation is less than $^1/_2$ PET. In the region no major rain-fed crops are grown and the natural vegetation is dominated by thorny low shrubs.

Thermal zones

In Ethiopia, average temperature decreases about 0.6 °C for every 100 m increase in elevation. In this regard, the temperature gradient determines the distribution of annual and perennial crops, livestock and the natural vegetation in general. The LUPRD (FAO 1984b) distinguished 10 thermal zones based upon mean temperature during the growing periods (Table 4).

Table 4 Thermal zones.

Thermal Zone	Mean temperature during growing period, C
1	> 27.5
2	> 25.0 ≤ 27.5
3	> 22.5 ≤ 25.0
4	> 20.0 ≤ 22.5
5	> 17.5 ≤ 20.0
6	> 15.0 ≤ 17.5
7	> 12.5 ≤ 15.0
8	> 10.0 ≤ 12.5
9	> 7.5 ≤ 10.0
10	≤ 7.5

Source: FAO 1984b

The zones help determine the types of crops, trees, shrubs and herbs to be found and grown, produced and reserved in a certain locality.

Length of growing periods

Length of growing period is determined by the interrelated analysis of precipitation, soil moisture holding capacity, potential evapotranspiration and frost period. The growing period is considered to begin when precipitation exceeds $^1/_2$ PET and end when precipitation falls below $^1/_2$ PET.

Length-of-growing period 0 to 90 days occurs in the north- eastern, eastern south-eastern and southern lowlands. There the natural vegetation is very scanty and consists primarily of thorny- bush acacias. The highlands and the north-western, western, and south-western lowlands are characterized by growing periods longer than 90 days.

Other land resource information essential for agroforestry planning

Mapped information on the physical environment (at scale of 1:1,000:000) is available from LUPRD. Since soils are the vital medium for plants growth, their nature, and characteristics should be known to help in planning, decision making and implementation.

In Ethiopia 18 dominant soil types, 380 landscape units and 120 soil management units have been identified and characterized. This information enables planners and decision makers to identify the relevant types of agroforestry based developments to be undertaken in the areas where they should be necessary.

Conclusions

Agroforestry planning requires scientific decisions on an integration of resource-conservation-based multiple use systems. Multiple use can be interpreted as integration of pulses, cereals, fruits and firewood production; or integration of wood and fodder production; or integration of fruits, recreation and nature conservation. However, choices of species and varieties should rely upon the available natural resource information.

On the other hand, plan implementation requires data on human and livestock population and the feeding and cultural conditions of the society for whom the effort is sought. Implementation in turn requires continuous monitoring of the benefits and changes in resources and ecosystem characteristics.

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Mulching as traditionally applied by small scale coffee growers in Tanzania

C.G.B. Tibanyenda

Directorate of Meteoorology
P.O. Box 3056, Dar es Salaam, Tanzania

Abstract

Microclimate management of coffee farming by small holders using organic mulching is dealt with. A review of the commonly used mulch – dried grass and sometimes banana leaves, applied to each or alternate inter-row is made. The marked effect on the climate of the soil enables the farmers to practice intercropping with suitable annual crops during the first few years of the coffee plants, and increased coffee yields thereafter. The gains accrued are mainly due to improved soil and water conservation, and addition of organic matter and nutrients. Both the effects and gains are treated qualitatively due to limited availability of figures.

Introduction

The application of mulch in coffee plots by small holders may date back to the time when coffee was first introduced in East Africa by missionaries from Reunion island between 1883 and 1896 (Acland 1973). At the time, the advantages of mulching as we know them today were unknown except probably that of weed control (or suppression). The mulch, most commonly used was, and still is, cut wild grass or sorghum trash. Some few small holders however do produce napier grass for this purpose. In this respect, we shall define mulch as covering of the soil surface with cut grass or crop residue.

The use of mulch in coffee farms has been on the increase over the years especially during the first few years after planting. The enthusiasm however has slackened at times during low coffee prices such as the world economic depression of the late 1920's and early 1930's and also the inter-world-war years. Through experience, farmers know the direct relatinship between mulching and better yields, although they might not be fully aware of all the beneficial effects that lead to this relationship.

Materials and their method of application by most farmers in Tanzania will be dealt with briefly in this presentation.

Mulching materials

Mulches are generally divided into two categories, organic and inorganic (Davies 1975). Organic mulches include cut grass (wild or grown), straw, non-synthetic cloth, creeping crops, weed and crop residues. Inorganic mulches though not used by farmers in coffee crops are: ash, water, minerals (sand and stones) and synthetic materials such as opaque or transparent plastics (Stigter 1982).

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The most common organic mulches used in coffee plots by farmers are cut grass, sorghum and maize trash. Wild grass is conveniently available for use in areas where there is less demand for land. It is cut at the end of the rains, baled and transported to the farms. A limited number of farmers use sown grass such as napier grass. It has a higher bulk than any other grass: up to 173 tons per hectare of green matter from two cuts per year (Acland 1971). Banana leaves, which are within easy reach when banana trees are interplanted with coffee for shade, are also used. Although it lasts longer than a year, this mulch is generally insufficient by itself.

In areas where maize and sorghum are grown for food, their trash is properly utilized for a mulch. They decompose very quickly but are only readily available at the end of the farming season. Other materials are also used if available, but they are in insufficient quantities to be of noticeable value.

Methods of application

The method of application is dependent on the planting pattern, which is usually by rows but is also influenced by the availability of land for other crops. If the same plot is intended for interplanting with other crops such as maize or beans, mulch is applied to the rows leaving the space between the rows for the annual crops. This practice of intercropping is normally carried out during the first few years of the coffee plants, and is stopped after the first coffee harvest when mulch is applied to the whole field except near the stems to enable easy harvesting.

Mulch is also applied to interrows. This is normally the case in areas where there is high infestation of weeds. Intercropping with annual crops then is generally not practiced but interplanting with banana trees is carried out by some farmers. Others apply mulch to alternate tree rows or alternate interrows. With this practice, intercropping with annual crops is easily carried out, although it would seem that such farmers are faced with non-availability of sufficient materials in the first place. With mulch applied to the whole surface, normally no other farming activity except field works is carried out on the farm. The practice of applying mulch to the whole surface can also be observed in areas where the cultivated land is situated on a sloping terrain, in which case mulching is mainly applied to arrest soil erosion.

Time of application

For a traditional farmer, mulching materials are readily available at the end of the rainy season (wild or grown grass) and after harvesting of the annual crops for trash or crop residue. Unless advised otherwise, the practice is to apply mulch at the end of the rains. This practice is beneficial in areas with heavy rains, e.g., the slopes of Mt. Kilimanjaro where amounts greater than 800 mm usually fall in April and May, and mulch only makes the soil too wet if applied before the rains. Where the rainfall is rather low, mulch gives higher yields if it is applied before the rains start (Acland 1971), this encourages maximum water infiltration.

Planting of coffee is normally done at the beginning of the main rains. To prevent soil erosion, mulch is sometimes applied only around the stem of the young coffee plant.

Effects of mulching

Soil moisture

Mulching enhances soil moisture status through improved infiltration and reduction in evaporation, the former being more beneficial than the latter according to Webster and Wilson (1971). It is therefore desirable to apply mulch at the beginning of a rainy season in order to aid infiltration, rather than at the end of the rains when it can only reduce the rate of drying out during the following dry season. Pereira and Jones (1954) showed this to be true on coffee in Kenya (Table 1). In fact, mulching alternate rows before the rains gave better yields than mulching all rows after the rains.

Table 1 Yields of clean coffee (after Pereira and Jones 1954;)

Year	Total Rainfall (mm)	No Mulch (kg/ha)	Mulched all rows before rains (kg/ha)	Mulched alternate rows before rains (kg/ha)	Mulched all rows after rains (kg/ha)
1950	610	94	188	133	88
1951	1372	841	1492	1307	1213

Soil temperature

Mulched soil has lower average temperatures and a restricted diurnal temperature range. This effect is of minor importance under tree crops with heavy shade, but even under cocoa Smith (1954) found that mulching reduced average soil temperature slightly and the diurnal range considerably. The lowering of soil temperature reduces losses due to evapotranspiration.

Erosion and soil characteristics

Mulches protect the soil from wind and hail; and prevent breakdown of soil structure by the impact of rainfall, thus decreasing soil erosion and run-off. They also increase earthworm and termite activity which provides many channels for the percolation of water. Through increased infiltration, leaching is promoted thereby reducing soil salinity in the top layers of the soil in saline areas. Decomposition of mulch organic matter thus improves the soil structure.

Weed control

One of the main beneficial effects of mulching is weed control or suppression. It is particularly important in areas with poor rains, as weeds compete with coffee plants for water and nutrients.

Growth and yields

The outcome of the aforementioned effects of mulching together with a few minor ones, combine to give higher yields of the coffee crop. Pereira (1954) quotes field trials in Kenya with large yield increases when an organic mulch was applied before the rains,

while Robinson (1964), found that a single annual application of trash mulch to coffee at 18 kg per tree significantly increased yield. High yields are not only realized in coffee but also the annuals (maize and beans) intercropped with it. Better yields of the annual crops, especially beans of the determinate-landraces variety, are realized from nearly-decomposed mulch applied to the surface before it is renewed.

The downward growth of tap roots and the development of the root system as a whole for coffee is increased by mulching (Bull 1963).

Limitations

If the mulching material is to be obtained from grown grass, then land is required for this purpose. This might prove difficult and expensive in areas with high demand for land. Also a lot of labour is involved in cutting and carrying the material from outside the plantation. To a smallholder, it might not be worth the trouble unless the crop sells at a relatively high price especially if the mulch decomposes rapidly.

Concluding remarks

In the tropics, the usual limiting factor for plant growth is moisture. The traditional farmer depends entirely on rainfall as a source of moisture in all agricultural activities. One can say crudely that the more the rainfall the better the yields. However, from time to time, particularly in the recent past, frequent droughts of varying degrees have been experienced in the tropics. This has made it absolutely necessary for the farmer to get the best out of the little rainfall. Incorporating mulching in the farming habits should definitely be encouraged in these areas to maximize the available moisture.

The difficulty with which mulching materials are obtained increases day after day. Firstly, there is no more free land where farmers can go and get wild grass at no expense. Secondly, due to high competition for land and expanding agriculture, proper planning of one's plot is required in order to be able to grow grass for mulching. It is therefore imperative that proper advice is available on the best type of grass to grow to economize on the land, taking into account the yield of mulch and the rapidity with which it decomposes.

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Agroclimatic zones of Zimbabwe and potential for agroforestry

K.W. Nyamapfene

Department of Land Management
University of Zimbabwe
P. O. Box MP 167, Harare, Zimbabwe

Abstract

Zimbabwe is considered to be divisible into five agroclimatic zones which are really agroecological zones. The paper describes the main agroclimatic features of each of these zones and evaluates the possible significance of each of the major features on agroforestry. It is recognised that only the availability of moisture in the form of rainfall, at the right time, is the main limiting factor for agriculture in general and agroforestry in particular. To a limited degree, temperatures are also considered limiting but only as far as excessively high temperatures in the arid and semi-arid parts of the country increase the possibility of moisture stress. Although frost occurs in parts of the country during the cool, dry season, low temperatures are not a serious limitation to agro-forestry. The areas that appear to be climatically most suited to agro-forestry are, for a variety of reasons, also the areas in which there seems to be the least need for it. The semi-arid and arid areas that are marginal for most other forms of agriculture appear to be the areas in which the greatest benefit could be derived from agroforestry. They are also the areas in which it would appear great difficulty may be experienced in trying to establish a useful and practical agro-forestry system. This last problem is the challange which the paper poses for the agroforestry researcher.

Introduction

The agroclimatic zones which will be used in this paper are based on a combination of Zimbabwe's rainfall map and the agro-ecological zones described by Vincent and Thomas (1960). An examination of the two maps (Figures 1 and 2) shows that the agro-ecological zones are very closely related to rainfall. The agro-ecological zonation, however, was based on several parameters such as soil type, vegetation as an indicator of agricultural potential, rainfall and, in particular, the effectiveness of the rainfall. Paramount importance is therefore attached to the availability of moisture in the right quantity and at the right time.

There is no doubt that climatic factors are a *sine qua non* for any agricultural activities but their impact will vary according to other physical as well as human conditions. For the purposes of this discussion it is proposed to put the impact of agroclimatic factors in the context of three other factors. These are:

1. the existence or absence of a tradition of agroforestry;
2. the desirability of it; and
3. the feasibility of it.

Figure 1 Mean annual rainfall.

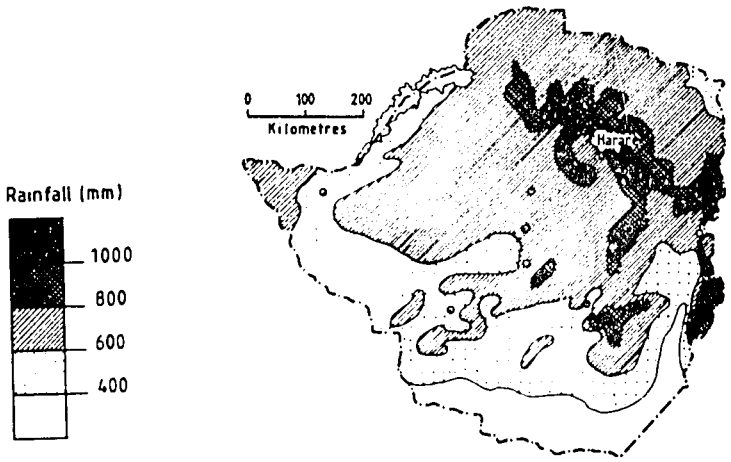
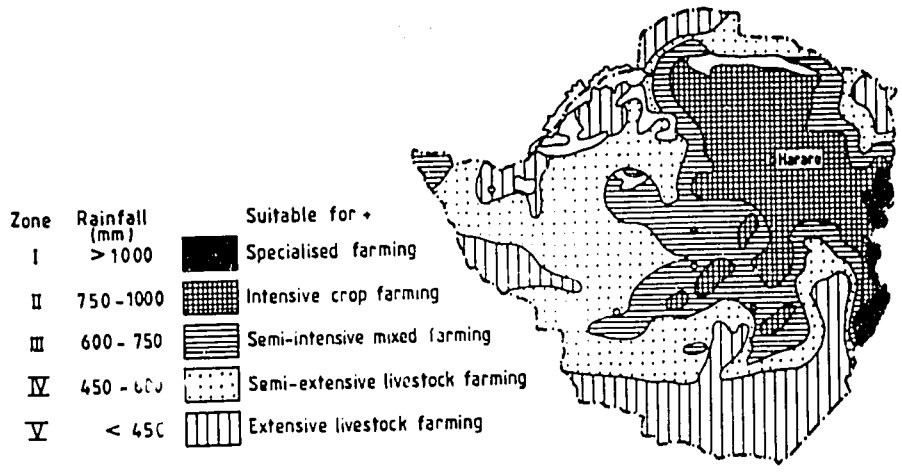


Figure 2 Agroclimatic zones.



The writer firmly believes that the existence of a tradition of agroforestry provides conditions which facilitate the re-introduction or modification of agroforestry systems and probably constitutes the most important guarantee in terms of potential for agroforestry. In many cases where there has been a tradition of agroforestry, agroclimatic conditions are often conducive to the development of a variety of such systems as is the case in most high-rainfall tropical zones.

Desirability of agroforestry has to do with those conditions in which it is perceived that agroforestry will result in a significant improvement in the physical condition of the environment or in the improvement of the social condition of the residents. This is often the case in arid and semi-arid regions. However, in such regions, agroclimatic considerations can be limiting or even overriding. It is felt that desirability of the system will create the necessary will without which no practice can be adopted regardless of how conducive the physical environment may be.

Feasibility simply refers to the presence of optimum conditions that would minimize impediments to the establishment of agroforestry, i.e., is it physically possible, socially acceptable and economically sensible?

The case of Zimbabwe

On the whole, Zimbabwe may be described as a semi-arid country in which more than 85% of the area receives less than 800 mm of rain per year. The rain is concentrated in the five months from November to March followed by a marked dry season.

Although parts of the country are susceptible to frost in the middle of the dry season, temperatures are not a major limiting factor for plant growth, except in isolated areas where ground frost can be a problem in the cooler months of the year. On the whole, therefore, Zimbabwe's potential can be considered to be largely a function of rainfall amount and distribution.

Agroclimatic zone I

This is a region of relatively high elevation with cool temperatures throughout the year and a rainfall generally well in excess of 1,000 mm per year. The rainfall is fairly reliable and although it is concentrated in the five summer months from November to March, this zone has the additional advantage that, in the dry winter months, it experiences light drizzles, called 'guti' in local parlance. This, together with the relatively cool temperatures at that time that minimize evaporation losses, means that the soil profile is moist throughout the year.

Most of the zone is on mountainous or hilly terrain with steep slopes that make soil erosion a serious hazard especially with the high silt and clay contents of the soils commonly found there. The soils are mostly Ultisols and Ultic or Oxic subgroups of Alfisols and some Oxisols. They are therefore of relatively low agricultural potential.

This combination of factors makes this zone highly suitable for agroforestry practices. Such practices are also desirable as they would ensure increased cover to protect the fragile lands. The introduction of agroforestry systems could be initiated in the areas where dairying is currently taking place with beneficial effect, especially if leguminous trees could be introduced for the benefit of the pastures. At present, the only form of agroforestry that has been attempted so far has been the growing of shrub and tree crops such as coffee and tea together with various larger trees for shade and for firewood to be used in the processing of the tea or coffee. However, one practice which has shown interesting possibilities is the practice of integrating coffee with the cultivation of

silverleaf desmodium (*Desmodium uncinatum*) and fine stem stylo (*Stylosanthes guianensis var. intermedia*). These pasture species provide a thick cover on the surface which apparently helps to conserve moisture while at the same time providing the coffee crop with nitrogen. In turn, the pastures are grazed by sheep at regular intervals thus keeping their growth in check and at an acceptable level with regard to potential competition for water and other nutrients.

Although climatically this zone is ideal for agroforestry and the practice would result in desirable, beneficial effects, the zone covers only 0.4% of the total land surface of Zimbabwe. With its ideal climate, competition for land here is very high and plantation agriculture and horticulture enjoy a high preference over any other form of land use.

Agroclimatic zone II

This zone has a rainfall in the region of 800 - 1,000 mm. It is also an area of relatively high elevation and concomitant cool temperatures. Rainfall is somewhat less reliable, particularly its onset. Some good, fertile soils, mainly Alfisols, typify the region. Climatically, this region is also suitable for the introduction of a wide range of trees and tree crops. However, this being probably the best agricultural land in the country, and also because of the proximity of most of the region to Harare, the capital, land here is at a premium and there has been strong resistance to any form of agroforestry.

A strong tradition of rotational monocultures revolving around maize, wheat, tobacco and, sometimes, groundnuts, is the norm here. There is also a considerable amount of dairy activity and it is in the area of dairying that some possibilities for agroforestry could be examined since this zone suffers some very high temperatures in the three months preceeding the rainy season, namely September, October and November. If nothing else, the introduction of certain tree species could provide shade during that period which is also a period when the 'veld' for grazing is of very poor quality. The selection of tree species for such a practice would have to take into account the severe frosts that occur in this zone.

Agroclimatic zone III

The rainfall here is moderate but comes mainly as infrequent heavy showers which, together with the generally high temperatures, reduces the effectiveness of the rain. The region is therefore subject to severe mid-season droughts. In their agro-ecological zonation, Vincent and Thomas (1960) point out that the region is

> '....marginal for maize and tobacco production or for enterprises based on crop production alone... The farming system in conformity with the natural conditioning factors should therefore be based on both livestock (assisted by the production of fodder crops) and cash crops, each playing a varying but approximately equal part.'

This zone probably has the most ideal combination of desirability and feasibility for agroforestry. The farming systems recommended for the zone lend themselves well to the possible inclusion of agroforestry. This could take the form of plants that have a rapid rate of growth and high nutritional value for livestock. At the same time the tree species thus introduced, if carefully selected, could, after the first few years of growth, prove to be hardier and more viable than any of the cash crops currently being produced there.

Agroclimatic zone IV

The rainfall is low (450 - 600 mm yr^{-1}) and tends to be erratic. Periodic seasonal droughts and severe dry spells during the rainy season are characteristic of this region. Except for the production of some drought-resistant crops in favoured localities, this is a zone in which cattle ranching appears to be the most viable use of land possible. The potential for agroforestry here will be discussed jointly with that of Zone V.

Agroclimatic zone V

Rainfall here is too low and erratic even for the production of drought-resistant fodder crops.

Zones IV and V offer the possibility of introducing some agroforestry systems integrated with livestock production especially as these are areas of extremely high temperatures for most of the year. High temperatures are known to have adverse effects on animal metabolism and therefore on the productivity of the animals. Although rainfall is low, it would be necessary to ensure an adequate supply of water for the trees only in the first year or two because most of the area covered by Zones IV and V has extensive reserves of ground water. Trees would be able to exploit this ground water better than most other crops. In time, the change in vegetation could result in desirable micro-climatic effects.

The possibility also exists to introduce commercial tree crops in these regions. For example, in the Zambezi Valley, some of the local people have successfully grown cashew nuts for their own consumption but the possibility of larger scale, organized production on scientific lines has not been investigated seriously.

Conclusion

Zimbabwe has a wide range of both macro- and micro-climatic conditions which offer reasonable possibilities for agroforestry. In those areas where climatic conditions are optimum, agroforestry faces unfair competition from traditional farming systems which are considered to be a more intensive and more economic use of the land. Some agroforestry systems appear to be possible in the low rainfall- high temperature zones. Here the introduction of agroforestry practices can increase the diversity of agricultural practices and ameliorate the hostility of the environment for other agricultural production systems. Thus the economic potential of these otherwise inimical environments can be increased.

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Climatic zoning for agroforestry in Somalia

P. Hutchinson

Food Early Warning Project
P. O. Box 943, Mogadishu, Somalia

Introduction

Though Somalia has a pastoral economy, with approximately one head of cattle, one camel, two sheep and three goats to every person, relatively little is known of the distributions of natural vegetation, nor has much serious consideration been given to the development of that agroforestry which already exists within the traditional patterns of agriculture and rangeland use. Investigations are still principally based on the identification of the extent, potentialities and use of indigenous species; and on the selection and possible applications of exotics. As a contribution to the resource base for agroforestry, this paper uses the method of Teel (1984) slightly modified, to establish climatic zones suitable for use in agroforestry.

Topography

Southern and Central Somalia consists of rather undistinguished relief rising from the coastal plains to a maximum altitude of 500 m asl near the Ethiopian border (Figure 1). The country's two most important rivers, the Juba and the Shabelle, dissect the western parts of the plain, but the lower reaches consist of meanders with flood plains. The Shabelle does not actually run into the sea. Just north of Mogadishu it turns parallel to the coast for a distance of some 300 km, before running out into swampland.

The northern regions are considerably different. The ground rises from south to north with a succession of ridges and upland plains, reaching maximum heights of 2000 m or more along the escarpment, which lies close and parallel to the north coast. The northern coastal strip is of variable width, but is very narrow, as little as 1 km, in some areas.

The synoptic climatology of Somalia

The climate of Somalia is determined by the north and south movement of the Intertropical Convergence Zone. In most areas of Somalia, this results in two rainfall season, the 'Gu' as the zone passes northwards, and the 'Der', on its southward movement. In both cases, however, the rain is produced by the moist air deriving from the Indian Ocean, in the southerly air stream. The north-easterly winds, deriving from Asia and Arabia, produce little significant rain.

Annual rainfall amounts are generally small, falling within arid or semi-arid zones of most classifications. With temperatures ranging from an annual mean of 18 °C in the northern highlands to just over 30 °C in one or two small areas. There is thus a considerable moisture deficit over the entire country.

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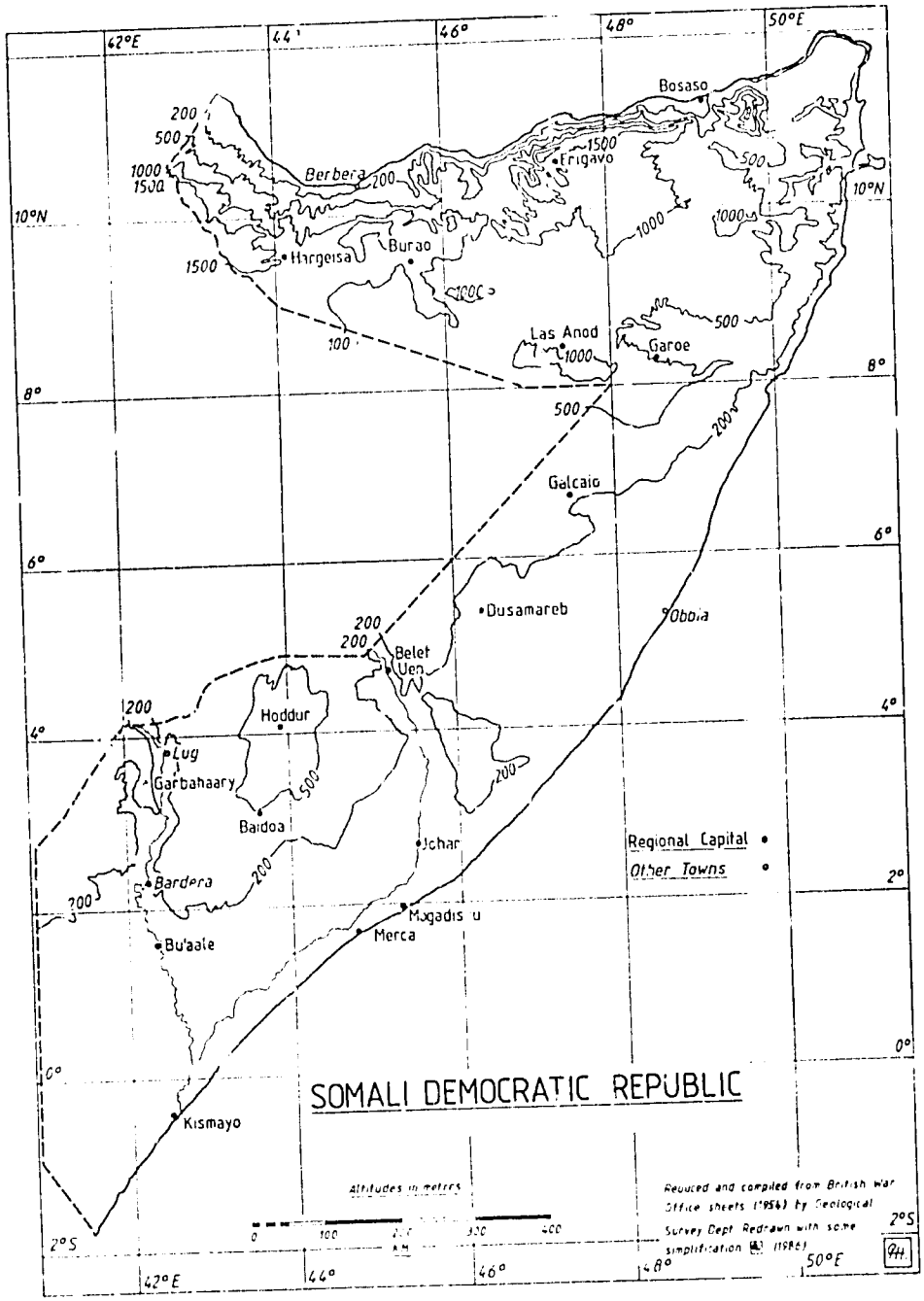
Figure 1 Map of Somalia



Agroclimatic zonation

For the agroclimatic zonation, the method of Teel has been used, with some modification. This method is very similar to the Webb et al. (1984) system, with only the various class limits being changed. In the method, all that is required is the mean annual rainfall and mean annual temperature, though due to the limited records available, a topographic map is also needed for spatial interpolation. Rainfall and temperature are classed and overlain, to give distinct agroclimatic zones.

Rainfall

No definitive rainfall maps yet exist for Somalia, though most maps are based on the data of Fantoli (1965), British Meteorological Office (1962), and Hunt (1951), none of which is more recent than 1960. A new map of mean annual rainfall has therefore been made based on the three sources mentioned above with more recent data, including the effect of altitude in the north.

Fantoli listed all known meteorological records for eastern, central and southern Somalia, up to 1960. Eighty-two rainfall stations are included, though some of these have records too short to be useful. The British Meteorological Office report provides summaries for 28 stations in northern Somalia, using data up to 1960. Hunt carried out an intensive field study in northern Somalia with 49 rain gauges over a six years period from 1945-1950. The Department of Civil Aviation provided information on 18 stations up to the present. The Food Early Warning Department produced data for 23 stations from 1980 to the present. Thus, although the records are scattered, and often broken, it has been possible to provide enough data, at least for a first approximation, to produce an annual rainfall map.

The northern part of the country, which, as mentioned above, consists of rather broken terrain, was subjected to a simple analysis to obtain a rainfall altitude relationship. The Hunt data, which at least has internal consistency was used for this, and the relationship is shown in Figure 2. Compared to previous maps, there are a few changes. In the lower Juba region, north of Kismayo, isohyets of 600 mm and 700 mm have been added, as more recent records show four stations having 600 mm or more. In the north, there has never been any consensus as to the real maximum values. Peak values have varied between 500 mm and 1100 mm. The actual maximum mean measured rainfall occurs at Dalo, which is on the edge of the escarpment, measured at 833 mm. This is likely to be close to the actual maximum spot value.

Temperature

As with the rainfall map, data for the mean annual temperature are derived from Fantoli 1965), British Meterological Office (1962), and from the more recent sources (Figure 3). Altogether, 40 station records were used, and these exhibited good inter-station consistency. In the north, 13 stations were used to derive a temperature-altitude relationship:

$$T = 29.22 - 0.0064 \times \text{altitude (m)}$$

with $r^2 = 0.92$. Note that the lapse rate of 0.0064 °C/m is rather more than that given in Webb et al. (1984).

Figure 2 Mean annual rainfall in Somalia.

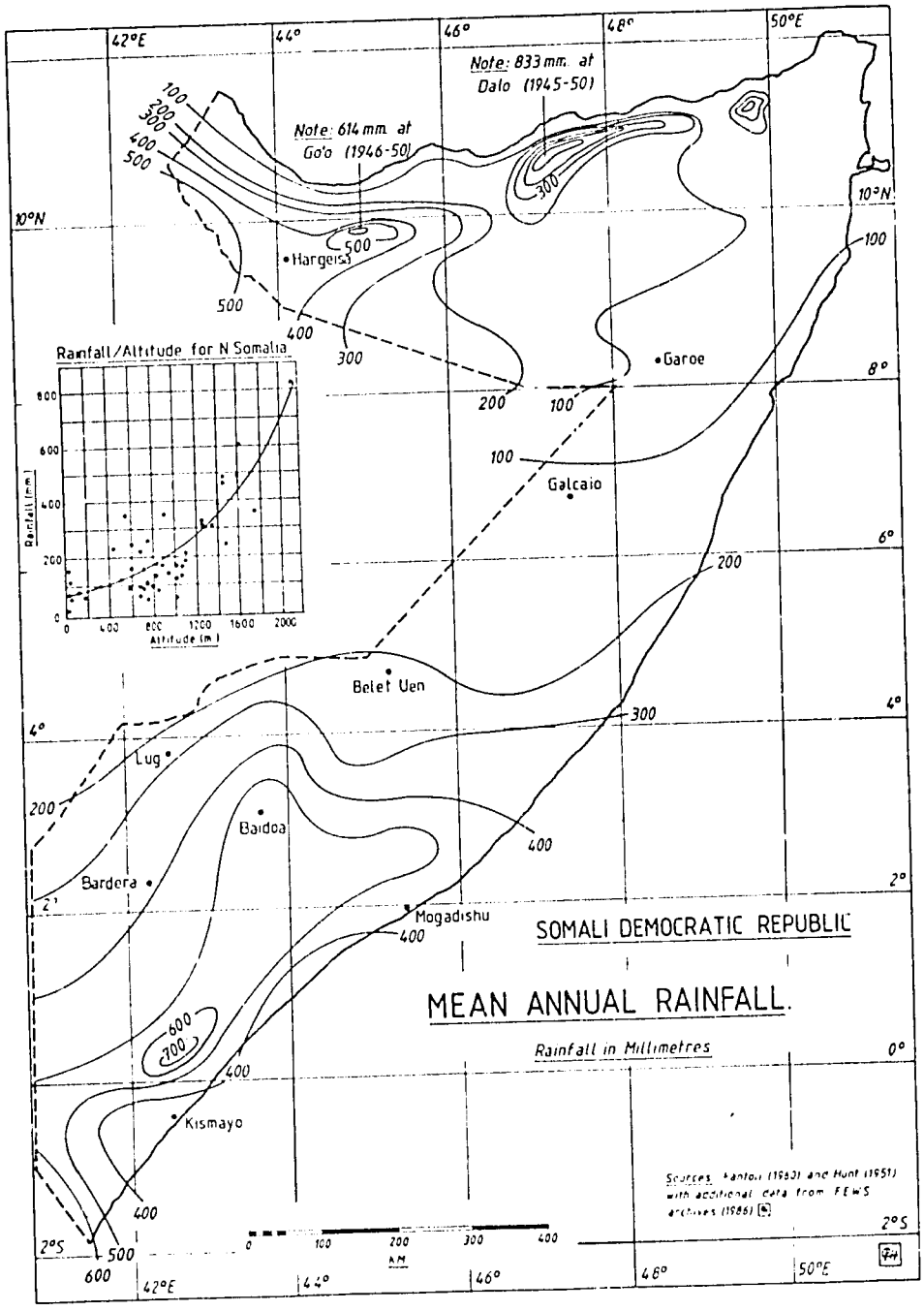
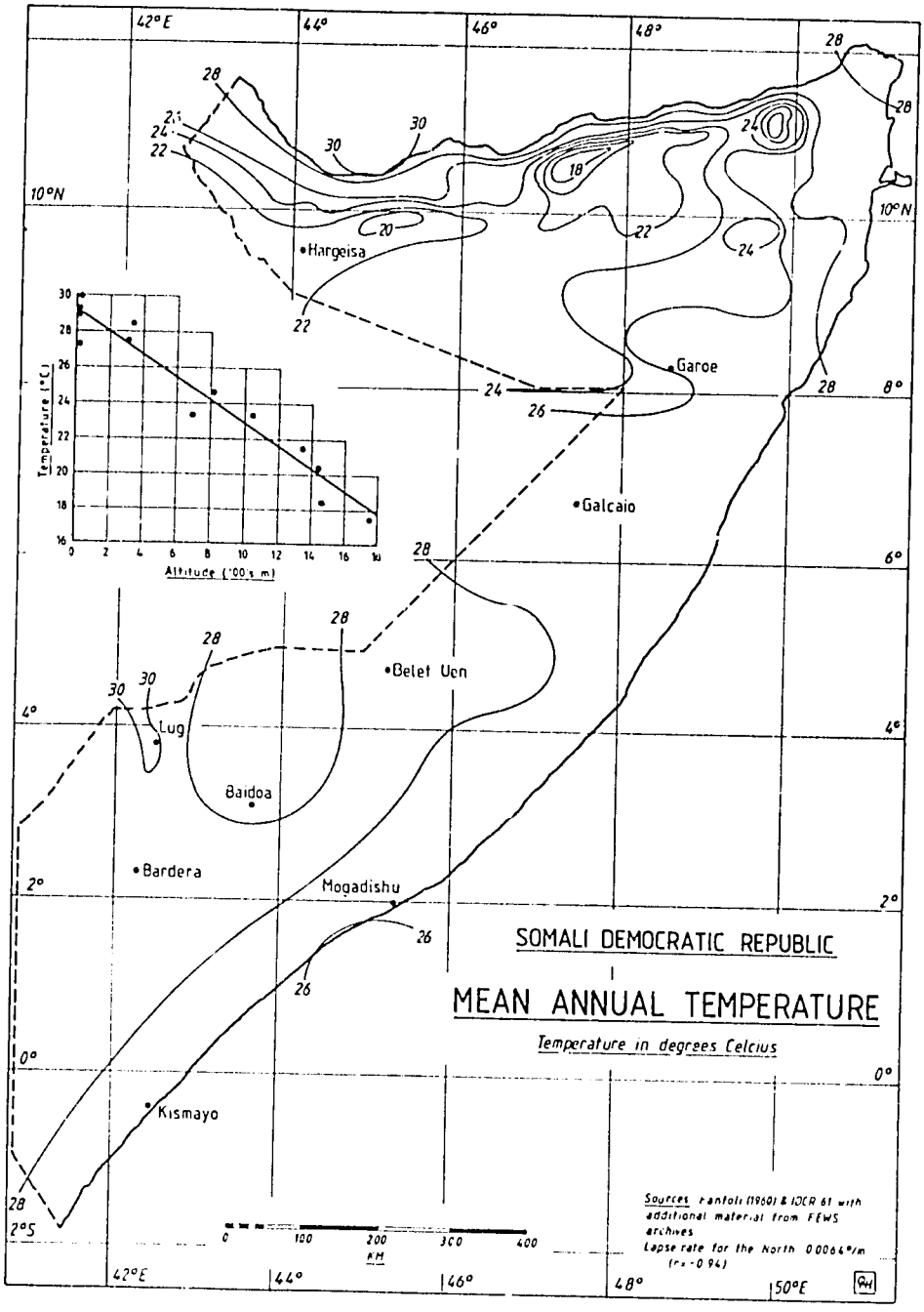


Figure 3 Mean annual temperature in Somalia.



The zoning system

Table 1 shows part of the original Teel tables. In the original, the rainfall classes are divided by potential evaporation to give unique classification. However, not enough is yet known about potential evaporation in Somalia for this to be possible. Rainfall has thus been used directly, setting class limits at 500, 325 and 150 mm. Because areas of less than 150 mm rainfall exist in Somalia, a further class has been added. The temperature classification has used directly, with the addition of an extra class to allow for temperatures of greater than 30 °C. The revised classification is given in the inset on Figure 4.

Table 1 Agroclimatic zones (adapted from Teel 1984)

Rainfall class			Temperature class	
Zone	Rainfall mm	Vegetation	Zone	Temperature (C)
I	1100 - 1700	moist forest	7	12 - 14
II	1000 - 1600	sub-humid	6	14 - 16
III	800 - 1400	semi-humid	5	16 - 18
IV	600 - 1100	semi-humid-semi-arid	4	18 - 20
V	450 - 900	semi-arid	3	20 - 22
VI	300 - 550	arid	2	22 - 24
VII	150 - 350	very arid	1	24 - 30

Source: Teel 1984.

Agroforestry climatic zones

The zones calculated with the modified system are shown in Figure 4. In the south and central regions almost all temperatures fall in class I. Thus the rather large zones are determined by the rainfall distribution in classes V, VI and VII. In the north-east, class VIII-1, very dry and hot, predominates. For the north and north-west, however, the zoning is more complicated. There is some similarity between the rainfall and the temperature zonation; but it is not exact, hence the complications. In the Erigavo area, the zoning is too complicated to be shown on the scale of the map used.

The simplified zoning system

To provide an easily-read map that may be of some practical use, I have simplified the classification scheme. Several adjacent rainfall and temperature zones have been amalgamated and some of the very small zones have been omitted. The classes are indicated by the numbers 0 to 11, which increase from dry and hot to wet and cool. Some of the original classes, such as VIII-4 and VI-0, are not found. Others, such as V-2, occur so rarely as to be neglected. If this presents a conceptual difficulty, then class 10 can be considered to include both V-1 and V-2, while class 11 can include V-3 and V-4. The result is a much simpler map (Figure 5). However, the area around Erigavo contains such a variety of zones that they cannot be conveniently mapped.

Figure 4 Agroforestry climatic zones (after Teel 1984).

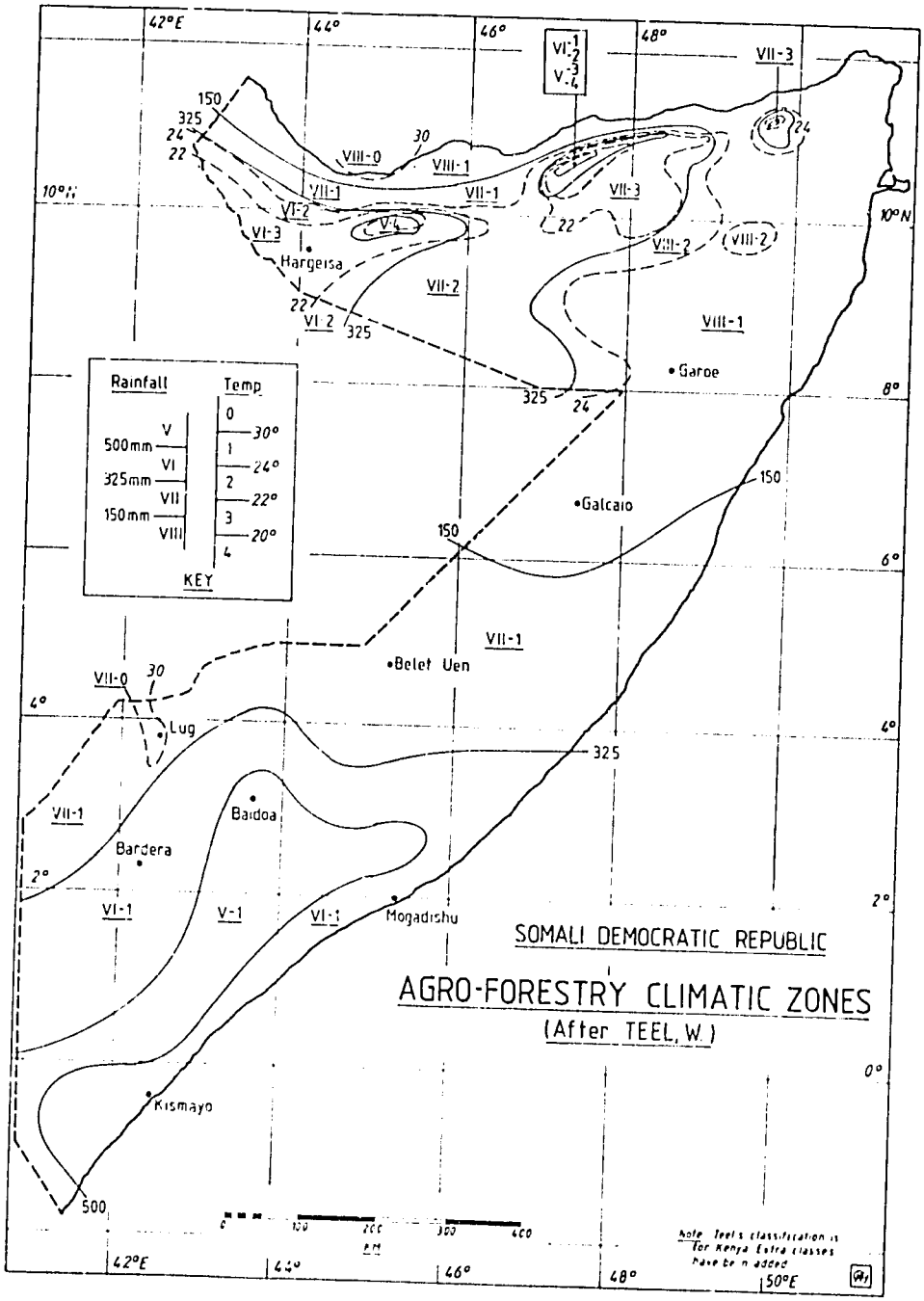
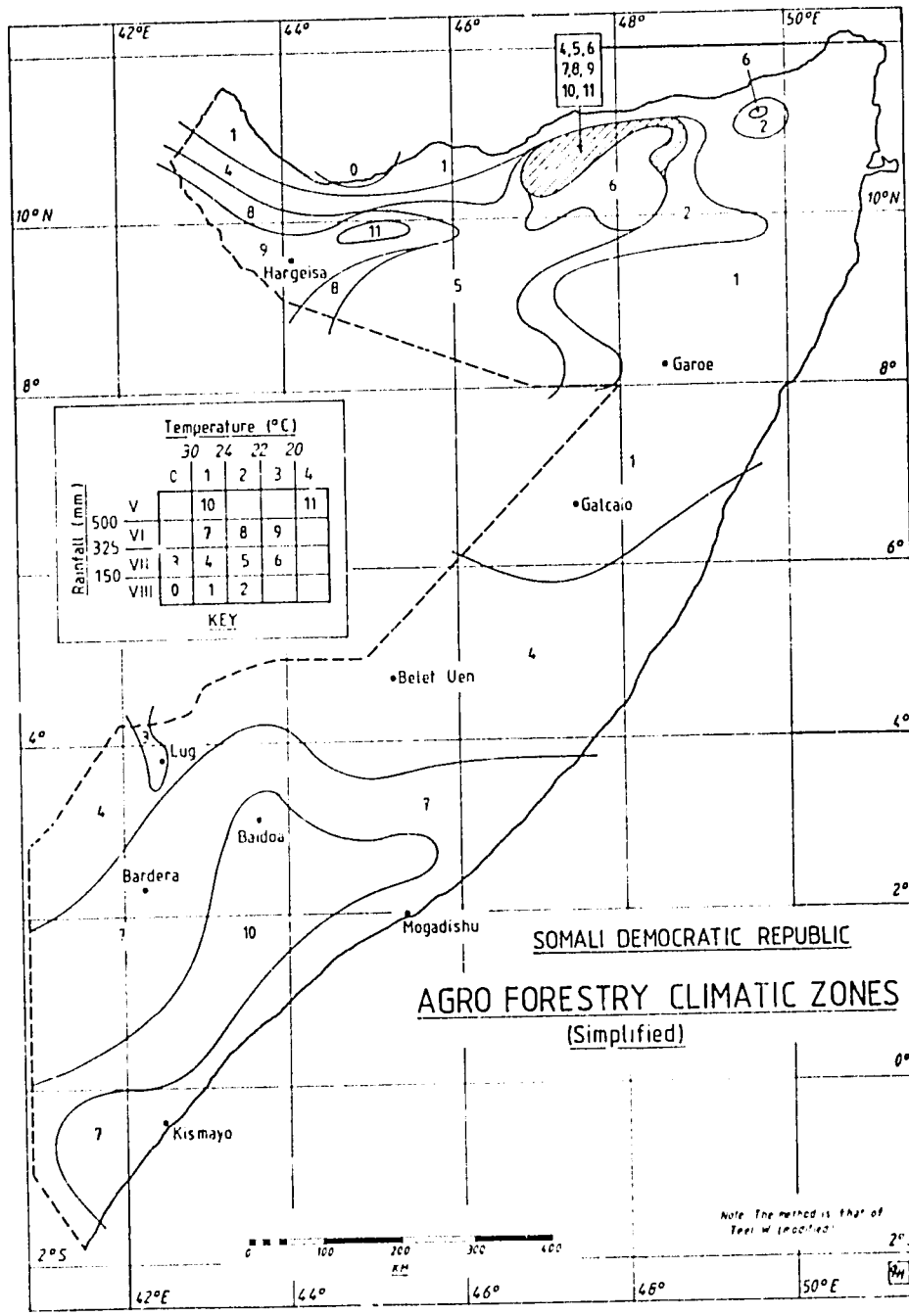


Figure 5 Simplified agroforestry climatic zones.



Discussion and conclusions

The next step should be that of confirming the validity of the zonation scheme by checking on the ground the occurrence of both native and exotic species of known climatic preferences. This would be a major study in itself. Although there is a considerable body of knowledge as to the extent of native species, this is not readily available, nor is there a complete list of the agroforestry uses of the native species. However, the need for this type of information is recognized, and some work is going ahead, principally at the National Range Agency. Until this is available, then some estimate of the potentialities and the availabilities of trees for agroforestry uses can be obtained by extrapolating information from adjacent countries, particularly Kenya.

Acknowledgements

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The influence of rainfall distribution to traditional agroforestry practices in western Kenya

B.R. K. Shuma, P.M. Mung'ala

Kenya Woodfuel Development Programme
The Beijer Institute
P.O. Box 56212, Nairobi, Kenya

Introduction

The Kenya Woodfuel Development Programme (KWDP) is a research and development implementation programme whose mandate is to contribute towards helping farmers to plant trees on their farms for self-sufficiency in fuelwood, among other benefits. The districts of Kakamega, Kisii, Murang'a and Nakuru were identified for the programme activities because of their high population and agricultural potential. KWDP, which works under the auspices of the Ministry of Energy and Regional Development (MOERD), was initiated in 1983 following the recommendations of the Kenya Fuelwood Cycle Study (1980-82). This study was carried out jointly by the Ministry and the Beijer Institute of the Swedish Royal Academy of Sciences. KWDP is financed through a Dutch Government grant for its programmes in Kakamega and Kisii Districts where ground activities started in 1984 and 1985, respectively.

The Programme's approach towards district implementation programmes is both holistic and step-wise in nature, whereby in the first step, the district's resources, including physiological, climatic, socio-cultural, demographic and other relevant information, are inventoried to assist in realistic planning-implementation strategies. It was during this survey that the KWDP learned a great deal from farmers' knowledge tree regeneration practices in Kakamega District. One of the study's important findings was that the highlands would experience serious fuelwood scarcity earlier than projected because the rising populations would necessitate rapid land demarcation and privatization.

This brief paper will highlight KWDP's findings on rainfall distribution and its effects on traditional agroforestry practices within the district. The KWDP has indeed used the information from the findings and the observed traditional agroforestry activities and has incorporated such knowledge in its planning strategies for the Kakamega District.

The main advantage of incorporating local farmers' knowledge in any planned implementation activities is that such planned activities are both realistic and acceptable to the farmers.

Rainfall distribution in Kakamega

The average annual rainfall for Kakamega District varies from 1,200 mm to over 2,000 mm, the annual rainfall increasing from the drier northern parts of the district to the much wetter southern areas. Most of this rain occurs between March and October with

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monthly averages of over 120 mm during those months. Peaks occur during the long rains, April to June, and the short rains, August to October. (See App. for rainfall figures from various stations, adopted from Farm Management Handbook of Kenya, Vol.II.)

Kakamega District (especially the southern parts) has its rainfall distributed more or less uniformly throughout the year except for the months of November through February, which receive less than 100 mm.

Tree regeneration activities

The survey found that traditional tree-regeneration activities in the district are very much influenced by the rainfall pattern.

Traditional on-farm nurseries

Our surveys revealed that there are many small on-farm bare-root nurseries in Kakamega, especially in the wetter southern parts of the district. These nurseries are very variable in size, ranging from small broken pots to nurseries of up to 3 m^2. We estimate that about 40% of the households in Kakamega established their own on-farm nurseries in 1983 with a preference for exotic species (eucalyptus and cypress comprised about 83% of all the species found in these nurseries). The end use for these trees is marketable building poles and timber.

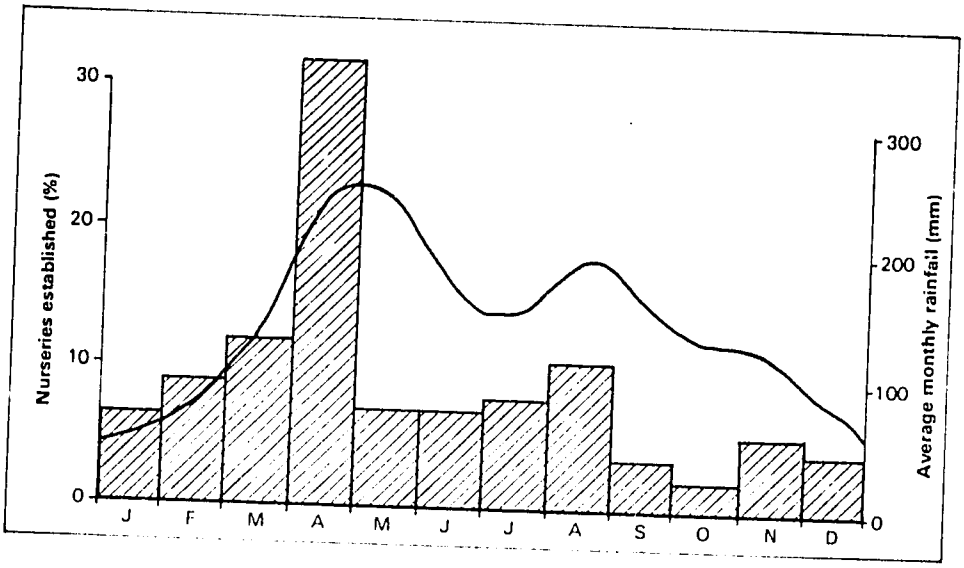
The nursery techniques practiced by farmers differ substantially from standard practices, and even within those techniques great differences occur. Farmers usually start establishing their nurseries at the beginning of the rainy season (Figure 1), although the normal forestry practice is that seedlings should be ready for planting-out with the onset of the rains. The district (especially the south) receives well-distributed rainfall, so that even with seed-sowing in March and April and outplanting in June and July, survival of outplanted seedlings is very high. Another possible explanation is that the farmers plant early to avoid the cumbersome task of having to water their nurseries during the dry months.

KWDP nursery implementation strategy as influenced by the farmers' knowledge and experience in Kakamega

The original funding proposal had recommended that KWDP establish about 600 centralized nurseries scattered throughout the district in cooperation with women groups, local chiefs and others. These nurseries were to utilize traditional forestry practices including expensive water works, polythene tubes, nursery labour, and so forth. However, following the findings of our surveys, we decided to adopt a different implementation strategy. Since farmers planted the species for which seed was readily available, we believed that we could get them to grow different agroforestry species using traditional knowledge if seed were made available. However, traditional on-farm nurseries would require some improvement in construction and management to give better survival at the time of outplanting.

Given the above situation, we prepared a pamphlet suggesting a few technical changes in nursery construction and operation. The farmers are initially issued with free seeds together with the pamphlet followed by a demonstration on how to construct such nurseries. Our initial monitoring indicates that this implementation strategy has been quite successful.

Figure 1 The initiation of farm nurseries in 1983 (vertical columns) and average monthly rainfall in Kakamega district



Tree propagation through wildlings

Tree establishment through planting of wildlings is also common in some parts of Kakamega District. Wildling collection is mainly confined to indigenous species and some fruit trees.

Collection of wildlings is determined by the seeding habit of the particular species. Most seeds ripen during the dry season. Such seeds, when they fall from the mother tree, start germinating at the onset of the rains. Two to three months after germination, most seedlings of these indigenous species and fruit trees are ready to transplant.

The KWDP plans to use this strategy to encourage the farmers in Kakamega to utilize wildlings especially for those agroforestry species whose seeds are more difficult to obtain and whose viability in storage is limited. Examples are *Grevillea robusta* and *Calliandra calothyrsus*.

Tree propagation through direct seeding

In some parts of Kakamega, farmers have traditionally propagated *Sesbania sesban*, *Makhamia platycalyx* and other prolific seeders either through broadcasting the seeds on their agricultural fields or through direct planting in prepared holes. This direct-seeding is controlled by the rainfall pattern. Direct seeding (especially for broadcast seeds), is done after land preparation during the dry season. Usually with the onset of rains, such seed starts to germinate. The farmers thin systematically, leaving an adequate number of seedlings, depending on the branching habit of the particular species.

KWDP intends to utilize this experience in developing tree- propagation strategies but with a number of modifications for the more prolific-seeding species.

Appendix: Rainfall figures from various stations in the Kakamega district

Table 1 Rainfall figures from various stations (Kakamega district) having at least 10 years of records up to 1976.

No and altitude	Name of Station	Years of rec.	Kind of rec.	Annual rainf. mm	Monthly rainfall in mm Jan	Feb	Mars	April	May	June	July	Aug	Sept	Oct	Nov	Dec
8934001	Kakamega District	55	Average	1930	60	95	151	254	260	190	164	230	186	134	118	87
1554 mm	Office		60 prob	1729	32	56	112	216	230	161	147	197	156	118	81	58
8934002	Bukura Farm Institute	52	Av.	1788	52	91	161	257	247	157	131	187	161	127	123	94
1463 m																
8934009	Kaimosi Mission	34	Av.	1815	74	100	154	259	251	165	157	198	161	120	108	78
1615 m			60%	1543	34	39	101	242	229	120	127	172	118	77	57	55
8934013	Mumias Girl's School	41	Av.	1756	58	80	155	258	258	168	136	155	164	139	115	71
1340 m			60%	1579	31	56	106	236	240	147	115	127	154	122	72	50
8934028	Kakamega Forest	38	Av.	2025	88	108	148	279	289	195	171	220	173	140	122	93
1676 m	Station		60%	1866	53	101	156	288	218	187	169	217	144	145	109	64
8934031	Yala St Mary's School	34	Av.	1832	73	89	145	277	264	150	118	165	154	136	145	116
1463 m			60%	1613	37	98	135	251	261	125	96	158	131	137	146	77
8934040.	Butere Health Center	34	Av.	1840	55	94	162	298	260	152	117	171	177	144	118	92
1435 m			60%	1649	22	44	131	270	235	144	90	144	143	117	92	51
8934061	Malava Dispensary	29	Av.	2085	55	78	164	244	294	204	212	257	205	173	115	83
1595 m				1871	25	32	85	214	251	163	162	190	147	147	65	34
8934071	Turbo Stanley 1 State	28	Av.	1332	89	42	78	157	166	142	155	225	134	82	69	52
1905 m																
8934078	Esirwa Kaimosi	30		2119	78	88	160	282	301	197	190	235	202	162	122	103
1707 m																
8934096	Kakamega	18	Av.	1918	55	111	178	240	239	150	133	224	172	169	152	98
1585 m	Station															
8934103	Vihiga, Maragoh	23	Av.	1875	91	106	169	290	242	125	102	158	144	144	161	140
1585 m																
8935015	Turbo Forest Lands	59	Av.	1258	36	43	76	151	153	141	184	229	112	60	53	21
1829 m	Estate															
8935042	Larhe Farm	38	Av.	1194	30	32	67	154	174	132	168	191	100	58	51	36
1844 m																
8935076	Turbo Selborne Estat	29	Av.	1169	35	40	72	142	148	124	147	202	108	67	43	40
1890 m																

Vegetation and bioclimate in Liberia

M. A-AS-Saqui

Central Agricultural Research Institute, Ministry of Agriculture
P.O. Box 3929, Monrovia, Liberia

Abstract

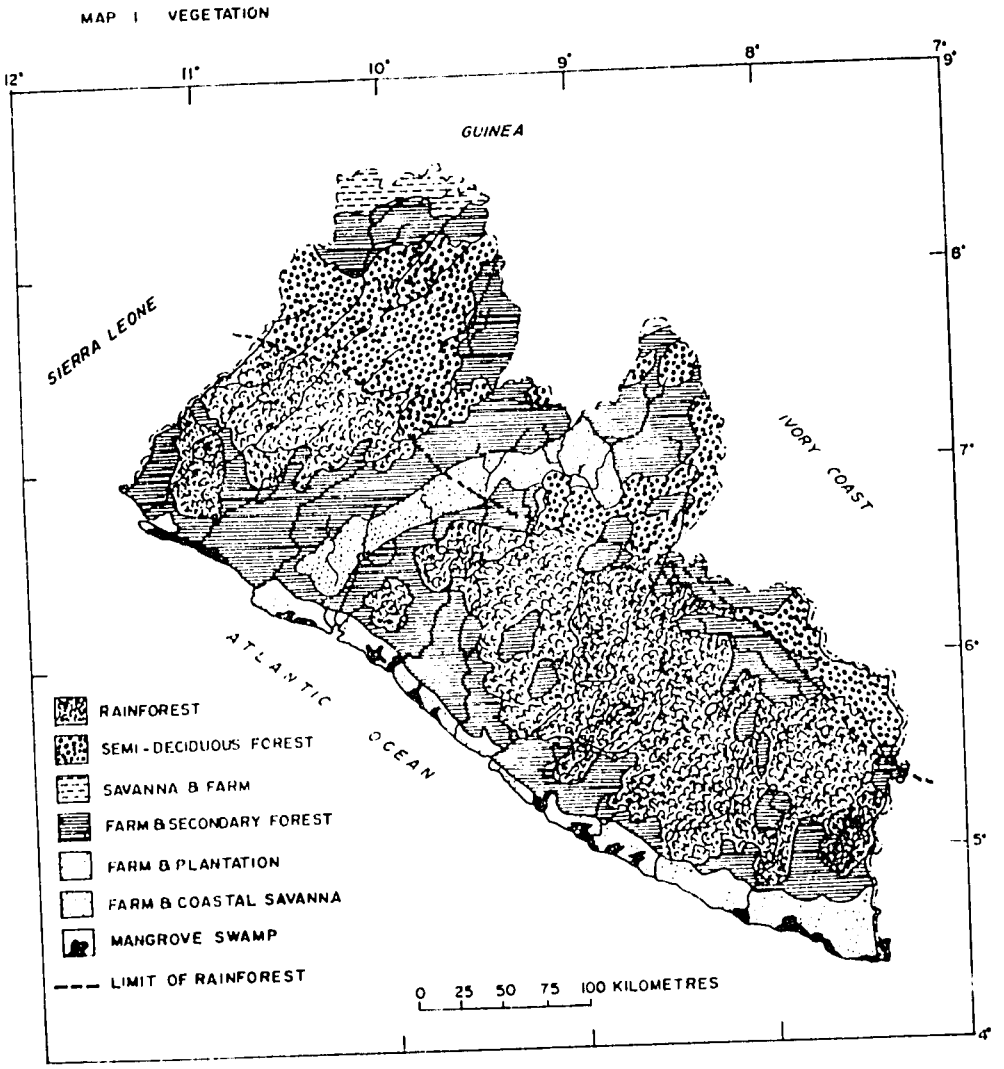
The tropical rainforest comprises in Liberia most of the country except a very narrow strip along the coast where mangrove vegetation alternates with coastal savanna. The meteorological condition in the whole country allows the vegetation to develop into a tropical high forest, and most probably the entire land area was once covered with it. Nowadays the total area of tropical high forest and secondary forest consists of one-third of the country, while the remaining 65% is composed of forested areas such as young secondary forest and intermediate forest and further non-forested areas such as farm lands, savannas, towns, swamps etc. Forestry plays a vital role in national economic development. Liberia has a network of several meteorological stations for agroforestry development, planning and management. Still the meteorological division needs to be strengthened and upgraded for effective services. The present status of meteorological service to agroforestry systems planning and management in Liberia is discussed and maps showing vegetation, average annual rainfall and temperature are presented. Future lines of work for improving the meteorological service are indicated.

Vegetation

The tropical rain forest belt in West Africa extends from Sierra Leone to Ghana and comprises in Liberia most of the country except a very narrow strip along the coast where mangrove vegetation alternates with coastal savannah. The climatic conditions in the whole country allow the vegetation to develop into a tropical high forest which most probably covered the entire land area. Today, tropical high forest and old secondary forest cover only one-third of the country; while the remaining 65% is composed of young secondary forest, intermediate forest and grass-woodlands. Although the general climatic conditions are nearly uniform throughout the country, rainfall and humidity decrease toward the interior. Consequently, vegetation is banded into zones more-or-less parallel to the coastline (Figure 1).

These zones are closely linked, but various kinds of transition occur, which are mostly influenced by topography and soil. The influence of shifting cultivation on the vegetation has been immense, and most of the high forests have at times been converted into farmlands. After farms are abandoned, natural vegetation recaptures the land and high forest gradually reappears. Several development stages can be recognized, such as 'recent farmland,' 'old farmland' and 'intermediate forest.'

Figure 1 Vegetation map of Liberia.



Bioclimate

In 1951, the Division of Meteorology was established within the Department of Public Works. It supervises a number of weather station throughout the country which measure daily rainfall and record maximum and minimum temperatures.

The equatorial position and the distribution of high and low pressure belts over the African continent and the Atlantic Ocean determine the climate of Liberia and, more generally, West Africa. Thus the climate of Liberia is marked by an even and fairly warm temperature throughout the year and above all by the very high humidity, above

90% much of the time. Unlike the temperate zones, the seasons are not determined by changing temperatures but by the prevailing precipitation. Therefore, a rainy and a dry season with transitional periods can be differentiated. Rainfall is heavy and intense. There is little year-to-year variability in the climate.

Rainfall

The Liberian coastline runs approximately from south-east to north- west and at right angles to the prevailing south-westerly rain- bearing winds. As the maritime air reaches the coast it is forced to rise, it cools, and condensation takes place which causes the extremely heavy precipitation. Consequently the rainfall is heavier than on any other part of the west coast of Africa except the Freetown Peninsula in Sierra Leone and a small isolated location near Buea in Cameroon. The annual rainfall near the coast is nearly 4550 mm (180 inches) but the amount has exceeded this in some years. Towards the interior, rainfall decreases except for the higher areas where the air is forced to rise, causing orographic precipitation. Because of its high altitude, the area around Mount Nimba receives much more rain (3225 mm = 127 inches) than would be expected from its geographical position. In the north-west there is a similar situation.

Figure 2 indicates a pronounced rainfall pattern. Generally a fairly distinct dry season extends from about November to April and a wet season the remainder of the year. The months of heaviest rainfall vary somewhat in different parts of the country, but normally are June, July and September.

In August most stations show a marked decrease of precipitation, and a short dry season known in Liberia as the 'middries' sets in for a fortnight or so. In September the rain starts with new force. The extreme south-east corner of Liberia is even noted for two distinct rainy seasons, with maxima in May-June and September-October, and with a well-defined short dry season in between.

The distribution of rain throughout the year and particularly the length of the dry periods are at least as important as the amount of rainfall. Since Liberian soils have usually low moisture-storage capacities, the amount and frequency of rainfall during the dry season becomes a limiting factor for the cultivation of many crops.

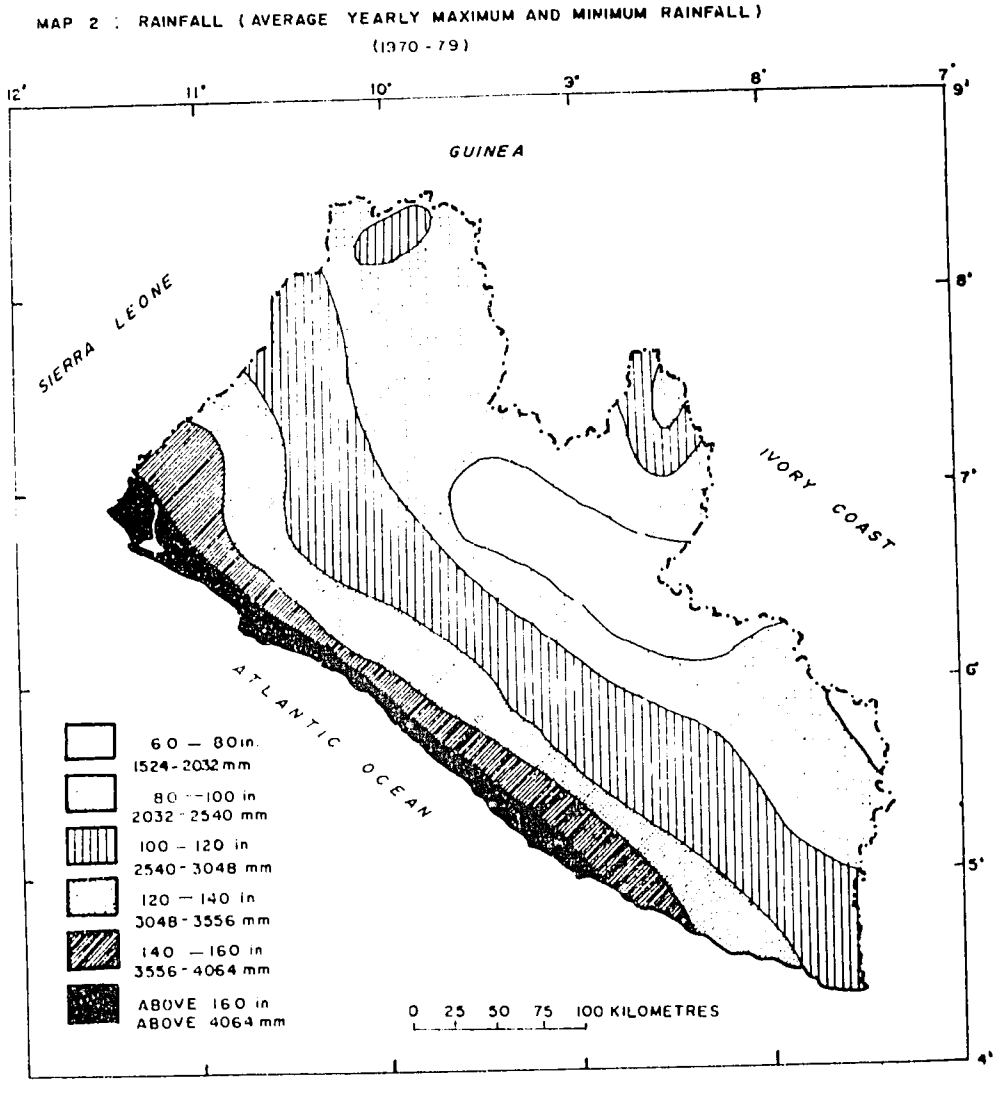
In spite of the heavy precipitation, it does not rain continuously during the rainy season. It is common to have sunny days even during the months when the rain is heaviest. In the interior heavy showers may occur, but only very rarely will it rain for the whole day. Naturally, the rain may last for a day or two without a stop. At such times the rain pours down steadily and water usually covers the ground for several inches.

Temperature and sunshine

Because of the equatorial position of Liberia the sun is almost overhead at noon throughout the year, and insolation is very intense. Therefore, high temperatures with little monthly variation should be expected. However, since temperatures are not solely dependent on insolation, but are affected by the degree of cloud cover, air humidity, rainfall and vegetational cover, temperatures in fact are much lower than anticipated.

Along the coast, the Atlantic Ocean has a moderating effect on the temperatures, and annual and daily variations are evenly balanced; while toward the interior the continental influence becomes more dominant, the range of temperatures widens, and the variation of minimum and maximum increases markedly. It is difficult to quote figures for temperature, since they vary considerably with location and altitude, but 27 to 32 °C (80 to 90 °F) during the day and 21 to 24 °C (70 to 75 °F) at night seem to be fairly representative. Because of the uniform and high humidity – the relative humidity ranges

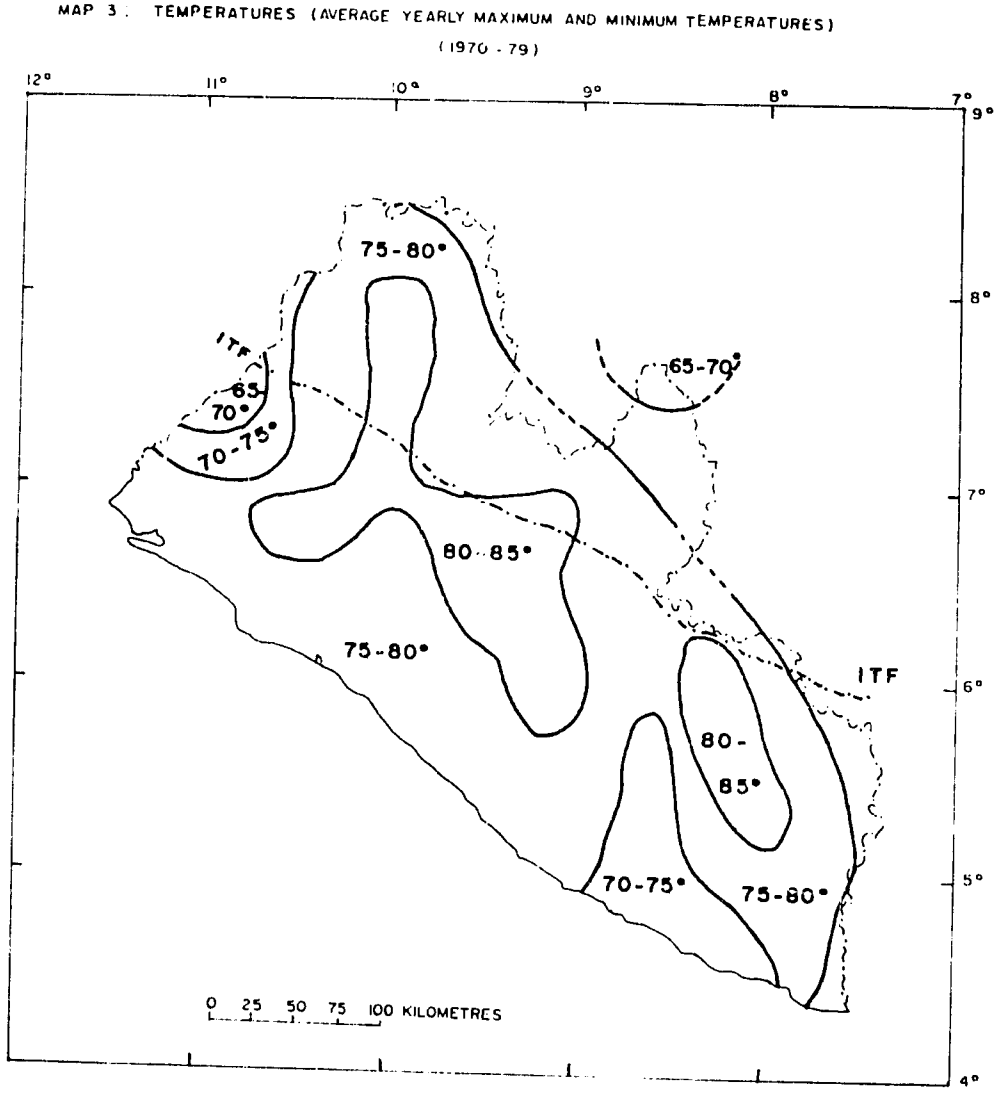
Figure 2 Average annual rainfall.



generally between 85 and 95% within the coastal area – temperatures seem much higher than they actually are. Only in the higher regions near the Guinea border, where the average altitudes are between 550 and 610 m (1800 and 2000 ft), is the climate more pleasant, since temperatures are much lower during the entire year. At times the inhabitants of these regions even suffer from the cold nights.

Figure 3 shows the average annual temperatures of Liberia. They range in the coastal area from 24 to 27 °C (75 to 80 °F) while in the interior they are usually several degrees higher except for the mountain regions. Although the country is situated north of the equator, the highest temperatures occur between January and April and the

Figure 3 Average annual temperature.



lowest ones are usually recorded during the months of August and September. These low temperatures are mainly caused by the large amount of cloud cover common over much of coastal West Africa during these months.

Sunshine is at a minimum during the wet months, particularly June to September, with a definite minimum in August. Days of long and bright sunshine occur between December and March, and an average of 6.3 or even 7 hours per day is not exceptional. During June and September only a few hours sunshine are recorded, and during August sunshine is particularly low, rarely exceeding the average of 1.3 hours per day. Sunshine and cloudiness therefore do not necessarily correlate with the rainfall; especially since August, when 'middries' occur, is the time of highest cloud cover.

The equatorial maritime air masses brought on the south- westerlies cause the very high humidity of Liberia. A relative humidity of 90 - 100% during the rainy season is common, while during the dry season the average humidity is somewhat lower and usually in the range of 85 - 95%. However, regardless of season, the relative humidity during the night and early morning hours is almost always in the range of 90 - 100%. Since this is also the time of lowest diurnal temperatures, it is evident that before sunrise the air is practically saturated with moisture. Data from other stations show very similar results, leading to the compelling conclusion that the percentage and periodicity of humidity is valid within the whole sphere of constant monsoonal air flow. Only the region north of the Inter-Tropical Convergence Zone, where continental air masses prevail from mid-December to the end of January, has arid conditions. Because of the extreme dryness of the Harmattan, the humidity may drop below 50% at times.

Environmental driving variables of ecosystems and their distribution on a complex terrain

A. Hocevar and L. Kajfez-Bogataj

Department of Agronomy, Edward Kardelja University
Jamnikarjeva 101, 61000 Ljubljana, Yugoslavia

Abstract

Using an example of general model of ecosystem productivity, the role of environmental driving variables is stressed. Use of the particular model when only light is the limiting factor is presented for a few places in Slovenia, Yugoslavia. The importance of other limiting factors, e.g., water, is illustrated; and simple methods of how to incorporate it in the model are presented. Several examples are given of how to assess the peculiarities of the environmental driving variables in a complex terrain which must be known for assessment of ecosystem productivity of an area.

Introduction

Since the first agricultural fields were established in ancient times, their productivity has been monitored in one way or another. Farmers and foresters and their ancestors tried to increase the productivity of ecosystems they manage. At first the understanding of ecosystem functioning has been vague and more or less at the descriptive level. Later on statistical relations among biological variables and environmental ones have been determined and models on these bases developed (Robertson 1983).

In the last two decades, the understanding of ecosystem functioning has been one of the main goals of research in this field. A further development is dynamic modelling of the ecosystem and its simulation on computers (de Vries 1982). These models are based on biological, physical and chemical principles. They try to explain the ecosystem functioning by selection of main variables and by the study of their interrelations. They have been applied in various versions at many locations throughout the world (Robertson 1983).

In the present contribution we extend the concept of ecosystem modelling from a particular location to an area with mesoscale dimension. To illustrate this we present a general model of ecosystem productivity and a particular model when light is the limiting factor. The model is applied to locations in north-western part of Yugoslavia. The importance of another limiting factor – water – is stressed and simple methods of incorporate it in the model are presented and the obtained results discussed.

General models

The productivity of a plant canopy ecosystem (P) is a function of biotic parameters describing phytometrical, physiological and optical characteristics of a plant canopy;

and abiotic parameters describing the soil and meteorological environment. The influence of management is implicitly included in the biotic and abiotic parameters. Since all parameters are interrelated, for producivity (P), we can write:

$$P = f(B_l, S_m, M_n) \quad (1)$$

where l, m and n are the numbers of biological, soil and meteorological parameters, respectively.

According to Gaastra (1963), the productivity sought as net photosynthesis is a function of weather. It can be separated into photochemical processes driven by photosynthetically-active radiation, biochemical processes governed by temperature of the plants and transport phenomena among the plants and their environment as determined by morphological and physiological characteristics of plant canopy, and the wind and temperature regime in and above the canopy.

Some interrelations of this function are already known but a complete knowledge of these complex relations is still far ahead. Models based on realistic simplifications of the ecosystem have been derived and many of them are at work in the world (Robertson 1983). Among simplified dynamic models we can distinguish four types: when light is the limiting factor (level 1); when water is the limiting factor (level 2); when nitrogen is the limiting factor (level 3); and when phosphorus is the limiting factor (level 4) (deVries 1982).

A schematic presentation of a general model of plant production in relation to weather (production level 1) is given according to Landsberg (1981) on Figure 1.

Models used at various locations in north-western Yugoslavia

For calculation of net photosynthesis of plant canopies in north- western Yugoslavia we used the modified computer program CALPROD (Band et al. 1981; Hecevar and Kajfez-Bogataj 1984). The basis of it is that net photosynthesis of a leaf is a known function of absorbed solar radiation and leaf temperature. The model belongs to level 1 and assumes healthy plants. The simplification is justified by the fact that at the studied locations, precipitation exceeds evapotranspiration during the growing period. The flow chart of this program is given in Figure 2.

Results obtained by this model for five locations in northern Yugoslavia using climatological data for submodels 1, 2 and 3 which take into account different plant response curves are shown on Figure 3 as daily net photosynthesis by month. Production viewed as net photosynthesis is largest at Koper, a warm and sunny place on the coast; and lowest in the mountainous Planica at a height of 850 m asl.

Figure 1 Schematic presentation of a model of plant growth in relation to weather. Solid lines represent flows of material, dotted lines flows of 'information.' Valves represent rates, boxes represent states and circles enclose the environmental driving variables. Numbers indicate the sequence of calculations for programming purposes, i.e., calculate (1) energy interception; (2) stomatal conductance – feed forward to net photsynthesis, transpiration; (3) transpiration; (4) leaf water status – geed back to stomatal conductance (iterate), xylem water potential – feed forward to partitioning equations; (5) net photosynthesis; (6) respiration;

(7) partition accumulated assimilates; (8) update mass of component parts (convert assimilates to leaf area, root length, etc.); (9) volume of soil exploited by roots; (10) update soil status in root zone – feed back to tranpiration. (After Landsberg 1981).

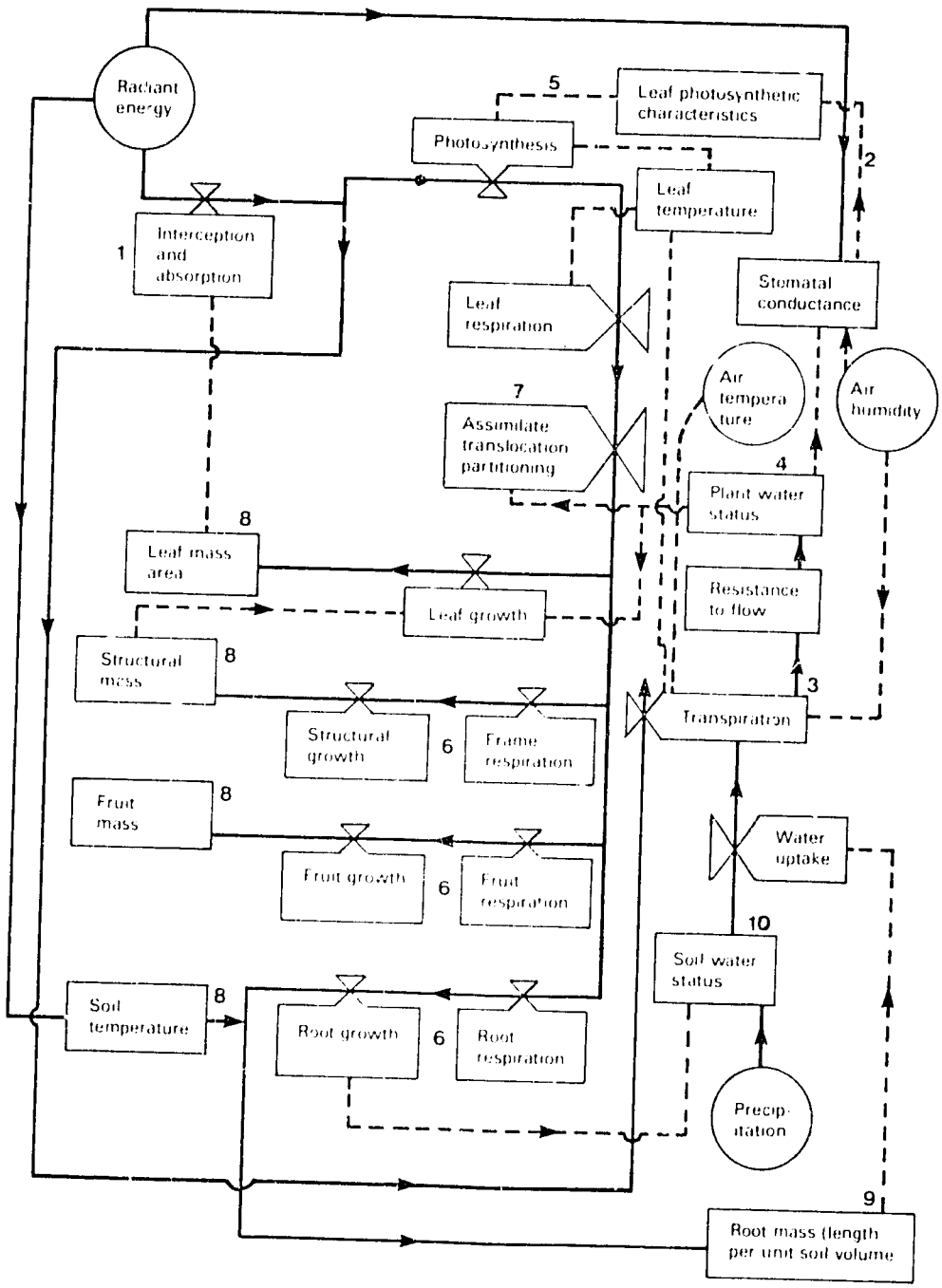


Figure 2 Modified CALPROD program flow chart, emphasizing input and output including water as limiting factor.

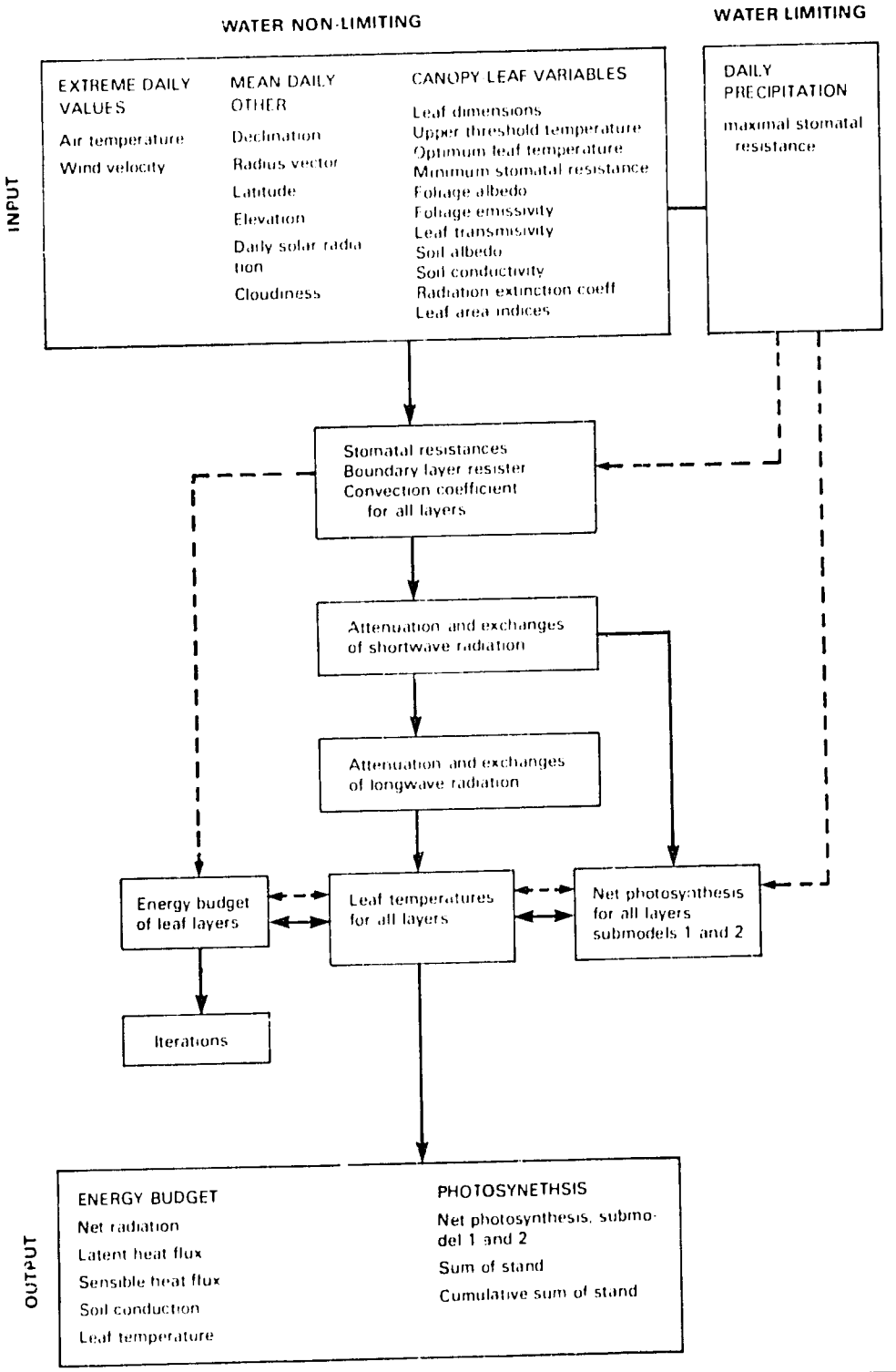
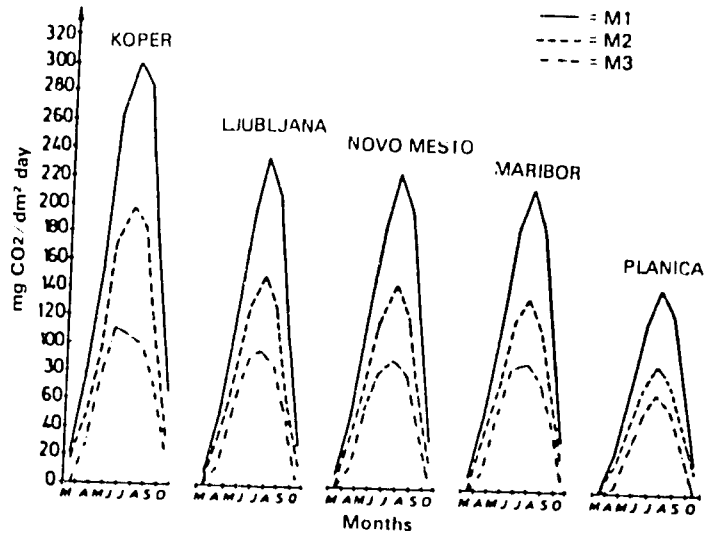


Figure 3 Daily course of mean net photsynthesis according to submodels M1 (high temperature plants), M2 (agricultural plants) and M3 (woody plants), for five locations in Slovenia for the vegetative period, March through October.



With the same CALPROD model we calculated also the productivity of buckwheat plant canopy using appropriate input data and photosynthetic response curves for *Fagopyrum esculentum* (Moench) (Kajfez-Bogataj and Gaberscik 1986). For the year 1984 the comparison of observed and calculated results shows a very good agreement (Figure 4). More information about this research can be found in Kajfez-Bogataj and Hocevar (1986).

With the same model we also calculated net photosynthesis of a beech forest at two elevations using biological variables for locations at Ljubljana and Planica. Comparison of observed and predicted net photosnynthesis shows fairly good agreement in spite of being the first trial (Figure 5) (Kajfez-Bogataj and Robic 1985).

In general, the north-western part of Yugoslavia with large amounts of precipitation (yearly amounts 1250-1750 mm) does not experience drought although some years may show a shortage of water. During these dry years, there are negative effects on plant canopy productivity, viz., stomatal resistance will be larger, transpiration will be smaller and therefore temperature of leaves will be higher, diffusion of CO_2 into stomata will be smaller and so net photosynthesis will decrease.

We incorporated the shortage of water in CALPROD by using a minimum stomatal resistance calculated as a function of water balance. Thus, additional input data and additional computations are needed for the maximum stomatal resistance and the main terms of water balance equation, daily precipitation and daily evapotranspiration (Bringfeld 1980; Maticic 1977). Additional input data and their influence on particular computation steps of the computer program are schematically presented on the flow chart by dashed lines (Figure 2).

Figure 4 Comparison of observed and simulated total dry matter production of buckwheat for Ljubljana, 1984.

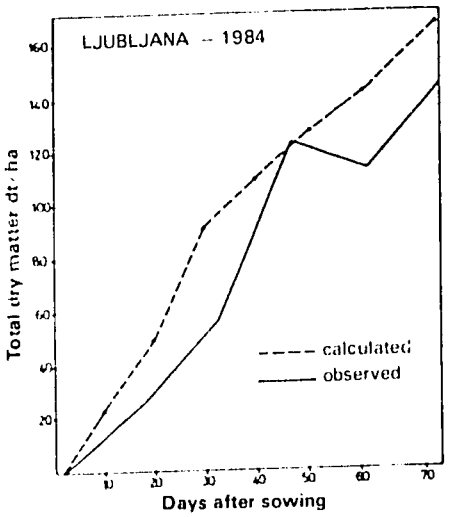
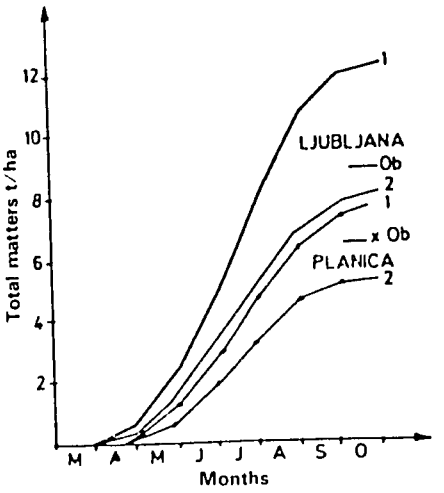


Figure 5 Comparison of predicted and observed dry matter production of forest calculated by submodels 1 and 2 at Ljubljana and Planica.



From data on daily precipitation and daily evapotranspiration we calculated minimum stomatal resistance as a linear function of time, the factor of proportionality being on the order of 2-7 s cm^{-1} day^{-1} beginning on the day when all the precipitation was used for evapotranspiration. Until this day, stomatal resistance had the minimum value given by the input data.

An efficiency parameter was calculated from the minimum and the maximum stomatal resistance and the calculated minimum stomatal resistance for particular day. Since its value has to be between one and zero, we applied the cosine-squared function.

Preliminary results obtained by the modified program which includes light and water as limiting factors show rather small changes in comparison with the previous ones except in Koper which is located on the Mediterranean coast. We speculate that the differences in water regime are not large enough from year to year and the model not sensitive enough to show a well-expressed influence of water shortage on net photosynthesis. In regions with large water shortages, we can expect that the mentioned modifications of the model will be of greater significance.

Extension of prodcution model to an area

The model can be applied to a large area if all of its parameters do not change very much over the area or to a smaller area in complex terrain. In nature, an ecosystem of an area normally consists of (j) elementary parts (Figure 6) which are defined by different values of parameters and therefore different productivities (P_k)

$$P_k = f(B_{lk}, S_{mk}, M_{nk}) \tag{2}$$

To obtain the productivity of an area we have to sum up the productivities of elementary parts:

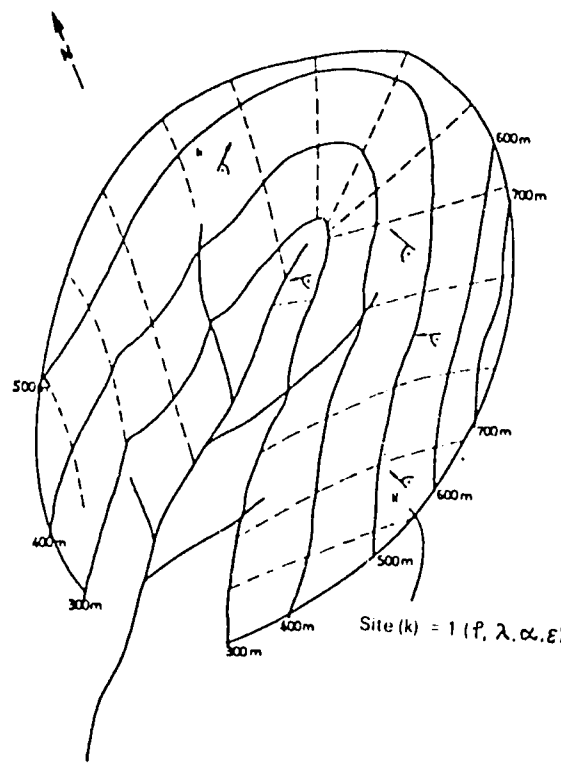
$$P = \sum_{k=1}^{j} P_k \tag{3}$$

where the area is divided in j homogeneous areas.

Environmental driving variables in the mesoscale

To calculate the production of a whole ecosystem in complex terrain we have to know how the values of its parameters vary over the area. In particular, the atmospheric parameters change their values very much from one elementary part of the ecosystem to the other. Complex terrain is very common in Slovenia; therefore its influence on the distribution of atmospheric variables values has been studied extensively. Some of

Figure 6 Ecosystem of a watershed and its elementary parts.



these studies will be discussed giving methods for evaluation of atmospheric variables as a function of terrain or site.

One such atmospheric variable is minimum temperature. It shows very distinctive features in valleys and basins on mornings after clear and calm radiation nights. A temperature inversion develop with air minimum temperature increase from the bottom of cold air lake basin. The rate is between 4.4 °C/100 m and 6.2 °C/100 m height along the slopes. These values resulted from measurements in Slovenia (Petkovsek et al. 1969) and in Pennsylvania, U.S.A. (Hocevar and Martsolf 1972) and are theoretically explained by Hocevar (1973).

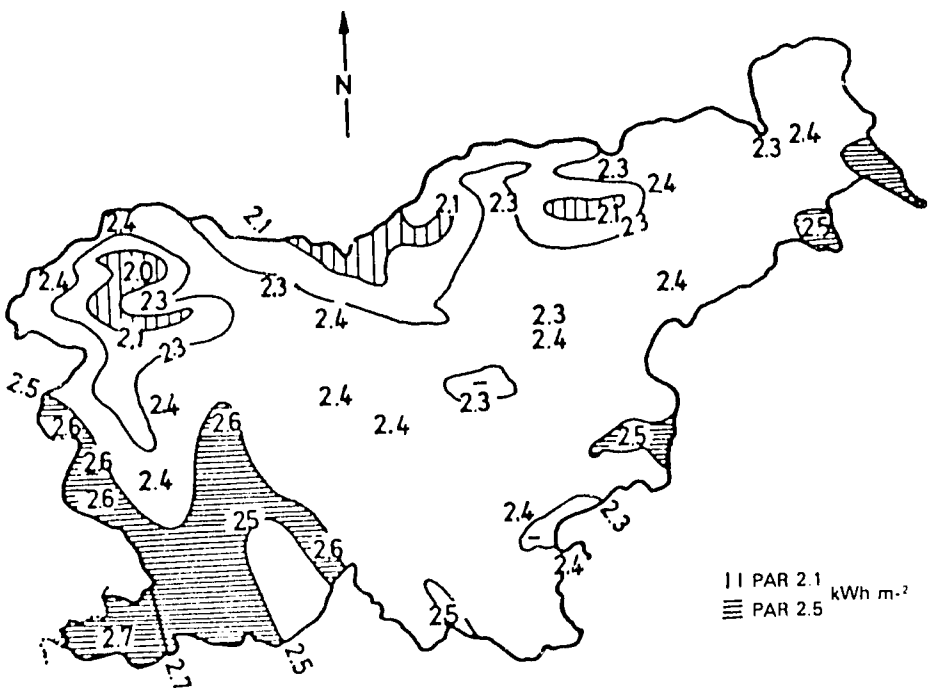
Photosynthetically–active radiation (PAR) determines photochemical processes (Gaastra 1963). We developed a method for estimating PAR for any site in complex terrain (Hocevar and Rakovec 1981). The method has the following steps: First, a map showing the areal distribution of PAR_h on a horizontal surface in the chosen period is prepared based on calculations from hourly measurements os sunshine duration at climatic stations (31 in Slovenia) and spatial features of convective cloudiness, fog and air pollution in the same time intervals. This is done for a typical day of every decade and every month of the year (Figure 7).

Second, PAR of an element of sloping surface (PAR_s) is calculated as the product of k_s and PAR_h, where k_s is a function of azimuth and inclination of the surface. Both k_s and PAR_h are functions of the treated time period, as well.

$$PAR_s = k_s (PAR_h) \tag{4}$$

A matrix of coefficients k_s was obtained from known values of PAR_s and PAR_h at locations observing meteorological parameters (Hocevar and Rakovec 1979).

Figure 7 Spatial distribution of PAR gained by a horizontal surface in Slovenia on a typical July day.



The third step is to account for obscuration of the sun by obstacles along the solar path. In our calculations, we reduced PAR by 80% when a site was so obscured and only diffuse PAR was present.

Model calculations of the three atmospheric variables, PAR, air temperature and soil surface temperature were made for an idealized basin with slopes of 20° and the

Figure 8 Daily course of PAR, soil surface temperature (T_g), air temperature (T_a), and mean sunshine duration on various sites in an idealized basin with 20° slopes using meteorological data for Dolenjska, Slovenia, on 17 June. Shaded portions of sunshine circles indicate fraction of hour that sky is cloudy.

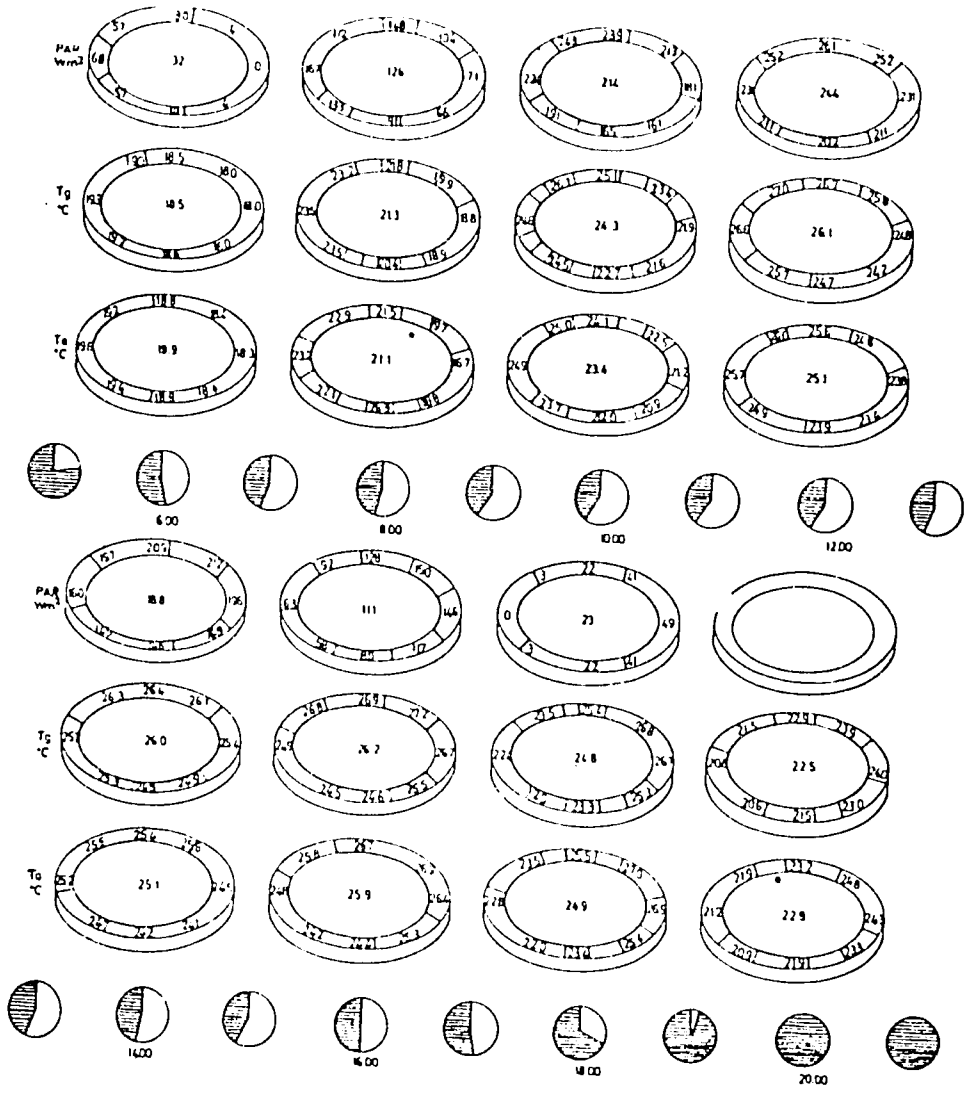


Table 1 Daily amounts of photosynthetically active radiation (PAR in $MJm^{-2}y^{-1}$ mean daily soil surface temperature (T_g) mean daily air temperature (T_a) spectively, at four differently oriented slopes (towards South S, towards East E, towards North N and towards West V d at the bottom of an idealised basin at clear sky (C) and at mean sunshine duration conditions (M). Added are also the ratio PAR(C)/PAR(M) and differences between T_g(C) - T_aM) and T_a(M), respectively.

		Bottom			S			E			N			W		
		C	M		C	M		C	M		C	M		C	M	
17. April	PAR	8.7	4.3	2.02	11.0	5.2	2.11	8.3	4.1	2.02	5.8	3.0	1.93	8.2	4.0	2.0
	T_g	12.1	10.5	1.6	13.0	11.1	1.9	11.9	10.5	1.4	10.6	9.6	1.0	11.9	10.3	1.6
	T_a	11.7	10.5	1.2	12.6	11.0	1.6	11.6	10.6	1.0	10.2	9.6	0.6	11.5	10.3	1.2
17. June	PAR	12.0	6.8	1.77	13.0	7.5	1.74	11.0	6.5	1.69	9.0	5.3	1.69	11.0	6.4	1.72
	T_g	23.6	21.7	1.9	24.3	22.1	2.2	23.4	21.7	1.7	22.3	21.0	1.3	23.3	21.5	1.8
	T_a	23.1	21.7	1.4	23.8	22.0	1.8	23.0	21.7	1.3	21.8	21.0	0.8	22.9	21.4	1.5
17. August	PAR	9.5	6.1	1.56	11.0	7.1	1.55	9.0	5.7	1.58	6.6	4.3	1.53	9.0	5.8	1.55
	T_g	23.6	22.7	0.9	24.5	23.2	1.3	23.4	22.6	0.8	22.2	21.8	0.4	23.4	22.6	0.8
	T_a	23.2	22.7	0.5	24.1	23.1	1.0	23.1	22.6	0.5	21.8	21.8	0.0	23.0	22.6	0.4
17. Oct.	PAR	4.3	2.4	1.79	6.8	3.6	1.75	4.1	2.2	1.86	1.7	1.0	1.70	4.1	2.4	1.71
	T_g	10.0	9.2	0.8	11.0	10.0	1.0	9.9	9.2	0.7	8.6	8.2	0.4	9.9	9.3	0.6
	T_a	9.7	9.3	0.4	10.8	10.0	0.8	9.7	9.3	0.4	8.4	8.4	0.0	9.7	9.4	0.3
17. Dec.	PAR	1.7	0.47	3.61	3.3	0.91	3.26	1.7	0.44	3.86	0.04	0.01	3.16	1.7	0.47	3.62
	T_g	-1.5	-2.9	1.4	-0.6	-2.8	2.2	-1.5	-2.9	1.4	-2.2	-2.8	0.6	-1.5	-2.8	1.3
	T_a	-1.5	02.7	1.2	-0.7	-2.7	2.0	-1.5	-2.7	1.2	-1.8	-2.8	0.7	-1.5	-2.6	1.1

observed mean duration of sunshine at Dolenjska, Slovenia. The results are given as daily courses (Figure 8). Daily mean values are compared with clear sky values in Table 1.

Conclusions

The results of modelling indicate that it can be a powerful tool for estimating ecosystem productivity. Dynamic modelling can be extrapolated from a point to an area. If the ecosystem is represented by its elementary parts, parameters defining those elementary parts must be known. This is especially true for highly changeable atmospheric variables in complex terrain. Some of the methods for evaluation of time and space distribution of those vital ecosystem parameters for which we give some practical examples have proved useful.

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Traditional agroforestry practices under the edaphoclimatic parameters of Cyprus

L. Leontiades

Department of Forests
Ministry of Agriculture and Natural Resources
Nicosia, Cyprus

Abstract

Various forms of agroforestry have been practised in Cyprus since time immemorial and many of them continue to be practised to the present day. Agroforestry was culturally, socially and economically imperative for the well-being of the rural household in that it provided a good variety of products on the limited land of the farmer, that made the family self- or almost self-sustained. Under the unpredictable and most frequently adverse (to annual crops) climatic conditions of Cyprus, this variety of crops was also of great significance in that it provided a buffering effect to the household budget and averted starvation in cases of failure of one or other of the crops.

Under such conditions, economic analysis, cost-benefit ratios and alternate rates of return from the land did not come in. Hence no serious attempt has ever been made to evaluate the inter-relations between ligneous plants and other associated plant or animal production on the same land.

In Cyprus there has been a gradual reduction in the practice of agroforestry in favour of intensive monocultural practices. This has come about as a result of a combination of factors, as follows:

- *Increased income and rising standards of living in rural areas enabled the farmer to become a partner in the nationwide economy, in contrast to the self-sustained household economy of his fathers. His purchasing power has increased and what he does not grow he can purchase. Under such conditions he finds monocultures easier.*
- *The increasing use of water for irrigation stimulated intensive monoculture practices with non-ligneous crops of high cash-earning value.*
- *Under rainfed conditions, short-rotation crops (annuals) lost their value due to climatic adversities, in favour of the ligneous, longer rotation crops, resulting in ligneous monocultures.*
- *High wages for manual work necessitated mechanization in agricultural operations and this favoured monocultures.*
- *Consolidation of small scattered holdings in many communities also favoured monocultures.*
- *The easy availability and increased use of fertilizers reduced the importance of crop variety in maintaining soil productivity and favoured monocultures.*
- *Lack of quantitative data and information on the values of agroforestry also favoured monocultures.*

Research and education on agroforestry are necessary in order to establish its value as an economic and ecological land use practice, especially in countries with sensitive agronomic conditions and adverse climatic patterns.

Introduction

There are indications that Cyprus was covered with very dense forests in prehistoric times. Homer refers to Cyprus as the Green Island (Dasoessa) and Strabo who visited Cyprus more than one thousand years later (in 45 A.D.) writes thus about Cyprus in his Geographica (Cobham 1908):

> Such then is Cyprus in point of position. But in excellence it falls behind no one of the islands: for it is rich in wine and oil, and oil, and uses home-grown wheat. There are mines of copper in plenty at Tamassos, in which are produced sulphate of copper and copper-rust useful in the healing art. Eratosthenes talks of the plains as being formerly full of wood run to riot, choked in fact with undergrowth and uncultivated. The mines were here of some little service, the trees being cut down for the melting of copper and silver; and of farther help was shipbuilding, when men sailed over the sea without fear and with large fleets. But when even so they were not got under leave was given to those who would and could cut them down to keep the land they had cleared in full possession and free of taxes.

Clearing and destruction of the forests continued throughout the long years that followed, until the year 1880 which became the turning point with the establishment of the forestry service and the beginning of rational forest management.

Forestry and food production were always competitive land use systems and there was hardly ever amicable symbiosis.

Foresty and food collection

For thousands of years, before man felt the necessity and had the capability to clear the forest and practise agriculture, he lived in harmony with the forest environment and fed himself with wild fruits seeds, roots, plants and honey that mother nature provided. He collected his food and moved about in search of it.

Collection of food from the forest was the earliest agroforestry practice. In Cyprus this practice survives to the present day with a big scope for increase. The modern Cypriot has preserved his rural habits through the ages and he takes great pleasure in the collection of food from the forest, though no longer for his subsistence but for a hobby and instinctive satisfaction.

Fruits like the berries of bramble (*Rubus fruticosus*) and the strawberry tree (*Arbutus andrachne* and *A. unedo*) and the fruit of the hawthorn (*Crataegus azarolus*) are delicacies of high esteem not only among the rural population but also among city dwellers. So are many herbs and vegetables that are eaten raw, cooked, or pickled; or are used to give flavour to food. A big number of plants is also widely used in herbal medicine and in extraction of essential and other oils.

Mushroom collecting from the forest is a very enjoyable hobby for the city dweller and a very profitable side-job for the villager. In 1986 the 'red mushroom' (*Lactarius*

deliciosus) of the pine forests reached the price of CY3.5 (U.S.$7) per kilogramme in the city markets and it was a significant source of revenue to those villagers whose area was favoured with the right rainfall and temperature for the growth of the mushroom. Truffles (*Terfezia spp.*) are another valuable mushroom that grows in symbiosis with roots of various trees, but good production years occur very rarely, as the fungus grows only if there are late spring or early summer rains, that occur very rarely in Cyprus.

Snails of various species are also a delicacy. They are collected from wooded and other rural areas when there is sufficient rainfall or atmospheric moisture to bring them out of their underground hibernation.

Honey, collected from the cavities of tree trunks was perhaps the earliest form of sugar used by man. In Cyprus, wild honey is not collected today. Instead there is a well-organized scientific production through intensive methods of apiculture. Honey provides subsidiary income to many farmers and saves foreign exchange through reduction of sugar imports.

The forests of Cyprus are also good biogenetic reserves inasmuch as many of the cultivated varieties of fruits and cereals are found therein in their original wild form. Examples of such plants are wild apple and pear trees, wild wheat and oats, and wild carrot and cabbage. The latter (*Brassica hilarionis*) is endemic to Cyprus. These wild varieties are important sources of genes in the effort to rear cultivated varieties which will show increased resistance to environmental adversities such as drought, frost and disease that are frequent in the Cyprus environment.

Forestry and hunting

After food collection, hunting was probably the oldest of man's activities in his long struggle to feed and clothe himself. Excavations in Cyprus have shown the existence of such animals as the fallow deer (*Dama mesopotamica*) and the wild boar (*Sus scrofa*) that were hunted for their meat and their skins. The wild sheep (moufflon) of Cyprus (*Ovis ammon orientalis* – Cyprus variety) was also hunted, as has been confirmed by bones of the animal found at Khirokitia in neolithic settlements dating back to 7,000 years B.C.

In 1396, A.D.O. D'anglure wrote (Cobham 1908):

> The following Sunday, the ninth day of January, the King sent us again presents, to wit one hundred partridges, sixty hares, and five wild sheep, a sight fair to see. He was a prince who greatly loved hunting. He had a little beast no bigger than a fox. It is called 'carable', and there is no wild animal but this little beast will catch it, especially the animals named above.

Hunting of the moufflon is also depicted very vividly in mosaics of the Graeco-Roman period excavated at Paphos. The animal today is protected and its hunting is strictly prohibited.

Hunting in Cyprus today is not done for the sake of obtaining food, but for sport and recreation. Cyprus, with a population of about 600,000, has a hunter population of about 40,000, perhaps one of the highest proportions in the world. The most common species hunted are partridge (*Alectoris graeca cypriotes*); hare (*Lepus europea*); wood pigeon (*Columba palumbus palumbus*); thrush (*Turdus spp.*); turtle dove (*Streptopelia turtur turtur*); and to a lesser degree, woodcock (*Scolopax rusticola*) and various species of ducks and waterbirds that come to Cyprus as winter visitors.

The catching of small birds on limesticks and nets has been reduced considerably the last three years through a government decision for strict enforcement of the law.

The catching of eels from forest streams and other inland waters has come almost to a halt, as eels have almost disappeared due mainly to the widespread use of insecticides, herbicides and fertilizers. Stream fishing is non-existent. However, through the good work of the fisheries service, the sport of fishing for trout and other fish in reservoirs that are artificially stocked with spawn, has gained ground in the last ten years. Rearing of trout and other fresh-water fish in farms is also practised. A prerequisite for trout rearing is cool, clear water that is secured only through the existence of forests and the absence of debris caused by erosion.

Forestry and grazing

The taming of animals by man and the practice of grazing in Cyprus are almost as old as the practice of hunting. Although extensive free range grazing on land that does not belong to the grazier is a primitive mode of subsistence, it survives to the present day. It was an easy method of providing meat, milk, cheese, wool and other products for the household and for trading. In the xeroclimatic conditions of Cyprus, grazing in the forests on ligneous maquis was a secure land-use practice, in that it was not affected by the frequent droughts that severely affect annual crops such as wheat, barley and legumes that provide forage in areas outside the forests.

Free-range goat grazing in the forests of Cyprus was common practice. However, after many years of experience and careful study and considerations, it was decided that free-range goat grazing and sound forest management on the mountain forests of Cyprus could not co-exist. At the same time, with rapidly rising living and social standards, the life of the landless shepherd did not appeal to the new generation. Through a series of measures initiated in 1880, forest grazing was continually reduced; and by the year 1940 almost all free-range goat grazing was eliminated from the mountain forests, through methods that generally met the consent of the graziers themselves. Today there is controlled goat grazing only on an area of lowland forest (maquis) which is about 5% of the total area of state forests.

To replace free-range grazing, intensive animal husbandry methods with better breeds of animals have been initiated and encouraged by government action. These methods have proved to be rewarding from both economic and social aspects.

Foresty and food production

The process of clearing the forests to produce food crops was intensified as man settled down and became a farmer and as the human population increased. It was only natural that in the long struggle of man to feed himself and survive, production of food would receive top priority. Man thus went on clearing the forests and extending the agricultural land. Notions of ecological balance, soil and water conservation, soil fertility, indirect influences of forests, let alone agroforestry, could not be even dreamt of. There was cut- throat competition between the people's needs for natural ligneous vegetation and for cleared areas suitable for cultivation and food production.

There is bitter evidence in Cyprus that man went too far in his uncompromising fight against the forest. He clear-felled forests and established food crops on steep slopes and other sites that were suited only for forest. The result did not take long to come and is evident today in the extensive areas of hilly land that lie derelict and devoid of

any vegetation, deteriorating through constant erosion and constituting a wasting asset through desertification. Derelict stone terraces and abandoned vineyards are still to be seen, as evidence of irrational human activity. In many such cases the forest is creeping back to occupy its ground.

Today more wisdom has prevailed in land use. Very steep, rocky ground has been left to forestry; and crop production has been restricted to the better soils, mainly in small patches along streams, where irrigation makes crop production feasible. The crops are usually deciduous fruit trees such as apple, pear, plum and peach; with annual field crops such as runner beans and potatoes grown before the canopy of the fruit trees closes. There is generous application of fertilizers. Under these circumstances, ligneous crops are not beneficial to the food crop and the two are not therefore mixed on the same ground.

Many lowland, flat areas where the forest cover has been removed, have been converted today to very productive agricultural land, where water for irrigation is available. Examples of such forest land that is used today exclusively for agriculture are to be found in the Kokkinochoria (Red-Soil Villages) which are the granaries of Cyprus for potato production. These lands are very near to sea level, the climate is very mild and they are ideal for late winter production of potatoes that earn the highest foreign exchange of any agricultural crop of Cyprus. There are two crops of potatoes every year on the same land. The limiting factor to more production is water for irrigation.

All this 'potato land' is leased to farmers by the Forestry Department at nominal rent. The farmers see no place at all for any ligneous production in combination with potatoes. Even where shelter is needed from the blasting effect of the sea, the farmers use mechanical wind barriers, e.g., fences with canes or nets and, rarely, windbreaks of lines of cypress trees. The reason for the mechanical windbreaks is that water and light competition between the trees and the field crops reduce yields considerably.

Forestry and water for agriculture

As was mentioned in the previous section, forests in Cyprus are today restricted to very poor soils on what may be termed absolute forest ground, where agricultural crops (which are more exacting to soil conditions) could not survive. Even so, there exists in Cyprus a very special form of agroforestry practice based on water relations. Through very extensive dam construction, large quantities of rain water are collected from forest areas and stored in reservoirs. This water is transported over considerable distances – as far as 120 km in the case of the Red-Soil Villages mentioned in the previous section – and used very profitably for the irrigation of agricultural crops.

Though in this case the forests and the agricultural crops are not on the same ground but hundreds of kilometers apart, there can be no doubt about their interrelation and about the importance of this system of agroforestry (which could perhaps be termed teleagroforestry). It can even be said that this system possesses advantages over the system of trying to grow both ligneous and agricultural crops simultaneously on the same ground.

Forestry and agricultural protection

The essence of this system of agroforestry is that forest trees are used to provide protection to agricultural crops.

Shelterbelts

The small size and wide distribution of rural holdings in Cyprus is a limiting factor to the establishment of shelterbelts. There are no large continuous holdings of agricultural land; practically all households in the rural community own a share of the land. The average size of holding is 3.8 ha, but varies according to region from 1.3 to 6.3 ha. Each holding is scattered in many small areas around the village. It is obvious that under these conditions the establishment of shelterbelts is not easy.

It can however be said that the existence of large continuous stretches of State Forests on the upper catchments of practically all the watersheds in Cyprus provides a huge continuous shelterbelt that affords protection to agricultural lands lower down in the watershed and especially to the land in the neighbouring foothills. The protection consists in the amelioration of the microclimate; by the reduction of extremes in low and high temperatures; the protective effect on plants and animals from the cold winds and the frost of winter; and the protection against soil erosion through the action of water that would come down the steep slopes dangerously had they not been clothed with the forest vegetation.

Windbreaks

The use of windbreaks to afford protection to agricultural crops is very common in certain parts of Cyprus. Their use is more frequent in western Cyprus, to protect crops from the cold spring winds during the flowering season, from the strong westerly winds throughout the year and from the blasting effect of the sea.

The trees most commonly used as wind breaks are cypress (*Cupressus sempervirens*), various species of eucalyptus, casuarina, tamarix, the wattle tree (*Acacia cyanophylla*) and, to a lesser degree, pines. The planting is usually done in two rows along the boundary of the holding and the trees are staggered in the two rows. The planting distance between the trees varies from 0.5 to 2.0 m depending on species and on the degree of protection required.

The most conspicuous examples of the use of such windbreaks are:

1. Extensive lines of cypress in the Limassol area to protect citrus groves from the effects of the sea winds;
2. Lines of poplars along irrigation channels in the mountain villages;
3. The relatively young windbreaks of tamarix in the areas of Argaka and Yialia, which make possible the establishment of banana plantations right on the sea shore; and
4. The cypress windbreaks that are being established at a very fast rate in the south coastal areas of Paphos, to shelter the plantations that are coming up in the newly irrigated areas of a big irrigation project.

Ligneous crop trees with annuals

The growing together in the same field of ligneous crop trees with annual crops is one of the oldest forms of agroforestry practised in Cyprus. Carob (*Ceratonia siliqua*) and olive (*Olea europea*) trees are indigenous to Cyprus and they grow naturally almost everywhere from sea level to about 1200 m asl. The fruit of these trees has been harvested and utilised in Cyprus since time immemorial. The carob fruit was known as the black gold of Cyprus as late as the 1940s, due to the significant foreign exchange

that was earned from its export; whilst olives and olive oil constitute a basic diet of a large majority of the population.

It was only natural that many farmers would utilize the crop from those trees that grew naturally on their land. In the same way they utilized the annual growth of grasses and other plants for the grazing of their animals – mainly sheep and goats. With the advent of agriculture and the evolution of cultivated varieties of annuals such as wheat, barley, oats, various vetches, etc., it was again natural for the Cypriot farmer to try to obtain the benefit of two or more crops on the same field, i.e. the fruit of the carob and/or the olive and a cereal or leguminous crop which he sowed annually. The latter crops are harvested as grain, or used as green fodder for grazing or for cutting and transporting to animals in the pen. In years of abundance, green fodder is also dried and used as hay.

After the harvest, a third 'crop' is left in the field: the stubble, which provides good grazing material in late summer and early autumn when little other forage is available.

A fourth crop, of a much longer rotation, are the woody parts of the trees obtained through pruning or, rarely, through the felling of overmature or dead trees. They are top quality wood and fetch prices as high as CY40 per ton, for use as luxury fuel for heating in open hearths in urban households, or for charcoal manufacture. This system of multiple agroforestry is very advantageous as it secures at least a basic subsistence income to the farmer under the unstable and often adverse climatic conditions of Cyprus, where droughts very frequently bring about complete failure of the annual crops of cereals and legumes. The revenue from the tree crops is not affected much by the annual whims of climate, and has a buffering effect on the farmer's income, which helps him go through adverse years.

A very intensive and very productive system of this form of agroforestry is practised when there is water available for irrigation. The extensive use of fertilizers also brings about increased production under this system. However, when water is available, the tree used is no longer carob and olive but mainly citrus, which is more profitable. Also the undercrops, if they exist at all, are not cereals and legumes for animal food, but strawberries, peanuts, beans, carrots and other vegetables that bring in high cash returns to the farmer.

Trees for shade

Summer temperatures in the flat, fertile plains of Cyprus may rise as high as 40 °C during the hot dry season from June through August. Under such conditions, the presence of trees with a large, dense canopy to provide shade for the farmer and his animals becomes invaluable. It is thus a very common phenomenon in Cyprus to see large isolated trees on agricultural and grazing lands. These trees and their surroundings are very lonesome and isolated during the cold season; but their shade makes them an oasis during the hot season, when man and animal seek refuge beneath their branches to find shelter from the scorching heat of the overhead sun.

The traditional trees used for shade are carob, mulberry (*Morus alba*), Persian lilac (*Melia azedarach*), oak (*Quercus lusitanica*) eucalyptus of various species, wattle (*Acacia cyanophylla*), pines and fig trees (*Ficus carica*).

Conclusions

Various forms of agroforestry have been practised in Cyprus since time immemorial and many of them continue to be practised to the present day. Agroforestry was culturally, socially and economically imperative for the well-being of the rural household in that it provided a good variety of products on the limited land of the farmer, that made the family essentially self-sustained. Under the unpredictable and most frequently adverse (to annual crops) climatic conditions of Cyprus, this variety of crops was also of great significance in that it provided a buffering effect to the household budget and averted starvation in cases of failure of one or other of the crops.

Under such conditions, economic analysis, cost-benefit ratios and alternate rates of return from the land did not come in. Hence no serious attempt has ever been made to evaluate the interrelations between ligneous plants and other associated plant or animal production on the same land.

In Cyprus there has been a gradual reduction in the practice of agroforestry in favour of intensive monocultural practices. This has come about as a result of a combination of factors, as follows:

1. Increased income and rising standards of living in rural areas enabled the farmer to become a partner of the nationwide economy, in contrast to the self-sustained household economy of his father. His purchasing power has increased and what he does not grow he can purchase. Under such conditions he finds monocultures easier.
2. The increasing use of water for irrigation stimulated intensive monoculture practices with non-ligneous crops of high cash-earning value.
3. Under rain-fed conditions, short-rotation crops (annuals) lost their value due to climatic adversities, in favour of the ligneous, longer rotation crops, resulting in ligneous monocultures.
4. High wages for manual work necessitated mechanization in agricultural operations and this favoured monocultures.
5. Consolidation of the small scattered holdings in many communities also favoured monocultures.
6. The easy availability and increased use of fertilizers reduced the importance of crop variety in maintaining soil productivity and favoured monocultures.
7. Lack of quantitative data and information on the values of agroforestry also favoured monocultures.

Research and education on agroforestry are necessary in order to establish its value as an economic and ecological land use practice, especially in countries with sensitive agronomic conditions and adverse climatic patterns.

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Water-harvesting based agroforestry in the arid regions of Israel

H. Lovenstein

Desert Run-off Farms Unit
Jacob Blaustein Institute for Desert Research
Ben Gurion University of the Negev
Sede Bager Campus 84993, Israel

Y. Zohar

Department of Natural Resources (Forestry Section)
Agricultural Research Organization
The Volcani Center
P.O. Box 6, Bet Dagan 50250, Israel

J. Aronson

Boyko Institute for Agriculture and Applied Biology
The Institutes for Applied Research
Ben Gurion University of the Negev
Be'er Sheva 84110, Israel

Abstract

A long-term project was initiated to develop sustainable agroecosystems for the production of food, fodder and firewood under rainfall-harvesting conditions in an arid region. The study is conducted in the Negev desert at the experimental sites of the Desert Run-off Farms Unit in Wadi Mashash and Avdat, where the mean annual rainfall amounts to only 115 and 80 mm, respectively.

Relying entirely on run-off water, research is carried out along the following lines:-

- *Plant introduction, with particular emphasis on* Prosopis, Eucalyptus, Acacia *and* Atriplex spp.
- *developing appropriate cropping systems based on the agroforestry concept, whereby the following aspects will be monitored in relation to water use efficiency.*
  - *combinations of trees, shrubs and annuals*
  - *plant densities*
  - *optimum coppicing cycles*
  - *fertilization at planting*
  - *animal studies.*

Introduction

For nearly thirty years, the Desert Run-off Farms Unit of the Ben Gurion University of the Negev and the Hebrew University of Jerusalem have studied methods to recreate and improve the rainfall harvesting methods developed 2400 to 1500 years ago. These studies have been carried out at experimental sites in Shivta and Avdat (mean annual rainfall 80 mm), located 70 km respectively south-west and south of Be'er Sheva (Evenari et al. 1982).

Based on obtained results a pilot farm was established in the early 1970s at Wadi Mashash (mean annual rainfall 115 mm, located 20 km south of Be'er Sheva, 31° 08'N, 34° 53' E, elevation 400 m asl, 60 km from the Mediterranean. All three locations are characterized by Köppen climate BWhs and BShs (winter rainfall in hot deserts, hot steppes) and by Thornthwaite moisture index, 40 - 60.

Starting with the successful cultivation of a wide variety of orchard and field crops, a major effort is now under way to develop new crops, cropping systems and applications of water-harvesting techniques, with particular emphasis on the needs and problems of people inhabiting the arid and semi-arid regions of the world. With water as key factor a well-defined relationship needs to be established between **water supply** – the water-harvesting system, and **water use** – the management of various intensified agrosystems to achieve maximum biomass production per unit of time, area and water.

Water harvesting

Farming based on rain-water harvesting is a system which allows agricultural activity in areas that normally do not receive enough rainfall, by concentrating rainfall-induced runoff from a catchment area into a smaller cultivated area. When rain intensity exceeds the infiltration rate of the soil, water is not absorbed by the soil and hence runs off along the surface to the low-lying parts. A catchment area is therefore characterized by sloping surfaces with low infiltration rates. The cultivated area, however, often comprises a similar soil type and earthen walls need to be erected to retain the accumulated run-off water, allowing for deep infiltration. This requires deep soils with a high water-holding capacity, storing enough water to support plant production during the dry season.

Based on this principle, various water-harvesting systems are in use, such as:

- terraced wadis (dry river beds, carrying water during high- intensity rains), sometimes constructed with conduit channels, tapping runoff water efficiently from adjacent hill slopes;
- diversion systems, where erratic flash floods in wadis are partly diverted to adjacent fields using diversion channels;
- macro-catchment basins ('limanim'), where runoff is collected from tributaries and artificially trapped in natural depressions with areas ranging from 0.3 ha to 0.5 ha; and
- micro-catchments, where runoff from a relatively small catchment area is harvested for the support of single trees.

Relying entirely on locally available materials, research is carried out to obtain higher run-off efficiency rates as well as to design water-harvesting schemes with a minimum amount of maintenance and repair.

Plant introduction

Plants, mainly those native to arid lands, are screened for their potential for production of food, fodder and firewood, the three most pressing needs in arid and semi-arid regions of many developing countries. The criteria for selection include: capacity for rapid growth; reliable regrowth after harvesting by coppicing (in the case of fodder trees and shrubs); acceptability as food and/or fodder, especially under current conditions; and finally, ecological adaptability to prolonged droughts, and brief, intermittent periods of flooding in the catchment basins. Most promising species are *Prosopis spp.* and *Acacia salicina* for fodder and firewood; *Eucalyptus occidentalis* and *E. camaldulensis* for firewood; *Leucaena leucocephala* for food, fodder, firewood and timber; *Atriplex barclayana, A. nummularia* and *Cassia sturtii* for fodder; and *Phaseolus acutifolius* (-tepary bean) as food crop.

Cropping systems

Once promising plant candidates are identified, more agronomical studies are carried out. Based on the agroforestry concept various combinations of trees, shrubs and annuals are established in various densities to assess overall biomass production in relation to water use. Deep-rooting trees may exploit the deeply infiltrated runoff water, while annuals extract water from the shallow soil layers. As different plant species show different demands of water at different seasons over the year, a temporal and spatial arrangement is thus created in water uptake. Furthermore, trees, because of their solar radiation-intensity-reducing and wind-breaking properties, can create favourable growth conditions for various under crops. For this purpose *E. occidentalis* and *A. salicina* are grown separately or mixed with sorghum and chickpea in different densities. Soil moisture depletion from the various soil layers is recorded through a comprehensive network of neutron access tubes, and water use by the different plant species is calculated. These are related to biomass production and plant development stage. Finally a crop simulation model will be assessed.

The above-mentioned trees are also tested for optimum coppicing cycles of 2, 3 and 4 years (Zohar 1974) under different plant densities of 600-1200 trees/ha. Depending on the regeneration capacity of the coppice shoots, an optimum harvesting management scheme can thus be determined (Zohar et al. 1986).

Additional experiments involve initial fertilizer application during planting to boost yield and soil tillage.

Animal studies

Animals such as sheep, goats and camels are integrated with these cropping systems. Grazing trials are performed to check fodder quality of different plants, fodder quantity uptake, timing of fodder application, and grazing conditions in relation to food conversion rates.

Conclusion

With a more concentrated water supply, management practices can be more intensified, creating possibilities for the development of agroforestry in arid and semi-arid lands.

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Meteorology applied to agroforestry systems in the Brazilian Amazon region

T. Deane de Abreu Sa Diniz

EMPRAPA-CPATU C.P. 48
CEP 66240 Belem, Para, Brazil

Abstract

Although there is growing interest in Brazilian Amazon region towards the adoption (mainly in upland; unflooded 'terra firme' area, once covered by tropical rainforest) of agroforestry systems, since those represent a promising option from the economical, ecological as well as social view point, the need for intensifying research in several disciplines, including agrometeorology, in order to reduce the risks on this kind of enterprise is evident. This paper aims to contribute towards the orientation of research on this subject, by presenting:

a) general characterization of the area;
b) main agroforestry systems presently practised;
c) presently available agrometeorological information and
d) research priorities on meteorology applied to agroforestry.

Introduction

Although agroforestry systems are commonly and successfully practiced in native communities in the Brazilian Amazon (Peck III 1979; Dubois 1982), this type of land occupation was not motivated by the early settlement projects planned for this region. This was due to the short term interests of these projects and the scarcity of experimental results for this type of agricultural exploitation. In recent years, however, there has been a growing interest among different categories of Amazonian agricultural professionals (researchers, planners and growers) in the assessment, refinement and adoption of agroforestry systems. This sudden popularity is due to several factors:

1. The low yield obtained in crop as well as animal husbandry projects established on Oxisols and Ultisols previously covered by rainforest, with the adoption of traditional crop and grazing management systems;
2. The recognition of the economic ecological and social advantages of agroforestry systems as compared with others, especially for humid tropical area of underdeveloped or developed countries with chemically poor soils (Peck III 1979; Dubois 1979a, 1979b; Alvim 1981; Combe 1982; Brienza Junior 1982a; Kitamura 1982; NAS 1982; Fearnside 1983);
3. The awareness of the increasing rate of deforestation occurring notably in some of the most recent regional agricultural frontiers, such as Rondonia State (Fearnside 1982, 1985; Buschbacher 1986);

4. The concern about the widespread ecological disturbances expected to be caused by forest removal, especially modifications in the water environment interactions in macro- as well as in micro-scales (Molion 1975; Salati 1983, 1985; Henderson-Sellers 1985);
5. The observed efficiency of some agroforestry systems in controlling pests, diseases and weeds, all of which represent serious constraints for traditional monocropping as well as multiple cropping in this region;
6. The more efficient use, by agroforestry systems, of solar energy which is predominantly available in diffuse form in this region.

The intensification of interdisciplinary agroforestry research is essential in order to support the expansion of this activity in the region. There is an urgent need for a careful survey so that suitable systems can be assessed for the different combinations of climate and soil found there, since the complex interactions among the distinct plant species which are part of these systems exhibit a local pattern which makes it difficult to extrapolate results obtained in isolated studies carried out in other regions.

Agrometeorology is one of the research areas deserving more intensive consideration in order to allow more efficient planning and management of agroforestry systems both because of its role in helping to find solutions for agroforestry questions and the incipient knowledge of the spatial and temporal distribution of many important meteorological variables; the little information on the climatic requirements of most of the native and some of the introduced crops, woody plants and pastures adopted in the region, and their various pests and diseases; and the almost complete non- existence of a micrometeorological characterization of these systems as compared with other systems of land use and to original vegetation conditions.

The aim of this paper is to provide a basis for the discussion and proposal of guidelines for the application of meteorology to agroforestry in the complex region of the Brazilian Amazon. It presents:

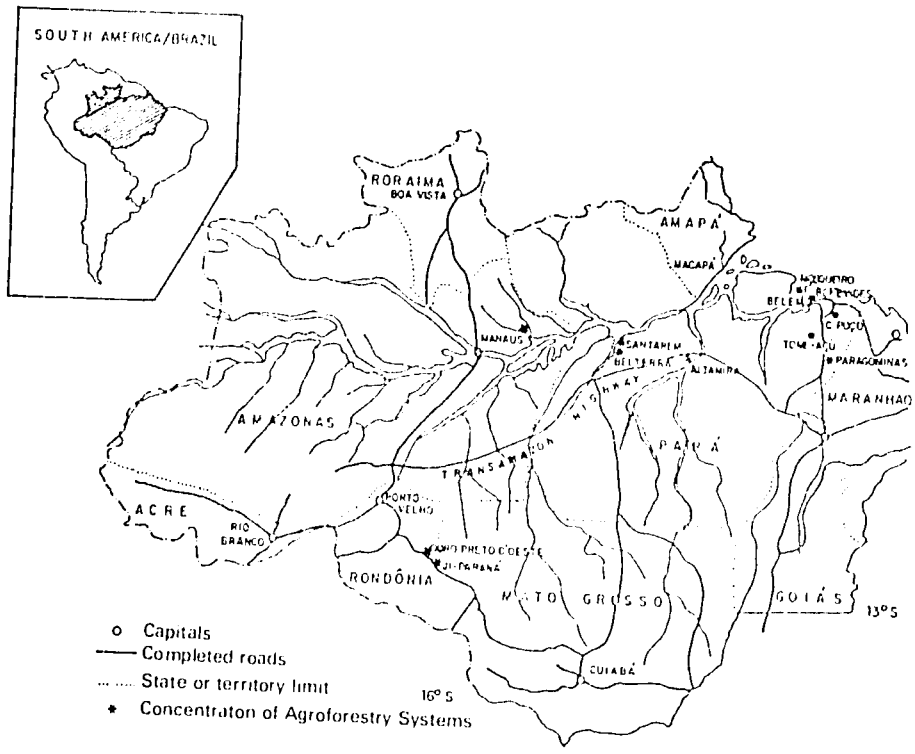
- A general characterization of the area
- The principal agroforestry systems now practiced
- Agrometeorological information at present available
- The main research priorities for meteorology as applied to agroforestry

Characterization of the area

Geographical situation

The Brazilian Amazon region referred to in this paper is the so-called Legal Amazon Region which covers approximately 5,145,000 km^2, corresponding to nearly 60% of the Brazilian territory and includes the whole of the states of Acre, Rondonia, Amazonas, Para, and Mato Grosso and the Federal Territories of Amapa and Roraima, and part of the states of Goias (north of 13° S latitude) and Maranhao (west of 44° W longitude) (Fig. 1).

Figure 1 Localization map of Brazilian Amazon with indication of areas of agroforestry sustems concentration.



Climate

The most significant spatial climatic differences found in this region are due to rainfall. In a broad sense, the average annual rainfall ranges from 1,500 mm to 3,500 mm (SUDAM 1984), and has a bimodal distribution. The main rainy period is from December to May. The second period with lower rainfall (but greater variability), is from July to November. The northern portion of the federal territory of Roraima (located in the northern hemisphere) has a rainy season from April to August (Bastos et al. 1984).

The thermic conditions of the region are characterized by the occurrence of large diurnal fluctuations and insignificant annual fluctuations. The average annual mean temperature ranges from 22 °C to 24 °C and the average annual maximum and minimum temperatures range, respectively, from 28 °C to 32 °C and from 17 °C to 23 °C (Bastos et al. 1984).

The spatial distribution of sunshine duration shows annual averages ranging between 1,400 hours and 2,500 hours, while present information on the global solar radiation distribution suggests annual average values between 8.4 MJ m^{-2} day^{-1} and 10.2 MJ m^{-2} day^{-1} and monthly average values between 7.2 MJ m^{-2} day^{-1} and 12.6 MJ m^{-2} day^{-1} (Bastos et al 1984).

Physiography and soils

The Amazon region is divided into two main physiographic sections i.e. the Amazon *plateau* and the alluvial flood plain. Other physiographic units also exist but in a much smaller proportion in higher altitudes (Silva et al. 1984).

On the *plateau*, which constitutes the Amazonian *terra firme*, Oxisols predominate, with smaller proportions of Utisols and Alfisols. The Oxisols and the Ultisols exhibit chemical and nutritional constraints and, as well as the Alfisols, have a low water-holding capacity (Lal 1987).

In the flood plain the main feature is the varzea of the Amazon river and its tributaries, where most of the soils have medium to high fertility although exhibiting constraints due to imperfect drainage and the risk of flooding (Silva et al. 1984).

In a broad sense, the evaluation of Amazonian land suitability shows approximately 72% of land suitable for all kinds of agricultural activity; 15% suitable only for forestry and animal husbandry activities; and 13% exhibiting serious limitations for any agricultural purpose

Vegetation

The original vegetation covering the Brazilian Amazon region was predominantly dense rain forest (49%); open rain forest (27%); and lowland natural grassland (7%) (Silva et al. 1984).

Agrometeorological information — present situation

At the present time agrometeorological studies designed specifically for agroforestry systems are almost non-existent for this region. However, much of the available agrometeorological information, if properly manipulated, can be useful for agroforestry purposes. The knowledge gained over the last ten years about the distribution patterns of meteorological variables, such as rainfall, solar radiation and wind, can at least guide the selection of suitable areas for different agricultural activities.

The bioclimatic requirements and phenological behaviour of the species that have been adopted in agroforestry systems are largely unknown since most of these species, especially perennial crops and woody plants, are of recent introduction. Present knowledge of the bioclimatic requirements of most of the tree species adopted in these systems is limited to the superficial evaluation of the climatic conditions in the natural range of a small number of species (Golfari et al. 1978). The same is true for most of the industrial perennial crops as well as for regional fruit crops (Falcao 1979; Ortolani et al. 1982; Diniz et al. 1984).

Micrometeorological studies have only recently begun in this region and have been carried out in areas of natural rain forest (Leopoldo et al. 1984; Shuttleworth et al. 1984, 1985). A study is currently being carried out in rubber-tree stands (O.M.R. Cabral, personal communication). Concerning the pests and diseases that affect agroforestry in the region as related to weather and climatic conditions, the most significant progress has been achieved with rubber-tree and cocoa crops.

Main agroforestry systems now practiced

In the region there are several types of agroforestry systems involving a high percentage of native species. These systems are planted in experimental and/or producer areas located mainly in the states of Amazonas, Rondonia and Para (Fig. 1; Tables 1 and 2) where distinct climatic conditions exist, particularly from the hydric view point (Table 3). Within the region, however, the most important concentration of plant combinations classed as agroforestry systems is found in the agricultural colony located in Tome-Acu, state of Para (Table 1), where systems have been adopted starting with the planting of medium cycle crops (papaya, banana, passion-fruit and black pepper) in association with annual species in intercropping (cowpea, rice, watermelon, melon and pumpkin). These systems then become bi-stratified agroforestry systems (such as cocoa vs. forestry species) through the introduction of long-cycle species (cocoa, coffee, guarana, rubber-trees, freijo and andiroba as well as many other forestry or fruit species) (Yared and Veiga 1985).

In this region, predominantly settled by Japanese immigrants and their descendants, the adoption of this kind of system is consequence of the search for new alternatives to overcome disease control and market constraints (Yared and Veiga 1985). The most widely used systems in this region are black pepper/cocoa and passion fruit/cocoa. In the former, black pepper is planted first, followed by cocoa three to four years later (Taketa 1982).

Among the systems which include forestry species the most widespread is black pepper/freijo following a variable spatial and sequential pattern which reflects the evolution they undergo (Yared and Veiga 1985).

In Capitao-Poco, Altamira and Prainha, in the state of Para (Table 1), double systems associating shading crops (Brazil nuts, rubber tree) and shaded crops (black pepper, cocoa and guarana) are grown at an experimental level. Other experiments are: a rubber-tree vs. black-pepper combination carried out in a producer area located on Mosqueiro Island, Para (Viegas 1982); the cultivation of corn followed by cowpea intercropped in oil palm rows in Capitao-Poco (Stolberg-Wernigerode 1983); Guarana crop associated with other economically viable crops carried out in Manaus, Amazonas (Canto 1982) where there are also systems such as regional perennial fruit crops planted after a sequence of short-cycle staple crops; and systems associating shading plants and cocoa planted by CEPLAC in many parts of the region (Silva and Santos 1982).

In the Tapajos region, Santarem county, state of Para, there is a notable use of forestry species (freijo, mahogany, andiroba and urua) in systems which include food crops (maize, cassava and banana) (Brienza Junior et al. 1983).

As far as silvopastoral and agrosilvopastoral systems are concerned there are some impressive experiences such as: the planting of Pinus caribaea in pasture areas covered by 'coloniao' (green pannic) and Amazon quicuio carried out at the level of a large enterprise, in Monte Dourado, Almerim county, Para (Lins 1982; Brienza Junior 1982); the combination of pastures for cattle husbandry in a rubber-tree plantation located at Benevides, Para (Dubois 1979b); and the association of forest species, pastures and short cycle crops that is being studied in Paragominas, Para (Marques et al. 1985).

Table 1 Presentation of species found in the concentration areas of agroforestry systems in the Brazilian Amazon.

Annual Crops								Forestry species									Pasture						Fruit Crops													Shade species	Perennial and semi-perennial/indust. species														Location	Source of reference
Cowpea	Soybean	Rice	Beans	Pumkin	Melon	Watermelon	Cassava	Corn	Sweet potato	Andiroba	Cedro	Freijo	Mahogany	Marfim	Pau-d'arco	Tarumanha	Ucuba	Faveira	Pinus	Eucalyptus	Tatajuba	Guandu	Quicuio	Desmodium	Andropogon	Pueraria	Centrosema	Colonião	Malapi	Jaca	Pupunha	Avocado	Biriba	Banana	Bacuri	Cupuaçu	Graviola	Orange	Limon	Passion fruit	Papaya	Bread fruit	Erythrina	Gliricidia	Açai	Cocoa	Coffee	Sugar-cane	Castanha do B	Coconut	Guarana	Black Pepper	Rubber-tree	Oil palm	Cotton	Cashew nuts		
•	•	•	•	•	•	•		•	•	•	•	•	•	•																	•		•	•	•	•	•	•	•	•	•	•		•	•	•	•	•	•	•	•	•		Tomé-Açu	Stohlberg-Wermegerode & Flohrschütz 1982, Brienza Jun. 1982b, Dubois, 1979, Takeda 1982
•		•					•	•				•																						•											•			•	•	•							Capitão-Poço	Brienza Jun. 1982b, Stohlberg Wermegerode, 1983, Frazão et al. 1982
																																													•											Belterra	Brienza Jun. 1982
•												•											•	•	•	•																				•											Manaus	Brienza Jun. 1982b, Cunto 1982, Arkoll 1982, Silva & Santos 1982
•			•				•	•	•			•							•			•	•						•	•	•		•	•			•			•	•	•					•			•							Altamira	Andrade s.d., Andrade et al. 1982, Frazão et al. 1982, Parva 1985
		•					•	•	•	•	•	•			•	•																		•																							Santarem	Brienza Jun. 1982b, Brienza Jun. et al. 1983
																							•																														•				Benevides	Dubois, s.d.
																				•			•				•																														Almeirim	Brienza Jun. 1982, Lins 1982
•							•								•						•	•	•	•	•		•																													Paragominas	Marques et al. 1985
																																													•						•	•				Prainha	Andrade s.d.
																																																			•	•				Mosqueiro	Viégas, 1982
																																													•			•								Cametá	Silva & Santos, 1982
			•	•			•	•									•						•											•								•		•	•							•				Rondônia (Ariquemes-Ji-Paraná, Cacoal e Ouro Preto)	Peck III, 1979, Silva & Santos, 1982

Table 2 List of vulgar and scientific names of the species found in agroforestry systems located in the Brazilian Amazon.

Vulgar Name	Scientific Name
Avocado	*Persea americana*
Acai	*Euterpe oleracea*
Cotton	*Gossypium herbaceum*
Andiroba	*Carapa guianensis*
Andropogon	*Andropogon gayanus*
Rice	*Oryza sativa*
Bacuri	*Platonia insignis*
Banana	*Musa paradisiaca*
Sweet potato	*Ipomoea batatas*
Biriba	*Rollinia mucosa*
Cocoa	*Theobroma cacao*
Coffee	*Coffea arabica*
Cashew nut	*Anacardium occidentalis*
Sugar cane	*Saccharum officinarum*
Brazil nut	*Bertholletia excelsa*
Cowpea	*Vigna unguiculata*
Cedro	*Cedrela odorata*
Centrosema	*Centrosema pubescens*
Coconut	*Cocos nucifera*
Coloniao	*Panicum maximum*
Cupuacu	*Theobroma grandiflorum*
Oil Palm	*Elaeis guineensis*
Desmodium	*Desmodium ovalifolium*
Erythrina	*Erythrina spp.*
Eucalyptus	*Eucalyptus tereticornis*
Faveira	*Parkia sp.*
Beans	*Phaseolus vulgaris*
Freijo	*Cordia goeldiana*
Bread-Fruit	*Artocarpus atilis*
Gliricidia	*Gliricidia sepium*
Graviola	*Anona muricata*
Guandu	*Cajanus cajan*
Guarana	*Paulinia cupana var. sorbilis*
Jaca	*Artocarpus integrifolia*
Pumpkin Orange	*Cucurbita maxima*
Lemon	*Citrus sinensis*
Macacauba	*Citrus limon*
Papaya	*Platymiscium sp.*
Cassava	*Carica papaya*
Passion fruit	*Manihot utilissima*
Watermelon	*Passiflora edulis*
Melon	*Citrullus vulgaris*
Corn	*Cucumis melo*
Mahogany	*Zea mays*
Matapi	*Swietenia macrophylla*
Parica	*Schizolobium amazonicum*
Pau-d'arco	*Tabebuia serratifolia*
Black pepper	*Piper nigrum*
Pinus	*Pinus caribaea*
Pueraria	*Pueraria phaseoloides*
Pupunha	*Guilielma gasipaes*
Quicuio	*Brachiaria humidicola*
Soybeam	*Glycine maxima*
Rubber-tree	*Hevea brasiliensis*
Tatajuba	*Bagassa guianensis*
Terminalia	*Terminalia ivorensis*
Urua	*Cordia alliodora*

Table 3 Average values of climatic variables in some agroforestry systems areas in the Brazilian Amazon region

	Manaus, AM						Ouro Preto d'oeste, RO					Tomé-Açu, PA				Altamira, PA					Belterra, PA			
Month	TX	TN	TM	IN	UR	PP	TX	TN	TM	UR	PP	TX	TN	TM	PP	TX	TN	TM	UR	PP	TX	TM	IN	PP
J	30.9	22.4	25.5	130.2	86	232	29.7	21.7	25.3	88	290	32.6	22.3	25.8	323	29.9	22.4	25.2	85	310	29.9	25.1	143.7	214
F	30.6	22.4	25.4	106.8	87	273	29.4	21.6	25.1	88	292	32.0	22.4	25.5	354	29.8	22.3	25.2	87	332	29.4	24.9	114.1	169
M	30.8	22.5	25.4	113.0	87	295	30.0	21.4	25.2	87	250	33.0	22.5	25.5	444	30.5	22.4	25.4	86	341	29.5	24.9	123.4	280
A	31.2	22.5	25.4	119.2	87	296	30.0	21.8	25.2	86	196	32.3	22.8	25.6	376	31.0	22.4	25.7	84	303	29.6	25.0	145.1	258
M	31.1	22.3	25.5	150.4	87	268	29.6	20.3	24.5	84	97	32.7	22.7	25.6	247	31.3	22.4	25.8	83	167	29.6	24.8	195.2	237
J	30.9	21.8	25.3	152.8	85	150	29.1	18.8	23.5	83	30	32.6	21.9	25.4	131	31.6	21.6	25.8	81	100	29.9	24.6	234.8	126
J	31.3	21.3	25.4	216.8	82	128	30.6	17.5	23.6	76	4	32.6	21.4	25.4	109	32.1	21.2	25.7	78	53	30.1	24.5	261.9	87
A	32.6	21.4	25.8	228.7	80	104	32.2	18.8	25.0	73	43	33.0	21.2	26.2	64	32.2	21.5	26.0	77	34	31.0	25.0	268.0	54
S	33.0	22.0	26.3	205.0	80	102	31.7	20.2	25.6	76	100	33.3	21.4	26.7	58	32.7	22.0	26.5	76	29	31.7	25.6	236.6	39
O	32.8	22.3	26.4	187.8	81	164	31.4	21.0	25.8	80	176	33.6	21.7	27.0	56	32.5	22.7	26.6	75	44	32.1	26.0	245.2	42
N	30.3	22.7	26.4	169.3	82	150	32.1	21.6	25.8	84	225	33.7	22.0	26.9	97	32.1	22.7	26.5	75	66	32.2	26.0	220.4	79
D	31.6	22.3	25.7	127.2	85	243	31.3	21.7	25.2	87	259	33.3	22.2	26.5	173	31.4	22.5	26.0	78	136	31.0	25.5	194.5	166
Year	31.4	22.2	25.7	1936.2	84	2405	30.6	20.5	25.0	83	1992	32.9	22.0	26.0	2352	31.4	22.2	25.9	80	1914	30.5	25.2	1375.5	1847

Fonte:
EMBRAPA-UEPAE Manaus (1971/82) — CEPLAC (1976/83) — INATAM (1968/83) — EMBRAPA-UEPAE Altaminra (1974/83 — INEMET (1972/83)

TX = Maximum temperature (°C.)
TN = Minimum Temperature (°C.)
TM = Mean Temperature (°C.)
IN = Sunshine duration (hours and decimals)
UR = Relative Humidity (%)
PP = Rainfall (mm)

Research priorities in meteorology as applied to agroforestry

Considering the small amount of agrometeorological information available to support agroforestry activities in the Brazilian Amazon, the following list of research priorities is recommended:

1. Climatic analysis of the areas for the establishment of present or future agroforestry systems. These studies should include statistical and other approaches suitable for limited-data areas. In this context remote-sensing techniques are becoming important tools for guaranteeing the spatialization of point observations, indispensable for suitability-assessment purposes.
2. Identification of edaphoclimatic requirements of the species used in agroforestry systems. For this purpose there must be interdisciplinary team work in which agrometeorologists work hand- in-hand with pedologists and eco-physiologists to determine the demand for the different components of the systems; and then to allow the planning of combinations of species which make it possible to optimize the use of the environment.
3. Identification of suitable periods for agricultural operations and practices. This topic should also include studies on the identification of periods of fire danger as well as pest and disease risks to aid prevention.
4. Micrometeorological characterization of different agroforestry systems, including micrometeorological monitoring of the heat and momentum fluxes as well as light and rainfall distribution for such heterogeneous systems. These studies will provide useful indications of the choice of plant combinations suitable for different systems; the evaluation of the impact of these systems on the area in regard to the original vegetation or other systems; and the genetic manipulation of the species involved.
5. The use of modelling in agroforestry stands, including the adoption of modelling techniques for the determination of water budget and light distribution within these systems.

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Agroforestry systems for the cerrado region of central Brazil: potentials and constraints

M. Haridasan

Laboratorio de Ecologia, Departamento de Biologia Vegetal
Universidade de Brasilia
C P 153081, Brasilia DF 70919, Brazil

Abstract

The Cerrado region of central Brazil extends over 180 million ha and is characterized by a prolonged dry season which limits agricultural production. Less than 10 million ha were under field crops until recently whereas more than 100 million ha were under cultivated or native pasture. Irrigation is not yet widespread. Besides the long dry season extending from May to September, wet season dry spells, known locally as veranicos, also limit the yields of field crops.

The water storage in the surface layers of the soil is often insufficient to meet the evapotranspiration demand of shallow rooted field crops because of the low waterholding capacity of the latosols and the very deep water tables. Deep well drained latosols which account for about 50% of the Cerrado region also present very severe limitations of aluminium toxicity, phosphorus deficiency and low base saturation. Soil erosion is a severe problem in most areas because of soil compaction and reduced infiltration rates resulting from the use of heavy machinery and overgrazing.

Agroforestry is not yet a common practice in the region whereas extensive areas are utilized for eucalyptus and pine plantations. The potentials for agroforestry systems in the Cerrado region are discussed in the present paper. Well-planned agroforestry systems in central Brazil should minimize the risks of

(1) economic losses due to dry season crop failures,
(2) degradation of pastures due to overgrazing,
(3) soil erosion and
(4) unemployment and/or underemployment of family labour, especially in case of unskilled rural families.

Introduction

The cerrado region of central Brazil extends over more than 180 million ha, accounting for nearly one-fifth of the total area of the nation. The region is heterogeneous in terms of potential for agriculture, pasture management, silviculture and agroforestry systems but is often considered to be a savanna-type ecosystem. It is interesting that the development of the Amazon region of Brazil and the possible consequences of destruction of the native vegetation of evergreen tropical humid forests there are being discussed at national and international levels with great alarm whereas the destruction

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of the equally fragile ecosystems of the cerrado region continues without ample discussions on viable alternatives of safe management of natural resources like soil and native vegetation (Alvim and Silva 1979; Goodland and Irwin 1975).

Intensive agriculture in many parts of the cerrados is a very recent phenomenon. Since the region of cerrados is not an administrative unit, it is very difficult to obtain statistics of economics, population growth, agricultural production and productivity for the region as a whole. Any generalization of policy recommendations is also difficult because of the enormous size, variations in climate, soils, vegetation and geomorphology, and uneven pattern of population growth. However, in the present paper I shall examine the possibility of agroforestry management in the region in very general terms.

Natural resouces of the region

Climate

The cerrado region may be divided into five principal subregions on the basis of climatic variations (Azevedo and Caser 1979):

1. The central (core) subregion with an annual precipitation of 1400- 1700 mm and a dry period of 4-5 months,
2. The north-eastern subregion with an annual precipitation of 500- 800 mm and a dry period of 8-9 months,
3. The north-western subregion with an annual precipitation of 2000- 2300 mm and a dry period of 3-5 months,
4. The south-eastern subregion with an annual precipitation of 1400- 1700 mm and a dry period of 4-5 months, and
5. The south-western subregion with an annual precipitation of 1100- 1400 mm and a dry period of 2-3 months.

Subregions 4 and 5 occupy relatively very little area. Azevedo and Caser (1979) subdivide these subregions into forty smaller geographical units on the basis of geomorphological characteristics. Detailed data on rainfall, temperature, evapotranspiration and radiation can be found in Hargreaves (1976) and Golfari et al. (1978). Johnson (1982) and Reddy and Amorim (1984) discuss the paucity of climatic data for the region and suggest modifications for calculations of potential evapotranspiration and radiation for the region, taking into account altitude, latitude and longitude for the different stations. Further refinements of the models can be achieved only when more careful measurements are available for longer periods.

Probably the least variable component is the average monthly temperature which oscillates around 20 °C in the core region. Maximum temperature oscillates around 27 °C and minimum around 16 °C. Day length and radiation are not limiting factors for plant growth during any time of the year. For example, mean monthly values of solar radiation is always above 15 MJ $m^{-2}d^{-1}$ in Brasilia with maximum values exceeding 18.5 MJ $m^{-2}d^{-1}$.

The most limiting factors for agricultural production are the variations and uncertainties in the rainfall distribution. Wolf (1977) discusses the occurrence of dry spells during the rainy season in Brasilia. These wet season dry spells, known locally as 'veranicos', may last over three weeks once in seven years. There is a 50% chance that the longest dry spell in any year will be 14 days or longer and a 15% chance that the dry

spell will exceed three weeks. Thus, even if the total rainfall during the season is satisfactory, crop failure due to water stress is a common occurrence in the cerrado region. In shallow rooted crops like soybeans, evapotranspiration may be reduced from a high value of 4 to 5 mm/day during the first week of veranico to 1 to 2 mm/day by the end of the third week, mainly because of low water potentials in the top layers of the soils (EMPBRAPA 1981, p. 64-65). Monthly averages of rainfall do not bring out the variations in precipitation but averages for 10-day periods might be sufficient to indicate periods of water stress (Wolf 1977). Deep rooted cerrado trees and shrubs, however, show no apparent signs of water stress during these dry spells.

Soils

Soils of the cerrado region do not fall into any distinct category as different from soils of other climatic regions of the country. Latosols are the most extensive soils in the cerrado region. These are, as a rule, well-drained very deep soils with a clayey texture and very little horizon differentiation. The most interesting feature of these soils probably is the very fine microaggregate structure of the subsoil (B) horizons, which, *in situ*, present a massive appearance. The microaggregates are very water-stable and make these soils highly permeable. Infiltration rates measured under native vegetation generally exceed 15-20 cm/h. The surface (A) horizon often has a stable granular structure under native vegetation but, devoid of a vegetation cover, is susceptible to compaction and erosion by water. Once the surface layer is eroded, the massive B horizons succumb very easily to formation of very deep U-shaped gullies. Under native vegetation the bulk density of well-drained soils is often less than 1 g cm^{-3} because of very intensive termite activity. Deforestation using heavy machines; and cultivation, as well as grazing by cattle, generally lead to soil compaction and reduced infiltration rates. Also, water retention capacity is reduced because of the destruction of the original highly porous structure.

The water retention capacity of cerrado latosols is very low (Wolf 1977; Lopes 1983; EMBRAPA 1982). This is attributed to the nature of the clays and the microaggregate structure which makes the soils behave as if the texture were more sandy. The very low water retention capacity makes the effect of wet season dry spells very severe. Once the soil becomes unsaturated, hydraulic conductivity of the soil decreases sharply (-EMBRAPA 1981, p. 71-72) and shallow- rooted crops will not have enough water flowing to the root zone from deeper layers with high water content.

Most of the discussions in the literature focus attention on fertility aspects (Lopes and Cox 1977; Goedert 1983) and response of crop plants to fertilizer application and liming. The most serious impediment to root growth in lower layers of the soil profile is probably deficiency of calcium (Ritchey et al. 1980, 1982) since calcium is not translocated to growing root tips if it is not available in the rhizosphere of growing rootlets. However, native shrub and tree species have very deep roots which help them extract water even during the dry season when top layers of the soil profile hold very little water.

Agronomic experiments during the last decade (EMBRAPA 1979, 1981, 1982) have shown that most of the crop plants respond well to liming and fertilizer application in the cerrado soils. However, the economic aspects of liming and fertilizer application do not seem to have received the attention the problem merits.

Also lacking is definite proof in many cases that it is the applied nutrient that is responsible for better growth and higher yields. It is not just one element that is lacking in cerrado soils. Response to liming could be due to higher availability of magnesium (Bataglia et al. 1985); that attributed to phosphorus could also be due to higher availability of calcium from superphosphate. Until we have more information from these

experiments on nutrient uptake by analyzing plant tissues we cannot determine responses involving different nutrient elements. Until then any economic analysis of the fertilizer recommendations will not be very meaningful. For example, at least in the case of two eucalyptus species, soil acidity and high exchangeable aluminium levels do not seem to pose any limitations, if other nutrients like phosphorus, calcium and magnesium are adequate (Haridasan 1985). Managanese and iron toxicities do not seem to pose serious problems in well-drained soils but may become crucial in water-logged soils. Micronutrient deficiencies may have to be corrected in intensive agriculture when high doses of fertilizers and lime are applied. Goedert (1983, p. 424-425) summarizes succinctly the need for basic research in soils and plant physiology to understand better the processes of nutrient uptake and crop growth in these nutrient-deficient soils.

The other classes of soils which occur in the cerrado region include podzolic soils, terra roxa soils, cambisols and waterlogged soils. Since there is no well-defined hierarchy in the Brazilian system of soil classification it is difficult to place these soils in other soil classification systems. Equivalent class names in other systems of classification such as that of Soil Taxonomy and FAO/UNESCO in the case of soils of the Federal District in the core region of the cerrados are indicated in Table 1. One of the main limitations is the lack of definition of criteria for a hierarchical classification. Many surveys utilize native vegetation or slope classes as criteria for subdivision of higher order categories without any definition of the variation in soil properties among different subclasses (Haridasan 1988). There is very little information available on the moisture and temperature regimes of these soils to place them correctly in Soil Taxonomy. In general, most of the well- drained latosols have an Ustic moisture regime.

Native vegetation

The cerrado region comprises of widely varying physiognomic forms of vegetation, which vary from tall closed canopy forests to grasslands devoid of any trees and shrubs. Eiten (1972) provides an excellent review of existing information on these physiognomic forms. The most common of these formations is an open tree and scrub woodland known locally as the cerrado, *sensu stricto*. The question of comparing the cerrado ecosystem(s) with other similar tropical ecosystems, especially the so-called grasslands and savannahs, always involves controversies and myriads of conflicting opinions as to the definition of different physiognomic forms of vegetation (Eiten 1978, 1986). Botanists have often worried about providing details of species composition and phytosociology but very little information is available regarding the adaptability of the cerrado species under different edaphic and climatic conditions. Interestingly, agronomists and soil scientists have seldom participated in this discussion, leaving it entirely to botanists to argue about the adaptive strategies of native plants. The only welcome exceptions were probably the surveys conducted by some British teams (Askew et al. 1970a, 1970b, 1971; Ratter et al. 1977, 1978). Even in their work the only information provided is on variations in physiognomy and species composition of vegetation communities in relation to soil fertility and other edaphic factors such as the occurrence of water table.

The role of climate, edaphic factors such as soil depth, water regime and soil fertility, and fire in the origin and maintenance of the cerrado, *sensu stricto*, is discussed by Eiten (1972). The consensus at the moment is that cerrado, *sensu stricto*, is more a consequence of the dystrophic nature of the soils on which they occur than a consequence of the climate (the long dry period) and intermittent fires which are common in the region.

The cerrado, sensu stricto, occurs exclusively on deep, well- drained dystrophic soils. When the soil becomes shallow as in the case of cambisols on slopping terrain the trees

Table 1 Classification of the soils of the Federal District in the cerrado region of Brazil

Brazilian system	Soil Taxonomy	FAO/UNESCO
Latossolos	Oxisols	Ferralsols
Latossolo Vermelho Escuro	Ustox	Rhodic/Acric Ferralsols
Distrofico	Haplustox/Acrustox	
Eutrofico	Eutrustox	
Latossolo Vermelho Amarelo	Ustox	
Nao concrecionario	Haplustox	
Concrecionario	Acrustox	
Podzolico Vermelho Amarelo	Haplustalfs	
Eutrofico	Oxic Haplustalfs	Luvisols
Distrofico	Oxic Haplustults	Acrisols
Terra Roxa Estruturada Similar	Oxic Haplustults	Nitosols
Litossolos/Cambissolos	Entisols/Inceptisols	Cambisols
Eutrofico		Eutric cambisols
Distrofico		Dystric/Ferralic Cambisols
Areia Quartzosa	Typic Quatrtzipsamments	Ferralic Arenosols
Solos hidromorficos		
Sem plintita	Inceptisols (Aquepts)/Entisols (Tropaquents/Fluvaquents)	Dystric/ humic gleysols
Com plintita	Plinthaquox/Plintaquolt	Plinthic gleysols

and shrubs become sparse to give rise to a more open vegetation form known locally as 'campo sujo'. When the soil is waterlogged permanently or at least during three to four months of the year the vegetation form is a pure grassland, called 'campo limpo'. Tall closed canopy forests occur in different situations such as along streams in valley bottoms (gallery forests), on well-drained mesotrophic soils (semi-deciduous forests), on calcareous soils (deciduous forests), and on dystrophic soils (cerradao). There is no consensus of opinion as to the contribution of edaphic factors in the formation of 'cerradoes' on dystrophic soils alongside more open form of cerrado when both occur on equally poor soils. Ratter et al. (1977, 1978) discuss the species composition of forests on dystrophic and mesotrophic soils. Some species occur only on dystrophic soils; others only on mesotrophic soils. And there are species that are indifferent to soil fertility. Physiological basis of this preference of soils in native species has not been

investigated in any detail yet (Haridasan and Araujo 1987). Goodland (1971b) suggested that cerrado-native species were adapted to high levels of available aluminium in the soil and exhibited sclerophyllous nature not only because of low fertility of the soils but also due to aluminium toxicity. Haridasan (1982) reported that several species of the cerrado vegetation accumulate aluminium in large quantities in their leaves but high levels of aluminium in the leaves of these plants are not associated with low levels of other cations. Besides high levels of aluminium in the soil, what limits plant growth in these soils are the extremely low levels of phosphorus and exchangeable cations, calcium, magnesium and potassium.

Present land use

The more optimistic estimates put the extent of land suitable for intensive mechanized agriculture in the cerrado region to be more than one-third of the total geographic area (Goedert 1983). However, intensive agriculture in many parts of the region is a fairly recent phenomenon. The area under field crops is less than 10 million ha (Table 2). More than twice this area is under cultivated pastures. The area under native pastures is estimated to be nearly 120 million ha which accounts for almost 60% of the total land area of the region. Most of the area cultivated are under monocropping. Crop rotation is common. However, agroforestry or agrisilviculture is not a common practice. Until intensive agriculture with field crops like soybeans, maize, wheat and sorghum was introduced, a common practice was to grow upland rice for two or three years after deforestation and burning and then use the land for pasture.

Table 2 Land use in the cerrado region of Brazil

Use	Area (thousand ha)
Native pastures	119686
Cultivated pastures	20000
Perennial crops and forest plantations	682
Cultivated	8978
Native vegetation	23717
Total	173063

There are only very few systematic, long-term studies reported in the literature on the decline in productivity of the cerrado soils. Research on many aspects of soil management began only about 25 years ago at the Instituto Agronomico de Campinas and later at the Centro de Pesquisa Agropecuaria dos Cerrados in Brasilia (Goedert 1983). It is estimated that less than 10% of the total cultivable area in the cerrado region has mesotrophic soils where soil fertility is not a limiting factor. Most of this land is already under cultivation. Therefore any expansion of area under cultivation would essentially be in dystrophic latosols.

Leite and Furley (1985) who studied one of the settlement colonies of small scale farmers concluded that low productivity of traditional crops was one of the detrimental aspects that caused the project to fall short of its crop and livestock production targets. Evaluating the success of the Sagarana Colonization project which started settling farmers in 1973, these authors reported that the productivity of the traditional crops

such as rice, beans and maize was below the targets established at the beginning of the project and none of the fruit crops like citrus, mango, guava and avocado was ever cultivated. The original assumption was that the farmers would utilize an integrated management system involving liming and fertilizer application and soil conservation measures such as contour planning and terracing. The original target for establishing pastures was also not fulfilled because of the low productivity of the pastures.

One of the most serious land management problems in the cerrados is the degradation of pastures due to overgrazing and low primary productivity of the ground layer due to poor soil fertility. The prolonged dry season adds to the constraints, limiting stocking rates to 0.2 animals ha^{-1}. Once the land has been under native pasture for 15 to 20 years many areas are simply abandoned because it is not economically viable under the present set up to continue to raise beef cattle. Land recuperation in these areas is a very severe challenge because of the impoverishment of the surface layers of the soil not only from overgrazing but also because of soil erosion damage. Invasion of these areas by native species to form a secondary forest vegetation is often a very slow process unlike in small holdings which are abandoned by settlers after deforestation and cultivation for two or three years in the Amazon region (See for example, Leite and Furley 1985).

An important aspect of the land use pattern in Brazil is the size of individual land holdings. Nearly 45% of the total land area in the country is accounted for by individual holdings of more than 1000 ha (Table 3). Another 35% of the area is accounted for by holdings of 100-1000 ha. Only less than 2.5% of the area is owned by individuals who possess fewer than 10 ha though they account for more than 50% of the total number of individual properties.

Table 3 Size of individual land holdings in Brazil in 1980 (IBGE,1980. Censo Agropecuario do Brasil).

Size of holding (ha)	Individual holdings (thousands)	%	Total area Million ha	%
less than 10	2598.0	50.40	9	2.5
10 – 100	2017.0	39.20	64	17.5
100 – 1000	489.0	9.50	127	34.8
1000 – 10000	45.0	0.90	105	28.8
above 10000	2.3	0.04	60	16.4
Total	5151.3	100.04	365	100.0

The population in the cerrado region was estimated to be 15 million in 1970 and nearly 21 million in 1980, with a 3.3% annual growth rate during the last decade (Goedert 1986). More than 60% of this population lived in urban areas in 1980. In the early 1970s less than 50% of the population lived in urban areas. With migration to urban areas increasing while more area is being brought under cultivation, availability of skilled labour for agriculture in rural areas will be scarce in the future. This might increase the need for mechanization and lead to faster deterioration of soil in cultivated land.

The reality is that the big farmers, at least for the present, are not concerned about long term damage that can result from the use of heavy machinery and excessive

quantities of fungicides, pesticides and herbicides. Soil conservation and preservation of natural ecosystems, especially of native plant species that might be of economic use in the future, seem to be only concepts idealized in many federal laws and regulations. Adverse effects of indiscriminate deforestation in the catchment areas of big rivers is always evident in frequent flooding of low-lying areas during the monsoon season on the one hand and the shortage of water in the reservoirs of major hydroelectric projects in the country during the dry season on the other hand.

Potential for agroforestry systems

The most interesting aspect of agroforestry systems is that it was once the essence of subsistence agriculture with very low inputs, especially in the tropics. Intensive monoculture involving mechanization and heavy input of fertilizers and other agrochemicals following the model of temperate zone agriculture is a fairly recent phenomenon, especially in the more extensive oxisols and ultisols. In the case of Brazilian cerrados, it is only in the last several decades that intensive monoculture has been replacing extensive pastures. Some of the peculiarities to be considered with regard to any discussion of possible agroforestry in the region are the following:

1. The very large extent – more than 180 million ha – and the low population density of the region: there is no great pressure on land in the cerrado region as in the more developed southern states of the country or the overpopulated regions of other tropical countries of Asia or Africa.
2. While tropical countries in Asia and Africa have already come to the stage of realizing the adverse effects of overexploiting soil and water resources in intensive monocultures, Brazil is just venturing into intensive monoculture on a large scale in the cerrado region.
3. The emphasis on agriculture in Brazil has not been on self-reliance of the country in food production or on small scale operations by individual families or cooperatives. Export-oriented crops such as coffee, cacao and soybeans have received precedence over other essential crops like wheat because of the necessity of earning foreign exchange.
4. Agriculture in the region is heavily dependent on credit from banks at all stages, including the purchase of products after harvest by the state. This is true of big farmers who own several thousand hectares as well as landless labour receiving new land from the government for the first time in settlement colonies.

What this means is that there is very little change possible in the existing pattern of land use without the government advocating it. At present there is no practice of any agroforestry system worth mentioning in the cerrado region unlike in other regions of the country such as the ones described by Alvim and Nair (1986) in southern Bahia; by Johnson and Nair (1986) in the northeast; and by Baggio (1986) in the south.

I shall therefore discuss the potentials of agroforestry systems in the cerrados with emphasis on overcoming important natural limitations of intensive agriculture in the region.

Reducing economic losses due to dry spells

As mentioned earlier one of the more serious limitations in agriculture and pasture management in the cerrado region is the occurrence of wet-season dry spells which may

last from a few days to more than three weeks. These dry spells cause severe damage to field crops and grasses which have shallow root systems because they occur when evapotranspiration demands are high (Fageria 1980; Espinosa 1979; Garrido et al. 1979). Though there is often sufficient water lower in the profile, surface soil layers have very little water because of low water retention capacity. Tree species are generally capable of utilizing the subsoil moisture unlike the shallow-rooted crops and grasses.

It is only within the last few years that the Federal Government announced plans to implement large-scale irrigation schemes in the cerrado region to increase agricultural production. However, it is unlikely to be a universal practice in the immediate future because of limited water availability. It is estimated at present that the potential for irrigation in the cerrados is only about one million ha. Wet-season dry spells could be very damaging if they coincide with critical growth stages such as flowering. The most serious problem in this regard is the adoption of monocropping systems by the farmers mainly because no alternative systems are known to them. Suitable agroforestry systems should offer some security against total loss of income, especially in the case of small farmers. Selection of suitable perennial crops tolerant to water stress and adapted to low soil fertility and high soil acidity could be one of the useful strategies in this regard. Traditional fruit trees like mango, citrus and guava as well as other native species which could be exploited on a commercial scale should be one of the options. Settlers in new colonization projects with relatively little experience in farming should find this option more secure than risking everything in shallow-rooted field crops.

Besides guaranteeing an alternative source of income, one of the possibilities that should be exploited in agroforestry systems for the cerrado region is minimizing evapotranspiration demand by providing shade or reducing wind velocity.

Since the low water-holding capacity of the cerrado soils is one of the limiting factors contributing to crop failures during wet season dry spells, improving the water retention characteristics of these soils should be one of the aims of better management systems. Long-term crop rotations with fast growing trees species which could increase the organic matter content of these soil should eventually help increase the water holding capacity of these soils and thus minimize the risk of wet-season dry spells.

In spite of the serious lack of fodder in native pastures of the region during the long dry season, very little has been done to utilize alternative sources of forage to supplement the limited grass supply. Silvopastoral combinations involving forage shrubs and trees should be a viable practice in this respect.

Avoiding deterioration of pastures

The main factors contributing to the complete deterioration of pastures within ten to fifteen years are poor soil fertility and overstocking. Any viable alternative to 100% utilization of such lands for animal husbandry on a long-term basis should involve fallowing the land periodically. Fertilizer application and liming are expensive options to increase the productivity of native pastures because the potential response of native grasses to fertilizer application is as yet unknown. In such cases economically viable management systems might incorporate forestry or fruiticulture alternating with animal husbandry. With ten- to fifteen-year cycles, degraded pasture lands might recover organic matter content and nutrient status if fast-growing tree species which would furnish plenty of leaf litter could be utilized. Grass-legumes mixtures are advocated in the cerrado region on the following grounds:

- better productivity per animal per ha per year;
- better reproductive capacity of the animals;

- reducing the adverse effects of dry season; and
- improving soil fertility, especially soil nitrogen status.

One of the serious handicaps in adopting this system is the high cost of establishing cultivated pastures in the cerrado region. Large areas of the region are expected to remain as native pastures for many years (Couto et al. 1983). One of the viable alternatives should be the adoption of agroforestry systems involving legume trees with the same objectives but with the additional advantage of better soil conservation.

Use of leguminous nitrogen-fixing species and those with associated micorrhyzae capable of solubilizing phosphorus should have the greatest potential in this regard (Faria et al. 1984; Lopes et al. 1983; Nair et al. 1984). Faria et al. (1984) made an extensive search for active nitrogen-fixing root nodules amongst Brazilian forest legumes and reported seven new nodulated species, including two new nodulating genera from *Caesalpinioideae*; 18 new species from *Mimoisoideae*; and 30 new species, including four new genera, from *Papilionoideae*. All these species have the potential for use in agroforestry systems in the cerrado though some of them are not native to the region.

One important aspect that should be investigated in this connection is the adaptability of native species with economic potential in dystrophic acid soils. It should be borne in mind that the predominant native vegetation of the cerrado is a consequence of poor soil fertility and not of climate alone. Other than the reports of Ratter and coworkers (1971, 1977, 1978), there is very little information in the literature on the distribution of cerrado species in different soils. Recent reports (Araujo and Haridasan 1988; Haridasan and Araujo 1987; Machado 1985) have shown that resistance or tolerance to high aluminium levels in the soil may involve more than one mechanism. While some aluminium-accumulating species occur only a dystrophic acid soils, others occur only in mesotrophic soils with near-neutral pH. A few occur on dystrophic as well as mesotrophic soils but grow better on mesotrophic soils.

Besides furnishing foliage for animal feed and improving soil fertility, another important use of trees in pastures is to provide shade and shelter for animals, especially on hot dry days. In many cases, farmers leave isolated trees in the middle of pastures, which is not an ideal solution. This practice often creates the problem of aggregation of animals. Also, individual isolated trees succumb more easily to strong winds. Another practice is to provide isolated patches of trees, especially around artificial lakes which provide drinking water. A better solution for providing shade and shelter for animals, at the same time providing forage and helping in soil conservation, would be to develop silvopastoral systems with overstorey tree species and understorey fodder species. Many species of the native tree vegetation such as *Taipirira guyanensis*, *Copaifera langsdorfii*, *Callisthene major*, *Siphoneugenia sp.*, *Hymenaea stigonocarpa* (-jatoba), *Dipteryx alata* (baru), and *Plathymenia reticulata* have the potential to be used as shade trees (Machado, personal communication). Exhaustive lists of indigenous tree species that can be used in agroforestry systems are easy to compile but experimental evidence is yet lacking to make any definitive recommendations for farmers. For example, several species which occur in the gallery forests in the Federal District have the potential for commercial-scale exploitation.

Soil conservation

Soil erosion is a severe problem in the cerrado region. Many publications erroneously state that soils of the cerrado region are not easily erodible. Sheet, rill and gully erosion pose severe problems in the cerrado soils because rainfall intensity is generally very high. The problem is worsened by the use of heavy machinery in latosols which after

compaction loses its originally-high porosity and infiltration capacity. The fact that the soil is left without adequate vegetative cover at the end of the long dry season makes the soil extremely vulnerable to early torrential rains.

The problem becomes more severe when Class IV to VIII lands are left without any vegetation cover after fire or deforestation to utilise available wood for charcoal production. Though existing laws prohibit destruction of gallery forest along rivers and streams in valley bottoms, indiscriminate deforestation of such vegetation is very common leading to not only erosion and increased runoff during the wet season but also to the drying of the streams in the dry season making little water available to cattle. Suitable agroforestry systems should therefore aim at not only conserving soil where it has not yet been degraded but should shift the emphasis in many cases to recuperation of degraded soils. Most discussions on agroforestry systems usually depend on references to publications from elsewhere to justify the possibility of utilizing exotic species for such purposes. What should be done in the cerrado region is to exploit the possibility of utilizing the native species which are adapted to the climate and low soil fertility. It is well established that the cerrado tree and shrub species have extremely deep root systems capable of utilizing subsoil moisture during the dry season and have several adaptive strategies to resist fires which are frequent in the region.

The main forest plantations in the region are eucalyptus and pine. Because of the present economic conditions in the country, indiscriminate destruction of the native vegetation and planting of eucalyptus and pine were encouraged. The long term effects of repeated cultivation of eucalyptus and pine are still unknown but depletion of soil fertility and accelerated erosion, especially on Class VI to VII lands are certain consequences. One way to avoid total deterioration of such lands would be to develop suitable covercrops in such plantations and follow fallowing or crop rotations with tree crops which help recuperate soil fertility, for example by nitrogen fixation. Another viable alternative would be to think of agrosilvopastoral systems with multiple objectives if we should conserve natural resources of the region. Such arguments apply not only for the conservation of soil resources but also for the conservation of genetic resources of native vegetation as well as native fauna. The extinction of many animal and bird species in the region are often attributed to large-scale eucalyptus and pine plantations.

Better utilization of rural family labour

One of the most serious social problems in Brazil is the very low income of rural families who do not own any land but work on the farms. Even those who own some land and those who receive land from the government as a consequence of agrarian reforms often abandon the land after one or two crop failures. This happens often because of low inputs such as good quality seeds, fertilizers and pest and disease control. Often the farmers have no income in such cases because they depend on monocultures. After deforestation, they cultivate rice or other field crops for one or two years and then abandon the area to fallow or pasture.

One of the serious consequences of such irregular productivity of cerrado soils is the abandoning of rural lands by small-scale farmers who migrate to urban centres. Furley and Leite (1982), for example, state that 50 families out of 208 who had received between 65 and 240 ha of land under the Sagarana colonization project abandoned their property within the first couple of years. They could not cope with officially-established targets for land clearing, planting of crops and repayment of loans. Diversification of crops and adoption of suitable agroforestry systems should provide a better chance of success in such cases. The development of agrosilvopastoral systems in such cases

should be based on the utilization of available family labour throughout the year providing full-time employment but at the same time avoiding overburdening. Small-scale animal husbandry is one of the possibilities to be considered in this regard in agroforestry systems in the cerrados, besides options such as apiculture and inland fisheries where the facilities exist.

Constraints and research needs

It is interesting that during the review of literature for writing this article, I encountered more articles on the possibility of agroforestry in the Amazon region than in the cerrados (for example, Hecht 1982; Eden 1982). The main limitation for the adoption and development of agroforestry systems in the cerrado region seems to be the lack of planning and forethought on the part of government agencies. The need for soil conservation on a long-term basis and welfare of rural families seem to be ideals advocated only on paper. The emphasis on monocropping and intensive agriculture in the region is in many ways artificial, sustained only by the eagerness of the government to support export-oriented crops with no concern about soil and water conservation or environmental protection.

There is no careful planning in the management of forests or pastures in the cerrado region. There is no replanting in degraded lands and there is no attempt to replenish the stock of felled forests. Eucalyptus and pine plantations are intended only to furnish wood for industrial purposes and are monopolies of large firms.

Some of the existing models can serve successfully for small farmers who may get to own land as a result of the proposed agrarian reforms (Furley and Leite 1982). Agroforestry should provide viable alternatives to existing models in such cases.

Yet another argument in favour of agroforestry systems in such cases is that the possibility of intensive agriculture does not exist because:

1. energy costs are very high; small farmers do not have the capital to invest in heavy machinery and other infrastructure essential for intensive agriculture;
2. there are no financial incentives or insurance against risks for small farmers to try new farming systems; and
3. government policy favours export-oriented crops because of the heavy debt crisis in spite of the food shortage within the country.

There has been no serious attempt to evaluate the potentials of agroforestry systems in the cerrado region. One of the serious handicaps seems to be that none of the more prestigious agricultural colleges in the country is located in the cerrado core region. Post-graduate courses in agronomy, soil science, animal husbandry and forestry should be encouraged in different universities in the region if new farming systems are to be experimented with. Research centres of the federal agricultural organization (EMBRAPA) are geared to attend research needs of individual crops; and, in some cases like the CPAC, to specific needs of the region. However, there is very little attempt to try novel ideas.

As mentioned earlier, there are several native species which have the potential for utilization in agroforestry systems. There are many fruit trees that have the potential for commercial exploitation. Herringer and Ferreira (1972, 1973a, 1973b) list several of these species. However, very little information is available on the agronomic aspects of these plants. Incorporation of these in agroforestry systems would warrant agronomic research on the following aspects:

1. Survey of genetic resources, which should include studies of natural distribution of these species in different climatic regions and adaptability to different edaphic conditions like soil fertility and water regimes.
2. Collection and preservation of germplasm since native vegetation is fast disappearing in the region with the extension of agriculture and pastures.
3. Agro-silvicultural trials to increase the productivity of the species for commercial exploitation.
4. Exploration of the possibilities of multiple uses such as controlling erosion, use as shelter belts, use for firewood or charcoal, use as animal feed, and nitrogen fixation.

There are no worthwhile attempts made to utilize native species in reforestation or agroforestry systems at present though there are isolated suggestions regarding the utility of several native species. For example, Escuder (1980) reports that leaves of many tree and shrub species such as *Kielmeyera coriaceae, K. obtida, Ouratea hexasperma, Syagrus spp., Palicouria rigida, Borreira spp.* and *Didymopanax macrocarpum* are common in the diet of sheep. Castro and Junior (1984) found that *Dispyros hispida, Ouratea hexasperma* and *Byrsonima coccolobifolia* foliage was consumed in great quantities and *Dalbergia violacea, Blepharocalyx suaveolens, Erythroxylum tortuosum, Davilla elliptica* and *Styrax ferrugineus* leaves in smaller quantities, especially during the dry season. Utilization of these species to supplement the ration of sheep and of other tree and shrub species to supplement the ration of cattle and goats are possibilities that should merit attention in the cerrado region.

Conclusions

Whatever the prospects for agroforestry systems in the cerrado region, no progress will be possible until the philosophy of conservation of nature -- soil, native vegetation, regional fauna and environmental quality – is accepted by the community. This dilemma is well expressed in a recent publication of the Ministry of Agriculture (Downes 1983) regarding the necessity for institutionalization of soil and water conservation in the country. Once this philosophy is accepted by the government and the farmers, adoption of agroforestry systems is only the next logical step because some kind of multiple use and periodic fallowing of agricultural land seem to be a must in tropical oxisols. The present outlook that Brazil still possesses land that can be yet brought under intensive mechanized agriculture just doesn't seem right if land deterioration is not to be our goal.

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Interaction of climatic components on agroforestry systems by management practices in Pakistan

A. Amin

Pakistan Agricultural Research Council
PO Box 1031, L-13 Almarkaz, Islamabad, Pakistan

Introduction

Pakistan having a total land area of about 88 million hectares is blessed with a variety of climates. Being predominantly an agricultural nation it is located between latitudes 24°N and 37°N and longitudes 61°E and 76°E. The area under agricultural use is about 25 percent while about sixty million hectares constituting about 68 percent of the total land area have been classified as rangelands. The forests cover about 4.37 million hectares which is about five percent of the land area.

Fuelwood production from farmlands

In Pakistan about 70 percent of households use wood as fuel which is usually supplemented by cowdung and agricultural residues (Sheikh 1985). The present consumption of fuelwood in the country is difficult to determine precisely but it has been estimated to be about 19 million m^3 annually. This requirement is met partly from the government forests which produce only 10 percent. The remaining 90 percent is produced from the farmlands. With per capita consumption of 0.4 m^3 annually, the country would need about 42 million m^3 of fuelwood by the year 2000 when the population would have increased to 152 million. Thus an additional 23 million m^3 of firewood requirements are met from the farmlands managed by the farmers. Therefore, these private lands offer considerable potential for planting trees in conjunction with agricultural crops.

Climatic regions

Climatically the country can be divided into the following major forest ecozones.

Mountainous regions

Mountains occupy the northern and western parts of the country. The northern mountains are the termination of Himalayan range with a number of small and large peaks which remain covered with snow. On account of this the climate is undifferentiated. In summer the mean daily maximum temperature is about 35 C and in winter the mean daily winter temperature is 0-4 °C with cold spells. The mean monthly rainfall in summer is about 236 mm and in winter 116 mm. Only about 25 percent of the area is under

rain-fed agriculture with main crops as maize and wheat. Rice is grown in small areas which are irrigated through springs (PARC 1980). The forests in mountainous regions are characterized by the following types.

Subtropical pine forests

These forests occur from a little below 900 m elevation up to 1650 m on the mountain slopes. The principal species is *Pinus roxburghii* mixed with *Quercus incana, Xylosma longifolium* and *Pyrus pashia*. The chir pine (*Pinus roxburghii*) however, occurs almost in purely dense form with undergrowth of *Myrsine africana, Carissa opaca* and *Dodonaea viscosa*. Fires are generally of frequent occurrence in these forests resulting in elimination of shrubs. These forests are subjected to heavy population pressure.

Temperate forests

The temperate forests range in altitude from 1650 m up to about 3000 m. These limits depend largely on the aspects of slopes. The principal commercial species are *Cedrus deodara, Pinus wallichiana, Abies pindrow* and *Picea smithiana. Taxus baccata* also occurs in the form of scattered trees or small patches. The trees are generally very large in size due to selection system of management and long rotations. The broadleaved species in these forests include *Aesculus indica, Quercus dilatata, Juglans regia, Acer caesium, A. pictum, Ulmus wallichiana, Viburnum nervosum, Lonicera quinquelocularis, Populus ciliata, Indigofera gerardiana*. The stocking rate in these forests varies with the extent of degradation largely due to expanding agriculture and summer grazing of alpine pastures. Most of these forests grow on very steep slopes. It is not uncommon to see slopes up to 80 percent which have been terraced for crop culture.

Dry temperate forests

The mountains located towards the west of the Indus are not very high and are associated with plateaus, semi-arid valleys and plain lands. The monsoon rains do not reach here and the low precipitation is confined to some winter rains and mostly snow. During winter the mean daily minimum temperature varies from 1 C to -7 C with occasional prolonged cold spells. The mean monthly summer rainfall ranges from 5-95 mm and in winter it is 30-35 mm. The summer is mild with mean daily maximum temperature being about 32 C. The winter is cold with mean daily temperature around -0.2 C with frequent cold spells. Parts of the loamy soils are used for growing maize, wheat and alfalfa. Fruit orchards of apples, peaches, plums, apricots and grapes are common. The coniferous species in these forests include *Pinus gerardiana* and *Juniperus excelsa*. Broadleaved species include *Fraxinus xanthoxyloides, Pistacia mutica, Caragana ambigua*. The canopy in these forests is open and trees generally remain stunted.

Alpine forests

The alpine forests occur between 3,000 m and 4,200 m. The forests consist of *Betula utilis* either with or without *Abies spectabilis, Pinus wallichiana, Salix spp., Juniperus squamata, J. communis, Rhododendron hypenanthum* and other herbaceous vegetation. The crop is very open and stunted. These forests are of little economic importance due to their poor stocking and inaccessibility.

Tropical thorn forests

The tropical thorn forests are also known as the desert scrub. The climate is arid and hot, subtropical continental. The mean monthly maximum temperature ranges from 45°5DC to 48 °C in summer and from 5 °C to 8 °C in winter. The mean monthly rainfall in winter is about 33 mm while in summer it is about 21-38 mm. The main crops in this region are wheat, sorghum, millet and gram (PARC 1980). A number of thorny species like *Prosopis cineraria, Capparis aphylla and Acacia modesta* are representative of this type. *Tamarix articulata, Salvadora oleoides* and *Prosopis juliflora* also grow commonly in these degraded lands. These forests provide firewood to the local communities and forage to the livestock. They consist of small patches of short-boled, low-branching tree species and a variety of shrubs scattered over a total area of 1.1 million hectares in the plains which offer great potential for development of rangelands.

Dry subtropical evergreen forests

The dry subtropical region has two distinct parts. A small narrow belt lying along the foot of the mountains is nearly humid with hot summer and cold winters and has a short dry season in early summer. The south-western portion is semi-arid and hot. The mean monthly maximum temperature is around 40 °C while the mean monthly lowest minimum temperature ranges from 0 to 1.5 °C. The mean monthly rainfall is about 200 mm in summer while it is about 50 mm in winter. Rain-fed cultivation is the main land use. The important crops include millets, maize, wheat, oilseeds, pulses and fodders.

The formations are constituted by evergreen species of small sized trees and shrubs and grow up to about 1,000 m altitude on the hill slopes. Typical tree species include *Olea cuspidata, Acacia modesta, Mallotus phillipensis, Flacourtia indica, Sageretia theezans, Gymnosporea royleana* and *Adhatoda vasica*. A large part of these forests has been degraded by heavy grazing, browsing, lopping and over-exploitation for firewood. These play an important role as vegetative cover of the main water catchments.

Indus plain

The Indus plain is the western part of the Indogangetic plain which forms one of the most prominent and extensive physiographic division of the subcontinent. The plain is believed to be more than one thousand m deep and is formed by large quantities of alluvial material deposited since time immemorial by the Indus and several of its tributaries. The Indus plain is composed of silt, sand, clay and rarely gravels. Much of the land in this basin was desertic and has been developed by irrigation. The land is fertile and heavily populated.

The eastern half of this region is semi-arid while the south western part is arid subtropical continental. The mean daily maximum temperature during summer is 40-42 °C and in winter the mean daily minimum temperature is 6 °C. The mean annual rainfall is 200-300 mm. Canal-irrigated cropping is the main land use and the major crops grown are rice, wheat, sugarcane, cotton, maize, berseem, millets, oilseeds and lemons. Fruit orchards of citrus and mango are also important especially in the central part (PARC 1980). Irrigated plantations comprising largely of *Dalbergia sissoo* and *Morus alba* over an area of 0.23 million hectares have been developed.

Riverine forests

Riverine forests also occur in the Indus plain within the protection embankments of the Indus river over an area of 0.3 million hectares. These are subject to seasonal flooding with erosion and deposition. Typical plant species include *Acacia nilotica, Prosopis cineraria, Populus euphratica, Tamarix dioica* and *Salvadora persica*.

The climate is arid sub-tropical continental with hot summers and mild winters. The mean daily maximum summer temperature varies between 40-45 °C and the mean daily minimum temperature in winter is about 8.5 °C. The mean monthly summer rainfall is about 16-20 mm in the northern parts while in the southern areas it is about 45-55 mm. Canal-irrigated agriculture is the predominant land use of the region. Cotton, wheat, mustard, sugarcane, berseem, rice, gram and sorghum are the main crops (PARC 1980).

Coastal zone

The climate in the coastal zone is arid tropical marine with moderately hot summer and very mild winter. Mean daily maximum temperature ranges from 34-40°C and 19-20°C, in summer and winter respectively. The mean monthly summer rainfall is approximately 75 mm while in winter less than 5 mm rainfall is received. Due to the sea breeze the relative humidity is generally high. It is not possible to cultivate any crops due to high tides from the sea.

The mangrove forests are located in the shallow waters along the coast near the mouth of the River Indus. These forests mainly comprising of *Avicennia officinalis* cover an area of 0.35 million hectares. Where accessible these forests are heavily cut for fuel-wood and are mostly shrubby. The leaves serve as a valuable fodder. These forests have little commercial value except for small quantities of firewood and grazing.

Agroforestry systems

In Pakistan, farmers grow woody perennials in conjunction with field crops, vegetables and horticultural crops to meet their domestic needs. The aims and rationale of most agroforestry systems at the farm level are to optimize the positive interactions in order to obtain a higher sustained and more diversified productivity from the available resources. Following are some of the examples of prominent agroforestry systems and practices in Pakistan.

Agrisilvicultural systems

Tree gardens

Common in all ecological regions of the country depending upon the choice of the farmer which is generally very varied but largely for firewood, fodder and to meet the domestic timber needs.

Multipurpose trees and shrubs on farmlands

Found in several forms both in low and high altitude areas, e. g., hill farming in temperate regions. This is common both on private and public lands either through the resources of farmers themselves, or financed through sponsoring agencies.

Crop combination with plantation crops

Integrated production systems in small land holdings, shade trees in plantations and other crop mixtures including various tree species in the form of household or community forestry.

Agroforestry fuelwood production

Common in various forms including some forms of social forestry.

Shelterbelts and windbreaks

In the arid regions of southern parts of the country where strong winds damage the agricultural crops, use of eucalypts and casuarina as shelterbelts and windbreaks of different kinds are very common.

Silvopastoral systems

Protein bank (cut-and-carry fodder production)

Multipurpose fodder trees on or around farmlands are frequently planted especially in high hills to meet the feed requirements of livestock during the fodder deficit period in winter.

Living fence of fodder trees and hedges

Planting of fodder trees as live fences and hedges like *Sesbania, Euphorbia, Acacia,* etc., to protect the property from stray animals or other biotic influences.

Trees and shrubs on pastures

There are several tree and shrub species being used very widely on pastures and rangelands in all ecological regions to supplement forage production.

Agrosilvopastoral systems

Woody hedges for browse, mulch, green manure, soil conservation, etc.

Very common in different forms especially in arid and semi-arid regions to provide browse or serve as mulch or litter to conserve the available moisture.

Homegardens

Common in all ecological regions especially the temperate regions where fruit orchards are very profitable enterprise.

Other systems

Aquaforestry

Silviculture in mangrove areas and trees on banks of fish-breeding ponds.

Apiculture with trees

Raising of honeybees on different tree species for production of honey is very common in all ecological zones.

Current research status

Very little scientific work has been carried out in Pakistan on agroforestry. Studies on windbreaks of *Eucalyptus camaldulensis* carried out during 1980-83 in the arid regions of Pakistan have indicated that after 3-4 years, quicker wood yields are available from the farmlands through thinnings. The net increase in yield of wheat, cotton and maize is negligible at this early stage of tree growth (Khalique and Sheikh 1985).

In another study, Rahman (1978) measured the yield of wheat grown in unprotected fields and that grown in fields protected by either a single row of *Tamarix gallica* or two rows of *T. gallica* and one row of *Calligonum polygonoides*. He found that the wheat grain yields were increased by 7.5, 15 and 13.5 percent, respectively, over the unprotected fields.

The wood-deficient areas, particularly the arid and semi-arid regions, offer considerable potential for planting of trees through cultural and management practices and modifying the micro- and macroclimate of the region. It is possible to reseed the arid and semi-arid regions with grasses like *Cenchrus ciliaris* and *Lasiurus sindicus* besides growing multipurpose fodder trees and shrubs including *Acacia albida, A. aneura, A. modesta, A. tortilis, A. victoriae, Ceratonia siliqua, Parkinsonia aculeata* and *Tecomella undulata*. Maximum survival of these species is obtained in sloping catchments without trench. Contour trenches give rather low survival due to flooding from flash rains causing long submersion of plants under high desert temperatures (Sheikh 1985).

Recommendations

As in other parts of the world, in Pakistan the beneficial effects of shelterbelts and windbreaks are quite convincing. The biological effects of windbreaks are numerous for agricultural purposes and in regions affected by strong and frequent winds especially in arid regions. Conventional design and composition of tree plantings either isolated or in the form of windbreaks have led to variable results in different climatic regions and cropping patterns.

Agrosilvopastoral systems need to be encouraged. Multipurpose tree species which not only provide wind protection, but other commodities such as timber, fuelwood, fodder, fertilizer, etc., should be planted. This would also provide plantings where interactions between shelterbelt trees and crops could be studied.

Besides technical problems, socio-economic factors such as land use and tenure, community involvement and organization, long term understanding of cost-benefit appraisal, public motivation and education are important particularly in the arid and semi-arid regions.

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Climatic resources for agroforestry in Vietnam

Ngo-Si-Giai

Hydrometeorological Service of Vietnam
No. 4, Dang Thai Than, Hanoi, Vietnam

Abstract

In Vietnam forests cover about 75% area of the country. They play a very important role in the formation of climate, water resources, soil, environmental conditions, and forest ecological systems and they are greatly influenced by hydrometeorological conditions too. In forest zones of Vietnam with different ecological conditions there is a meteorological and agrometeorological station network founded long ago. The application of meteorological and agrometeorological information to planning and management of agroforestry systems has gained in importance as it has intensified day by day. The humid and tropical climatic resources in the forestry of Vietnam, especially in mountainous areas of Tay nguyen (the Highland of the Central part of Vietnam), the East of South Vietnam, North East and North West of North Vietnam are multiform and rich. That is why forest flora has high potential productivity.

Unfavourable conditions such as dry and hot wind, drought, heavy rain, flood, fire, landslide, erosion and unrational exploitation have caused remarkable changes in hydrometeorological regimes. Here, there are also proposals in the directions of the study and methods of the applications of agrometeorological information (methods forecast of forest fire and methods of forecast of biomass growth of forest trees in every year) in the planning and management of agroforestry systems, especially in new planting and regeneration of forests.

Introduction

In Vietnam, forests and mountains cover about 75% of the country. Climatic resources of Vietnam are multiform and play a decisive role in the formati .n of forest systems and their yield. The estimation of climatic resources is of great significance in planning, management and exploitation of agroforestry systems.

In the various forest zones, the Hydrometeorological Service of Vietnam has founded a meteorological and agrometeorological station network long ago. Since 1960, hydrometeorological and agrometeorological data have been actively used in the planning and management of the forest zones.

This paper discusses two problems: estimation of climatic and forest resources of Vietnam; and the application of meteorological information in forecasting forest-fire danger.

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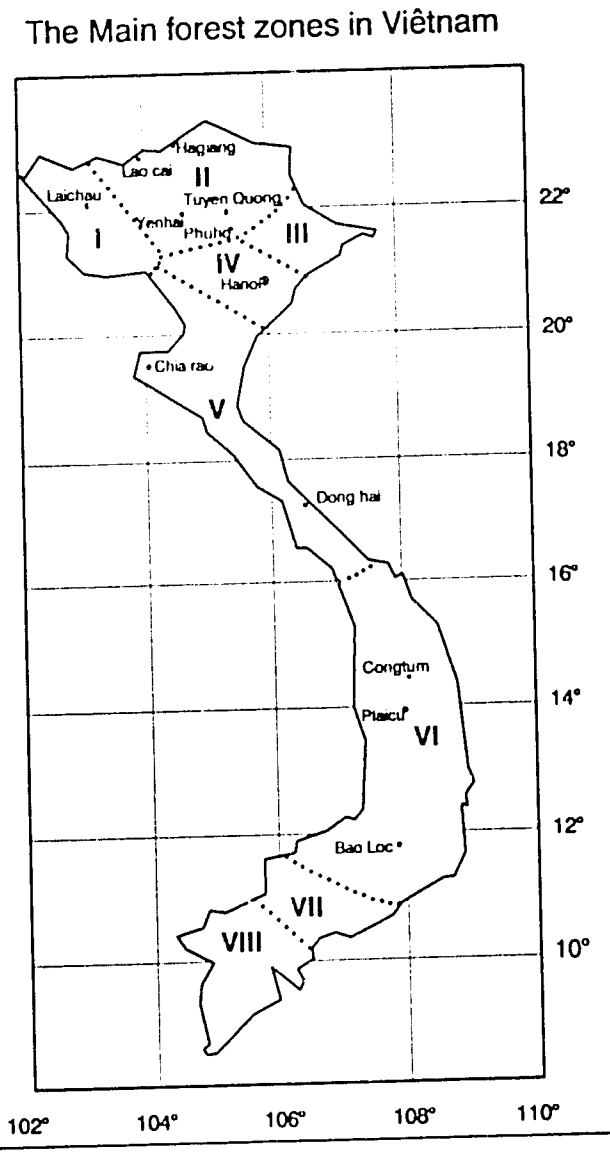
Bioclimatic resources

Forests in Vietnam are divided into eight main zones:

I North-western zone, 9% forested;
II North zone of north Vietnam, 20% forested;
III North-eastern zone, 15% forested;
IV Red River delta, 5% forested;
V North zone of central Vietnam, 15% forested;
VI Maritime provinces and central Vietnam, 20% forested;
VII Eastern zone of south Vietnam, 10% forested; and
VIII Mekong delta, 6% forested; (Figure 1)

Figure 1 Main forest zones of Vietnam.



The following are average meteorological data of two characteristic forest zones:

Laichau (Zone I): 244 m asl; 22° 03' N; 103° 09' E.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temp. (°C)	17.3	18.8	21.6	24.6	26.5	26.5	26.5	26.6	26.1	23.9	20.7	17.2
Rain (mm)	16	42	61	122	278	413	409	246	156	66	39	1

Congtum (Zone VI): 536 m asl; 14° 20'N; 107° 59' E.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temp. (°C)	20.9	22.6	24.8	25.5	25.4	25.0	24.3	24.3	24.1	23.6	22.9	20.7
Rain (mm)	3	9	40	107	204	248	342	352	325	151	59	11

Degree-days above the base 15 °C, representing the growth period for forest trees, are calculated for twelve forest locations and presented as frequency distributions in Table 1. Rainfall sums during the growth period are also presented. In forest zones I, II and III in north Vietnam, degree-day sums indicate favourable conditions for forest growth (due to the long winter), but rainfall in this period is very small. Moreover, rainfall is not regularly distributed in the year. It occurrs mainly in a rainy season that brings the danger of serious floods which cause severe soil erosion and landslides.

Results of analysis and calculation show that the hydrothermal coefficient of Xelianinov (Trung 1970) is suitable for determining forest zonation in Vietnam. It can also be used planning and management of agroforest systems. The hydrothermal coefficient is calculated as:

$$HC = R / (0.16 + T_{15})$$

where R is the sum of rainfall (mm) in the period with temperature above 15 °C; T_{15} is the sum of average daily temperatures above 15 °C; and 0.16 is an experimentally-determined coefficient for Vietnam.

Distribution of the hydrothermal coefficient has a seasonal character. In nearly all forest zones in the rainy months, June through September, the coefficient is high (Table 2). In winter and spring months, it is very low. If we assume that a monthly hydrothermal coefficient (HC) equal to 1 means a deficiency of moisture, and HC equal 0.5 means a great deficiency of moisture, then there are 8 out of 10 years very deficient in zones I, III, IV and VI. Thus the hydrothermal coefficient can be used in the planning of new forest plantations and the determination of techniques for intensive farming.

Number of rainy days

Beside a total rainfall in the period with temperature greater than 15 °C, the number of rainy days is an important climatic parameter for the planning of forestry systems. A harmonious occurrence of rainy days and sunny days is optimal for the growth and the formation of biomass of forest trees.

In general, in the growing period of forest trees (from February to November), the number of rainy days in zones I, II and III is rather regularly distributed with 14-20 rainy days per month. In such months each two days has one rainy day, especially in central part of Vietnam (zone V) the number of rainy days in every month from March to June is less than the one of other months. In Playcu (zone VI), the number of rainy days in spring months is very small: 0.1-0.9 days per month.

Table 1 Probability of exceeding sums of temperature ≥ 15 °C and rainfall in months with average temperature ≥ 15 °C (base 1960 -1980).

Location		Probability of exceeding tabular values (%) 5	10	20	30	40	50	60	70	80	90	95
Moc chau	R	2150	2020	1865	1775	1705	1640	1570	1500	1430	1350	1280
(zone I)	T	6160	5940	5700	5510	5480	5260	5140	5000	4860	4620	4560
Bac can	R	1910	1820	1690	1590	1500	1425	1363	1305	1250	1300	1133
(zone II)	T	8200	7920	7600	7400	7200	7080	6950	6840	6730	4680	6453
Thai nguyên	R	2660	2520	2320	220	2100	1970	1860	1760	1640	1500	1400
(zone II)	T	8620	8520	8360	8220	8080	7960	7820	7680	7550	7350	7240
Phu Ho	R	2870	2330	2060	1920	1840	1750	1680	1600	1510	1400	1300
(zone II)	T	8900	2660	8400	8220	8100	7960	7830	7680	7560	7400	7280
Ha giang	R	3090	2940	2780	2620	2530	2430	2330	2200	2080	1910	1770
(zone II)	T	8500	8280	8000	7840	7720	7620	7520	7420	7300	7160	7040
Tuyenquang	R	2270	2150	1865	1880	1780	1660	1550	1470	1390	1280	1190
(zone II)	T	8640	8500	8320	8100	8040	7900	7760	7620	7500	7360	7250
Van chan	R	2120	1970	1790	1670	1380	1480	1410	1350	1286	1180	980
(zone II)	T	8260	8020	7780	7650	7500	7480	7260	7120	6970	6780	6600
Dai tu	R	2890	2600	2280	2090	1940	1800	1660	1550	1440	1330	1250
(zone II)	T	8540	8360	8140	7960	7820	7650	7500	7340	7160	7940	6820
Do luong	R	2720	2420	2180	2060	1930	1800	1660	1510	1340	1140	1020
(zone V)	T	8940	8800	8600	8520	8260	8120	7960	7820	7660	7500	7400
Tay hieu	R	2750	2450	2040	1800	1670	1550	1450	1350	1175	930	750
(zone V)	T	8740	8600	8420	8260	8120	7980	7840	7660	7550	7160	6940
Bao loc	R	3600	3350	2950	2800	2650	2550	2450	2300	2150	1880	1700
(zone VI)	T	X	X									
Playcu	R	3110	2875	2600	2400	2230	2100	1980	1860	1750	1630	1520
(zone VI)	T	8260	8160	8050	7980	7940	7900	7820	7760	7680	7560	7460

Total rainy days in forest zones show small differences. Maximum is 154 days in the north (Bacquang, zone II) and 189 in the south (Bao loc, zone VI). However in order to estimate more correctly we calculated the number of rainy days with probability 80% in the period with temperature greater than 15 °C and found that there are 8 out of 10

Table 2 Average monthly hydrothermal coefficient in different forestry zones of Vietnam.

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Phu ho	0.64	0.85	0.60	1.61	2.22	2.90	2.59	3.30	2.25	2.33	0.94	0.42
Dai tu	0.56	0.70	0.63	1.61	2.78	3.37	3.62	4.68	3.17	2.62	0.70	0.49
Bac giang	1.41	1.49	1.28	3.60	1.04	1.18	11.58	7.60	5.12	5.32	1.32	1.96
Thai nguyên	0.48	0.71	0.69	1.87	2.62	4.24	4.38	4.26	3.28	2.02	0.62	0.56
Bac can	0.42	0.60	0.71	1.67	2.19	3.63	3.56	3.74	2.06	1.25	0.62	0.46
Van chan	0.35	0.52	0.57	1.38	1.86	3.04	2.60	3.86	3.44	1.92	0.53	0.36
Playcu	0.85	0.68	0.38	1.30	3.66	4.84	5.98	6.95	4.99	2.09	0.87	0.13
Tay hiu	0.42	0.47	0.44	0.96	1.76	2.01	1.78	3.52	4.94	3.60	1.02	0.44
Moc chau	0.42	0.70	0.99	1.71	2.84	3.49	3.67	4.88	4.94	2.44	1.10	0.35
Yen bai	0.75	1.01	1.20	1.93	3.01	3.46	3.58	4.40	3.93	2.40	1.11	0.63

years in which the number of rainy days in zones I, II, III and IV is no more than 120 days; and in zones V and VI is no more than 140 days. Reality shows that the period with average temperature more than 15 °C in Vietnam is usually year-long. Therefore, the greater the number of rainy days with probability of more than 80%, the greater the productivity and biomass of the forest zones.

Number of hot-and-dry days

In 1968, 1969, 1970 and 1971, climatic surveys in many forest zones showed that hot and dry winds cause great damage to forest trees. The meteorological factors causing the damage are high temperature, low atmospheric humidity, and low soil moisture resulting from low rainfall. The criteria for a hot-and-dry day are $T_{max} > 37$ 28M C, $R_{min} < 50\%$ and rainfall in the previous two days < 5 mm. In the forest zones of Vietnam, hot and dry days are common from March to October (Table 3), and are the main cause of forest fires.

Table 3 Number of hot and dry days (T_{max} 37 °C; R_{min} 50%) in forestry zones of Vietnam.

Location	Zone	March	April	May	June	July	Aug.	Sept.	Year
Yen chau	I	4.7	10.7	14.7	5.5	4.0	1.7	0.2	41.3
Dien bien	I	1.5	3.8	5.0	1.7	0.2	0.3	0.2	12.7
Lai chau	I	1.7	6.2	10.0	4.2	1.7	3.2	2.3	29.3
Lao cai	II	0.0	0.7	4.7	4.5	3.5	2.7	1.3	17.4
Langson	III	0.0	0.0	1.0	1.0	0.5	0.2	0.0	2.7
Bacgiang	III	0.0	0.0	1.8	2.6	1.8	0.2	0.0	6.4
Hanoi	IV	0.0	0.0	1.5	4.5	2.5	0.3	0.0	8.8
Donghoi	V	0.0	2.4	4.8	7.6	7.6	5.6	1.2	29.2
Vinh	V	0.4	2.0	6.6	9.6	8.1	4.4	0.5	31.6
Cua rao	V	0.7	7.7	16.5	10.0	13.0	7.0	0.7	55.6
Thanh hoa	V	0.0	0.2	2.2	4.8	3.7	0.7	0.0	11.6

Forest resources

Forest land in Vietnam comprises more than 20 million ha, of which land with forest trees is about 7.8 million ha. In general, the forest is poor, the quality and quantity are low, and the capacity of the forest for commercial exploitation is limited. This is so because much of the forest is in a primitive and unmanaged state. Although the total biomass is large, the quantity of usable material is very small. On the average, annual growth of natural forest is only 1-2 m^3/ha although pine shows a growth of 3-5 m^3/ha. The calculation of potential productivity shows that with the same forest trees, the productivity would be 10-15 times greater if the forest were better managed.

Knowledge of yearly growth of forest trees allows management to devise an exploitation plan. In each of the last 20 years, 15-16 million m^3 of wood was removed, 3-4 times more than the natural growth of the forest.

Forecasting forest fire weather

Forest fires have rapidly reduced the forest area of Vietnam. In the last 20 years fire has damaged about 10 million m^3 of wood. Forest fires from natural causes are rare and appear only in meteorologically favourable conditions. The forest fire season is usually from November to April in the highlands of central Vietnam. In the north it is from May to October. Forest fires usually occur in the time from 1300 to 1900.

In order to effectively and actively defend the forest resource, it is necessary to predict the potential for fire in each zone. In Vietnam, it was determined that the main meteorological factors that cause forest fire are air temperature and humidity, wind, and soil moisture. We have used two methods to forecast fire danger: the methods of Nesterov and Trung (Trung 1970).

According to Nesterov, the complex index, D, is the sum of products of saturation vapour pressure deficit and the air temperature at 1300 of all days since the last rain:

$$D = K \times D_{-1} + T_a \times T_d$$

where D_{-1} is the value of the index on the previous day; K is a rainfall coefficient which has the value 0 for a rainy day and 1 for a dry day; T_a is the air temperature at 1300; and T_d is the dew point temperature at 1300.

The index is divided into the following classes:

Class	Level of danger	Index
I	no danger	0 – 150
II	average danger	15 – 250
III	high danger	25 – 500
VI	very dangerous	50 – 2000
V	the most dangerous	> 2000

In Vietnam, we also use the drought index of Trung (1970) for the determination of forest fire seasons :

$$X = S \times A \times D$$

where X is the drought index; S is the number of dry months with real rainfall < 2 x average temperature; A is the number of months with rainfall < 1 x average temperature; and D is the number of months with rainfall < 5 mm.

Outlook

In the future, the Hydrometeorological Service of Vietnam plans the following services to forestry:

1. Study the relationship between the growth of biomass of forest trees and different climatic and ecological conditions.
2. Estimate climatic and hydrological resources for planning and management of forestry zones.
3. Forecast capacity of yearly growth of forest trees in different forestry zones to establish yearly exploitation plans.
4. Develop methods of forecasting forest fires in Vietnam.

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The need for climatic information for agroforestry systems in the Philippines

B.P. Sapitula

Agroforestry Department, Don Mariano Marcos Memorial State University
Bacnotan, La Union, Philippines

Abstract

The paper presents the status and extent of use and the need for climatic information for agroforestry systems in the Philippines and hopes to draw suggestions from the participants for a better system of implementation of our programme in agroforestry.

Existing agroforestry systems in the Philippines have no sustained productivity because aside from being still in the experimental stages, the lack of acceptance by the upland farmers and considerable support from the government, environmental factors like climate which directly affect plant/animal growth and survival have not been significantly considered.

Moreover, there are not enough meteorological stations which could provide climatic information. Many existing ones do not have the necessary instruments. Most of the existing meteorological stations are providing data for their own projects or other linked agencies' consumption. There is very minimum effort of trying to provide such useful information to the upland farmers to assist or guide them in the selection of site, selection of plant or animal species, proper combination of agroforestry crops, timing of cultural treatments, pest and disease control, conduct of development activities and other actions aimed at improving the productivity of their agroforestry farms.

Because of this present situation there is a dire need for agencies in gathering and monitoring climatic information to coordinate with agencies implementing agrofrestry programmes to come up with a better plan and effective implementation of the programmes. There is a need to increase the present number of stations and the kind of instruments presently used to efficiently provide agrometeorological information necessary to support developmental efforts of the government to increase the level of productivity especially in the hillside farms.

Introduction

Information on various weather elements are being monitored for use from specific areas relevant to agricultural planning to information required in the construction of infrastructure; for the development of alternative sources of power, e.g., water, wind, and sun; for the safety, efficiency and regularity of all types of transportation and movement of perishable merchandise; and information required by legal authorities and insurance companies in resolving cases.

In agriculture and forestry, climatic information has as much importance as in other fields. From the time the seeds are sown until the plants are harvested and stored, crops are more or less at the mercy of the weather, particularly during certain critical periods

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in their growth. Variations in the weather during the growing season, such as delay in the outbreaks of rain, untimely or excessive rains, droughts, etc. would very seriously affect the development and the final yield of the crops.

Studies conducted in other countries such as India have given ample evidence for concluding that of all the 'controls', climate had the greatest effect on crop yields over a series of years (Acuna 1980). In the field of agroforestry, climatic information could be used as a basis for determining which species of plants and animals could better survive in an area; in the implementation of a cropping pattern in terms of proper combination of the crops; in the proper timing of cultural and development activities; and finally, as a factor that could be considered in planning and implementing a project to ensure effective and economic conduct of different activities. This should remind planners, agriculturists and foresters on the importance of climatic information and the need to take all efforts for its consideration in planning and implementing a project.

This paper presents the status and the extent of use and the need for climatic information for agroforestry systems in the Philippines.

Monitoring agrometeorological information in the Philippines

The Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) is the government agency mandated to monitor atmospheric, geophysical and astronomic information for their useful utilization. The agency is best known to the public through its daily weather forecasts, advisories, bulletins and warnings through the broadcast and print media. It has the following functions (PAGASA 1977):

1. Observes, reports, and forecasts the state of the atmosphere, sea and rivers.
2. Issues warnings of severe weather systems, tropical cyclones, rough seas, floods (in specific areas) and related hazards.
3. Provides climatological, meteorological, geophysical and astronomical information and related environmental data.
4. Provides assistance on the interpretation of environmental data and weather forecasts and on related problems.
5. Maintains and disseminates precise Philippine Standard Time.
6. Collaborate with other agencies on disaster mitigation and community preparedness.
7. Pursues integrated research and training programs in areas within its distinctive competence.
8. Actively involves itself in interagency, international and regional endeavors and projects in the fields of atmospheric science, geophysics and astronomy.
9. To undertake these functions, the PAGASA maintains and operates several networks of observing stations country-wide supported by communication links. The following are the types and numbers of stations composing the networks:

Meteorological forecasting center	1
Main meteorological office	1
Synoptic	54
Upper-air synoptic	9
Radar	9
Climatological	450

Agrometeorological	28
Visual storm signal	36
Main flood forecast center	4
Hydrometeorological	66
Storm surge monitoring	4

PAGASA is divided into major offices or divisions; one is the Agrometeorological Division which manages the operations of the different agrometeorological stations. These stations were established to gather and provide, on a routine basis, simultaneous meteorological and biological information. A list of existing stations is given in the Appendix.

A typical agrometeorological station in the Philippines has the following recording instruments set up in a well-exposed area: raingauges (ordinary and automatic) for precipitation intensity; sunshine recorder for sunshine duration; pyrheliometer for solar radiation; evaporation pan for evaporation rate; soil thermometer to record soil temperature; hygrothermograph to record relative humidity and atmospheric temperature; and an anenometer for wind velocity.

At present, there are 28 agrometeorological stations of which about 75% are auxiliary stations stations owned by other government agencies, schools or private institutions. They receive assistance from PAGASA in the setting up of the instruments and for technical support. Many of these stations are located at agricultural and forestry schools (Acuna 1980) and most of them are in an experimental site to monitor the effects of weather elements on crops.

From the various meteorological stations, data are relayed to the Agrometeorological Division which is responsible for the processing and interpretation of data prior to dissemination. To complement its services to the public, it conducts lectures and advisories, offers technical assistance to other agencies and individuals, and disseminate information through the broadcast and print media. It also conducts weather-crop relation studies and their application to farm operations. The response of the crops to weather conditions at different times of the year are used in recommending crop-weather calendars for specific localities (Acuna 1980).

Extent of using climatic information in agroforestry systems

Most of the existing agroforestry systems in the Philippines do not have sustained productivity. Among the various reasons for the relatively unsuccessful implementation are:

1. Existing agroforestry farms are experimental, still trying to discover the proper combination of species and proper cultural activities to improve productivity;
2. Aside from the lack of manpower, the extension service has not really achieved a considerable degree of its objectives;
3. Negative attitudes of the upland farmers to the technology being introduced;
4. Lack of considerable government support for the program (e.g., insufficient funds for research and extension); and
5. Non-consideration of some physical and environmental factors in the planning and implementation of agroforestry projects.

Agencies involved in the implementation of agroforestry programmes are the Bureau of Forest Development (BFD); Forest Research Institute (FORI); University of the Philippines at Los Banos; College of Forestry (UPLBCF); Philippine Council for Agriculture and Resources Research and Development (PCARRD); logging companies; some upland farmers; and several schools offering agroforestry and forestry programmes such as the Don Mariano Marcos Memorial State University (DMMMSU).

FORI and the College of Forestry at UPLB conduct researches on agroforestry and other related fields. The results of these researches are transmitted to the implementing agency, the BFD, for execution. It is the responsibility of the BFD to establish extension services to transmit the improved technology to the farmers. But since agroforestry is still a relatively new concept and with the presence of tree components requiring a long period to maturity, there are still very few completed research projects. In the case of the UPLBCF, it has its own Social Forestry department to implement research findings in the field.

Nevertheless, the mode of implementing their programmes is the same. Because it is difficult to change the farming system of a certain upland community, the approach is to introduce improvements to the existing cropping schemes.* And because of the lack of provisions and acceptance by the upland farmers, existing agroforestry farms are located in selected pilot project areas and will serve as demonstration farms to adjacent communities.

Some improvements being introduced are the planting of forest crops (e.g., ipil-ipil, acacia, agoho, narra, mahogany); short-term crops (e.g., sweet potato, peanut, ginger, monge bean, corn); medium-term crops (e.g. pineapple, cassava); and long-term crops (e.g., papaya, cacao, coffee, black pepper); and the application of farming techniques (furrow contour, hedgerow and furrow contour, contour strip cropping, terracing and buffer contour) (FORI 1986).

Some logging industries such as the Paper Industries Corporation of the Philippines (PICOP) have also promoted the practice of agroforestry by inducing farmers to plant fast-growing tree species on their farm lots and then buying their wood products at reasonable prices.

Universities and other agencies conduct agroforestry researches with the financial assistance of PCARRD, the National Science and Technology Authority (NSTA), the International Foundation for Science (IFS), and other funding institutions. But most of the researches being conducted are cropping patterns, still discovering whether a certain tree crop is compatible with a set of agricultural crops already thriving in the locality.

Within some of the different research stations, meteorological instruments are set up to monitor the effect of climatic factors on crops. In short, climatic information is only being used in agroforestry research to assess the effects of weather elements on crop responses and performance. In most of the other agroforestry systems, farmers plant the combination of trees and agricultural crops that have been thriving in the locality and those that could provide their economic needs. With this practice, at least, climatic factors have been considered; but there may be more crop combinations that would perform better in the area if they were guided by meteorological information.

As of this time, most of the agrometeorological studies conducted on agroforestry have been on provenance trials, soil moisture, germination, soil erosion, shading by trees, environmental changes as a result of farming schemes, plant diseases, rehabilitation of forest areas, and time of planting (Gayanila 1984). With these, it seems that

* Personal interviews with Nicanor Iscala, BFD; Marcelino Dalmacio, FORI; and Vicente Ato, UPLBCF.

many important researches have already been conducted but most of the results have not yet been transformed to marketable goods for the farmers. The extension services must do a lot of work in this regard.

Conclusions and recommendations

The response of many plants to the different weather elements is still the subject of continuing research. With only 28 agromet stations, it could be inferred that there are not enough stations to provide climatic information specifically for agroforestry. Almost 50% of these stations are located in schools and other agencies not directly involved in agroforestry. They are not really being used to provide direct information to the upland farmers but to satisfy the immediate needs of the agencies' projects. For schools, for example, the instruments are used for instruction and in supporting research projects.

Because of this situation, there is a dire need for agencies involved in gathering and monitoring climatic information to coordinate with agencies implementing agroforestry programmes, with the goal of producing better plans and implementation of programmes. This will maximize the use of the very few agromet stations.

There is an apparent need to increase the present number of agromet stations and the kind of instruments used to provide agrometeorological information. Likewise, a more comprehensive and effective extension programme should be formulated to disseminate more information in a manner acceptable to the upland farmers.

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Appendix: Existing agrometeorological stations

1. Mariano Marcos State University – Batac, Ilocos Norte
2. Isabela State University – Echague, Isabela
3. Benguet State University – La Trinidad, Benguet
4. PAGASA Office – Beguio City
5. Bureau of Plant Industry – Baguio City
6. Central Luzon State University – Munoz, Nueva Ecija
7. Hacienda Luisita – San Miguel, Tarlac
8. Central Agromet Observatory – PAGASA, Quezon City
9. Cuyambay – Tanay, Rizal
10. University of the Philippines at Los Banos, Laguna
11. Camarines Sur Agricultural College – Camarines Sur
12. Albay Provincial Nursery – Albay
13. University of Eastern Philippines – Catarman, Northern Samar
14. Mambusao Technical College – Mambusao, Capiz

15.Visayas State College of Agriculture – Baybay, Leyte
16.Sab-a-Basin – Tacloban City
17.La Granja, La Carlota – Negros Occidental
18.Calape – Bohol
19.Bayugan – Agusan del Sur
20.Trento – Agusan del Sur
21.Central Mindanao University – Musuan, Bukidnon
22.Dagat Kidavao – Valencia, Bukidnon
23.Kahaponan Auxilliary Station – Valencia, Bukidnon
24.Mindanao State University – Marawi City, Lanao del Sur
25.Twin Rivers – Tagum, Davao del Norte
26.Philippine Coconut Authority – Davao City
27.University of Southern Mindanao -- Kabacan, North Cotabato
28.Palawan National Agricultural College – Aborlan, Palawan

SECTION 4

Measurement and analysis of agroforestry experiments

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Inexpensive instrumentation for monitoring PAR in agroforestry

S.M. Newman

Applied Biosystems Unit, Energy Research Group
Faculty of Technology, Open University
Walton Hall, Milton Keynes MK7 6AA, England

Abstract

A review of methods for sensing and integrating the transmissivity of agroforestry canopies to photosynthetically active radiation with reference to sampling pattern, costs and ergonomics.

Introduction

I define agroforestry as an activity where woody plants (usually trees) are used in more or less intimate association with animals and/or crops in order to make use of ecological and economic interactions in the production of a wide range of materials including food, fuel, timber, fodder and chemicals.

Photosynthetically active radiation (PAR) is defined as that part of the electromagnetic spectrum with wavelengths between 400-700 nm. It is that part of the sun's energy that is tapped by green plants and upon which all life ultimately depends. It is extremely useful to know how the canopy of the woody and non-woody components in an agroforestry system intercept this radiation. By knowing how much is intercepted one can calculate the photosynthetic efficiency of the system and match this against alternative canopy structures or theoretical models. By knowing about the transmissivity of the tree canopy, that is how much light passes through it, one can gauge the potential for growing an understorey crop in close association with the trees. Knowledge of the spatial and temporal variation of this available PAR is useful in the design and optimization of both overall and component crop yields. There are many general reviews on the measurement of PAR and the physiological effects of reduced PAR availability in plants (Anderson 1964; Coombs and Hall 1982; Monteith 1973; Sestak et al. 1971). In this paper I have attempted to concentrate on those aspects of special importance to the study of agroforestry.

Spatial aspects of agroforestry canopies

The spatial arrangement of systems includes horizontal and vertical planes. Horizontally one can consider the system to be an arrangement of holes in the ground of a particular geometry with crops allocated in different ways. The arrangement of holes can be regular, random or with systematic variation. Regular arrangements can be square, triangular or rectangular. Plants can be allocated to these holes as rows, e.g. as

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in alley cropping; in a random fashion, as in hand-broadcast mixtures in *Acacia* scrub; or in rectangular plantations, as in fruit and nut orchards).

Vertically the system can also be complex with what could crudely be described as canopy layers from different species with trees usually, but not always, occupying the top layer and herbaceous crops the bottom layer. In the more complex systems such as modified forest gardens, intermediate layers with shrubs and/or climbing vines complicate the vertical system further.

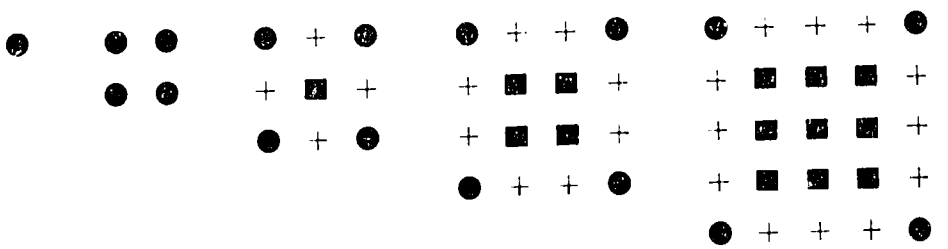
Spatially, then, the most important attribute of agroforestry systems is that they are very complex. They contain complexity in that they are discontinuous and that they contain mixtures of species with different leaf and whole-plant morphology and phenology.

Edge effects or how big is an agroforest?

I am not going to argue that a field crop with a single tree planted at its centre is an agroforestry system. Nevertheless, there are many cases where the tree component is so widely spaced that for all intents and purposes the system is a collection of individual trees. This occurs in tea and coffee where leguminous shade trees are widely spaced and during the establishment phase of plantation tree crops when they are intercropped. Edge effects are important in small agroforests and should be studied rather than ignored or designed around. Figure 1 shows the importance of edge effects for different sized plantation and represents a tree classification based on neighbours. Many agroforests are run by smallholders and are consequently small.

One can observe that if aspect is ignored then in most systems we have three broad categories of representative tree. If the trees are of different heights or species this will further complicate matters. It is a traditional and significant practice in Kerala to grow areca nut in a mixed age system with trees of 5-year age differences (Aiyer 1949). It is also evident from Figure 1 that for a repetitive rectangular array a sampling unit is a rectangle either with a tree at the centre or with a tree at each corner. For small agroforests tree height is of crucial importance in that it will directly affect the distribution of PAR available to the understorey. This is due to the important contribution made from radiation incident from the edges.

Figure 1 The size of the array of trees in a plantation and its impact on the number and form of representative trees assuming no major effects due to aspect.



Number of sensor points required

A single sensor is of no use as this will not be able to discriminate between changes due to the canopy or the atmosphere. Two sensors – one above the canopy and one below – will give a measure of canopy transmissivity; but where should the lower sensor be placed? In order to take into account the effect of aspect at least four sensors placed north, south, east and west will be required to adequately characterize an arrangement where the trees are not grown in continuous rows, i.e., the canopies do not touch within the row. I would suggest at least eight sensors to characterize an individual tree's #effect on the understorey replicated enough times so as to represent trees of a certain size or location. The understorey sensors should be placed at a few centimeters above the maximum height of the crop. Other layers of sensors will be needed to characterize PAR available to other species or other leaf layers if required. As the study will relate everything to the upper reference sensor, more than one should be used to insure continuity of the record in case of sensor failure. I would suggest therefore that a minimum of 15 sensors is required in most serious studies.

Active area of a sensor and costs

Obviously the larger the sensor the larger the area that PAR can be averaged over. The size of the sensor will be limited by cost and the resolution of the study. It is unlikely that any manufacturer will produce a sensor at a price lower than £ 100 that is guaranteed against some standard. There are several designs in the literature that can be built in a standard workshop. In order to choose the correct design it is important to define appropriate characteristics.

Ideally a PAR sensor should have the following characteristics: a suitable spectral response; a correct angular response; a rapid response time; a small surface area; a long life; and a negligible temperature response.

Two types of sensor have been used by plant scientists that differ in spectral response, i.e., the energy or PAR sensor and the photon or quantum sensor. The energy/PAR sensor has a more-or-less flat response between 400-700 nm and is calibrated in W m^{-2}. The photon or quantum sensor has a response based on Einstein's law of photochemical equivalence and is calibrated in E $m^{-2}s^{-1}$ (McPherson 1969).

The quantum sensor is often preferred for measurements of photochemical efficiency in relation to absorbed PAR whilst the energy sensor is preferred for the measurement of PAR in relation to canopy transmissivities and where other meteorological and physiological measurements are available in energy units (Blackburn and Proctor 1983). The latter sensor can be calibrated against measurements taken by a Kipp solarimeter. Energy sensors have become increasingly popular since the publication of detailed crop response spectra (McCree 1976).

The standard angular response for sensors that is required is a close match with Lambert's cosine law (Anderson 1964). This is a physical standard and may not always be close to biological reality. This is the case in some terrestrial systems where the leaves are predominantly aligned away from the horizontal, and in most aquatic systems (-Williams and Jenkinson 1980). This is commonly observed in *Piper nignum* trained on tree trunks in agroforestry systems of the humid tropics.

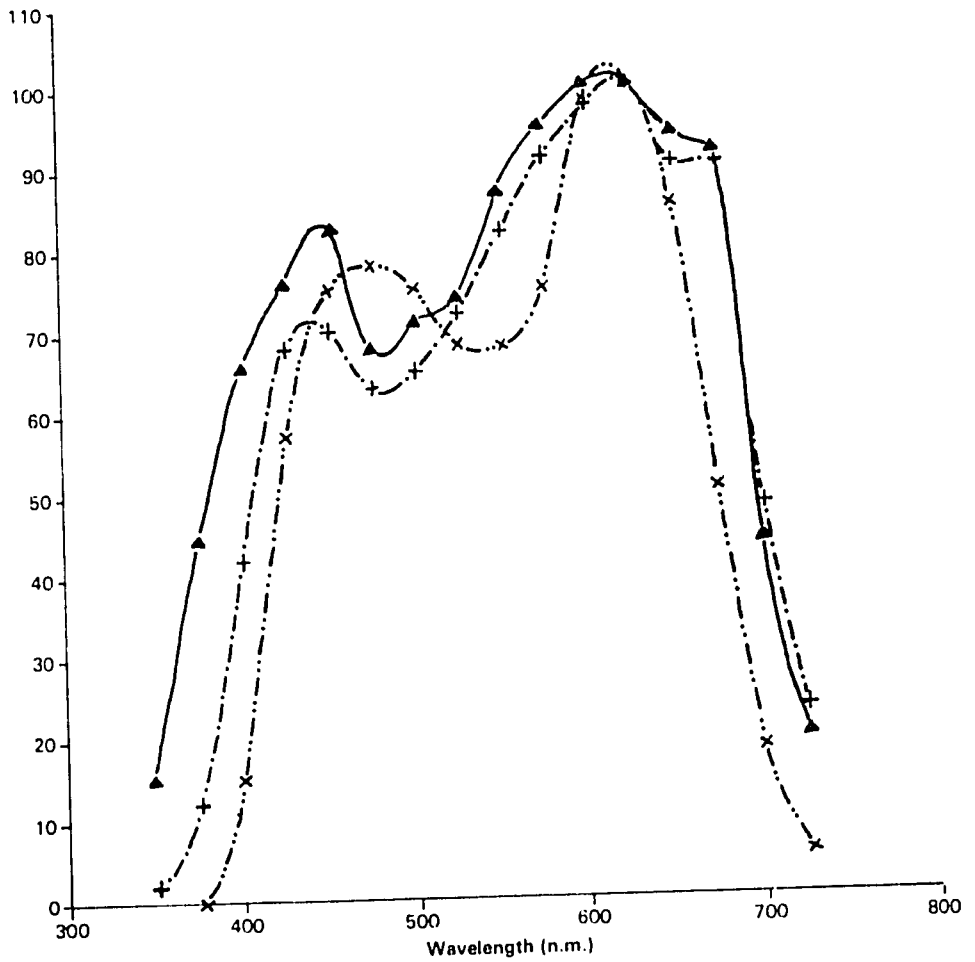
The response time of a sensor should be short in order to account for rapid changes in irradiance and photosynthesis, if instantaneous or short integration periods are used (Szeicz et al. 1964). A small surface area is required for complex systems where the spatial variation is important. Tube solarimeters are useful where spatial averaging is

required as in row crop situations but tend to have deficiencies in angular response when filtered to measure PAR (Blackburn and Proctor 1983). Any sensor should have minimal interference from moisture and temperature and should not 'fatigue' with high light intensities, as has been the case with many of the filters in tube solarimeters.

The most popular sensor designs are based on silicon photocells with glass filters to remove the infra red response. These are stable and readily constructed (Williams and Austin 1977; Woodward and Yaqub 1979; Newman 1985). Selenium-cell-based sensors have the advantage of lower filter costs and are cheaper per unit active area in many instances (Newman 1984; Powell and Heath 1964; Jackson and Slater 1967).

All sensors are used with a load resistor in the short circuit mode in order to give a linear current-irradiance relationship and improve temperature stability. The spectral response of a PAR sensor built by the author from readily available components is given in Figure 2, along with the spectral response of crop species.

Figure 2 Spectral response of senor (x) and mean response of 20 field crop species (+) and 8 species grown in the field (▲). (McCree 1976; Berman, Biran and Braunstein 1978).



Temporal aspects of PAR in agroforestry

Essentially this is no different from other systems in that the focus of the study will relate PAR to the period when the leaf area of the components is active. In order to compensate for changes in solar incidence angle, sampling should occur through the day either by instantaneous sampling over the sensor array or by integrating the value over the entire period. Changes in phenology throughout the year will be important in many studies.

Methods for integration or instantaneous logging

Electronic data loggers are now a reliable method for giving detailed information on the temporal variation in intensity of PAR. But at scan rates requiring five minutes (Anderson 1964; Newman 1984) or even two minutes (Salminen et al. 1983), analysis of the large quantities of data generated may require a main frame computer. The expense of the logging and analysis of data and the problems of security and signal loss due to damage to wires often precludes their use in remote sites.

In estimating canopy transmissivity, an integrated reading taken over the period of a day or more will often suffice. Several methods of integrating light measurements have been developed. These can be classified into electronic, electrochemical and photochemical methods. Commercial electronic integrators tend to be rather expensive, costing well over £ 100 (Appendix). Designs for the construction of inexpensive electronic integrators have been published (Woodward and Yaqub 1979; Saffel et al. 1979; Collocott 1980). The basic working principle is the conversion of the voltage output from a PAR sensor to a frequency which is fed to a counter. These devices can be difficult to construct in quantity and may require frequent changes of batteries if used for a long period (Woodward and Yaqub 1979). Recent advances in Complementary Metal Oxide Semiconductor (CMOS) chips with low power consumption should improve this (Collocott 1980). One design (Saffel et al. 1979) uses a calculator for the display counter and should reduce costs.

Electrochemical integrators that use the voltage output from a sensor have been used in the past. These involve some form of electrolysis or electroplating to integrate the output. Examples included the Siemans-Megatron direct-current meter which involved the measurement of gas volume from the electrolysis of dilute sulphuric acid (Trickett and Moulsley 1955), unfortunately no longer available. Another way is to measure the change in weight of copper deposited on copper or silver electrodes dipped in copper nitrate solution (Powell and Heath 1964; Jackson and Slater 1967; Fairbairn 1954). A further method involved the use of mercury coulometers where the position of a small volume of electrolyte is measured after the change in volume of mercury electrodes in a capillary tube. Weighing coulometers are difficult to read and will not stand any sudden shocks during transit or use.

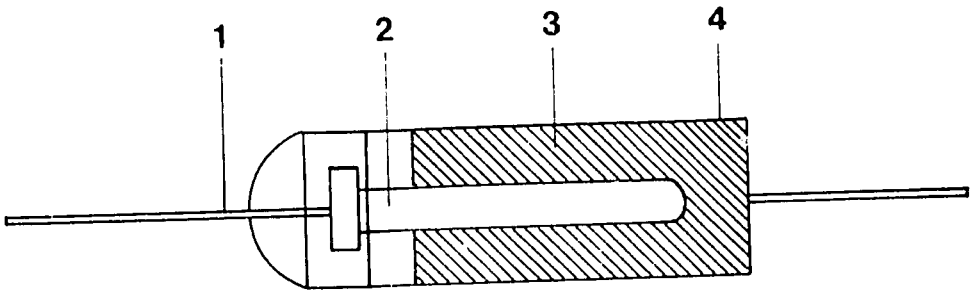
Photochemical sensor integrators in the form of photosensitive film/solutions have been used but suffer from sensitivity to infra red and ultra violet radiation and a poor angular response (Anderson 1964).

More recently, coulometers known as E cells have been used (Berman et al. 1978). These are inexpensive, accurate, can be read electronically and were used in the system outlined below.

E cells as integrators

E cells are small inexpensive components consisting of a silver can electrode housing a solution of silver ions and a gold electrode (Figure 3). They are distributed by G. E. Electronics in the UK (Appendix). The cells have an impedance of about 200 ohms at room temperature. They can be connected directly to a photocell sensor with an output of 50-100 μ A per kW m^{-2}.

Figure 3 Design of an E cell coulometer. Wire (1); gold electrode (2) insulated from silver can (4) by plastic plug; silver can contains silver ion electrolyte (3). (Monteith 1973; Berman, Biran and Braunstein 1978).



The electrochemical capacity of the integrator is about 2.2 x 10^{19} silver atoms. The small self-contained component which looks like a small electrolytic capacitor can be readily mounted into a bnc plug. During operation, radiation reaching the sensor is converted into a current which is used to plate silver from the electrolyte onto the gold electrode. In order to 'read' the device, the E cell is removed from the circuit and a current passed in the opposite direction. The characteristics of the cell change drastically when all the silver is depleted from the gold electrode. As this point a potential difference exists that signals that the end point has been reached. The time taken for this end point to be reached is directly proportional to the total quantity of radiation falling on the sensor.

Using home made sensors the cost of a sensor integrator unit was below £ 10 (-Newman 1985). The total capacity of the E cell is 1000 μ A h. The output of the sensor is varied by changing the active area of the photocell. One determines the maximum amount of radiation to be recorded in kWh and attenuates the sensor to keep the integrator below full capacity during operation. This attenuation is achieved by optically masking the surface of the surface area or selecting components with appropriate surface area. It cannot be achieved by electrical means. Periods of one hour to one week can be integrated but radiation sensors should not be left unattended for more than one day due to errors produced by dirt and dust deposits.

Inexpensive interfaces for low cost microcomputers can readily be constructed (Newman 1985) to time deplating and convert this into the quantity of PAR per unit area. Calibration is carried out using a Kipp solarimeter. Other sensors could be used for measuring quanta or spectral quality. The instrument is stable at a wide range of

temperatures (-15°C to +60°C) and can be used for over 10,000 times at low generating currents without loss of performance (Newman 1985). A certificated instrument will handle 40 channels and an RS232 interface is now available commercially (Didcot Instruments)

Conclusions and suggestions for further research

Due to the complex nature of agroforestry, any characterization of PAR will require the use of many sensors. The most popular sensing instrument used in complex discontinuous canopies is the filtered photocell in the form of a PAR or quantum sensor. Self-contained battery-powered integrators or E-cell integrators are recommended rather than data loggers for less-detailed agronomic studies due to lower cost, greater reliability and ease of data analysis. A list of UK manufacturers of equipment for PAR measurement is appended.

Further statistical research is required to optimize sampling pattern in a spatial and temporal sense. Recent developments in materials such as photochromic glass should allow the development of stable chemical methods for integrating PAR.

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Woodward, F.I. and M. Yaqub. 1979. Integrator and sensors for measuring photosynthetically active radiation and temperature in the field. *J. Appl. Ecol.* 16: 545-552.

Appendix: Instrument suppliers

Delta T. Devices Ltd., 128 Low Road, Burwell, Cambridge.
Didcot Instruements Ltd., Station Road, Abingdon, Oxon.
G.E. Electronics Ltd., Eardley House, Campden Hill Road, Kensington, London.
Skye Instruments Ltd., The Old Manse, Skeabost Gridge, Portree, Isle of Skye.

Appropriate instrumentation and the appropriateness of instrumentation for agroforestry and agricultural research in developing countries

C.L. Coulson

Department of Crop Science, The University of Nairobi
P.O. Box 30197, Nairobi, Kenya

C.J. Stigter

Department of Physics and Meteorology, The Agricultural University
Wageningen, The Netherlands

Abstract

Instruments for the measurement of crop and environmental parameters may be mechanical or electrical, simple or complex. The use of some instruments in developing countries can be problematical for various reasons.

General and specific problems of commercial instrumentation as well as the benefits and problems of alternative strategies, as they relate to developing countries, are discussed.

Introduction

Recent events in certain African countries have highlighted the critical nature of their food production and the catastrophic results which can occur when adverse natural forces impinge on fragile ecosystems. The need for agricultural research in such areas is self evident and represents an important facet of the total endevour aimed at solving or at least ameliorating the problem.

Increased food availability will depend on increased crop yields (McCarthy and Mwangi 1982); although pricing systems, extension services, storage technology, etc. will play an important part. Yield sustainability is important. The measurement of environmental variables (temperatures, rain, solar radiation, etc.) in crop space management and an understanding of crop response to these factors is important in assessing a crop's potential productivity for various agroclimatic situations and management practices.

Such physiological and agrometeorological research frequently requires electronic or mechanical instrumentation. The electronic instrument may be of the manual kind requiring the presence of the operator or the automatic kind which may be left to collect data, the data being later retrieved at some convenient time. Non-electronic instruments may range from the simple evaporimeter to the more complex actinograph.

Here we examine the problems of such instrument-based research in developing countries; propose some solutions, although perhaps partial; and discuss the spin-off benefits and problems arising from the suggested approach.

Appropriateness of instrumentation

It can be appreciated that some commercial equipment may not be suitable for use in developing countries (Coulson 1984). Besides some of the reasons that are outlined later, fundamental questions can be raised concerning the validity of measurements made by some instruments. Some of these questions can be asked regardless of the climate in which the instrument is operated, while some may result because of the extreme climate in which they are operated. Both these situations affect researchers in the Third World. In the case where the basic functioning of the equipment is suspect, the developing-country researcher may not have the back-up facilities to investigate the problem. The lack of scientific journals and technical books may be an added disadvantage. In developing countries where food production may be limited by the climate and working conditions, both of these are likely to be extreme. Such factors as the radiation load on equipment and sensors, the effects of dust, high humidity storage conditions, the rough roads that have to be travelled, etc., may render the instrument inappropriate for use in the conditions that prevail. The fact that an instrument may not perform well under them may not be fully apparent to the manufacturer or local researcher at the time when the equipment is ordered. At the more banal end of equipment problems is the fact that some equipment is not easy to physically use outdoors, though this may be as applicable in developed countries as in developing ones. However, what may be minor inconveniences in temperate climates can become major problems in extreme conditions.

Appropriate instrumentation

In the context of appropriate instrumentation we should initially consider innovation rather than invention. For our purposes, innovation can be regarded as the use of existing technology for appropriate local use. The early stages of appropriate instrument development or the assessment of alternative ones should initially involve the simplest but most useful ones, though complex commercial equipment can be tested, in some cases using relatively simple techniques. If the construction of an electronic instrument is being considered, two main problems should be assessed. The first is that the skill levels available will partially dictate the complexity of the instrument and the probability of its successful completion. Complex equipment can be expected to take longer to make and have a smaller chance of success than simpler equipment. An early and complete failure in an attempt to build or test an instrument does little to encourage further attempts. A second problem is that it is likely the components for a complex instrument may cost a lot more and may not be locally available. The cost of components in a developing country can be very high due to import duty and sales taxes and having to order them from overseas can involve long delays. It is quite possible that to make an instrument can cost more in parts than importing the ready made one, should one be available. In this respect projects with overseas 'back-stopping' have an advantage since urgently needed components or advice can easily be provided.

The equipment

Electronic

The advances in electronics over the recent years have led to increased sophistication and complexity in field instrument design. The miniaturization of circuits resulting from the advances in semiconductor device technology (Page 1985) is starting to revolutionize the instruments used in crop field research in the same way it revolutionized microcomputers. However, the restricted demand for electronic field equipment has not yet led to price reductions and, in some cases, more 'user friendliness', as has been the case with home-based consumer items.

The specialized knowledge required to design and produce commercial field equipment successfully separates the majority of users from understanding the principles of instrument sensors and signal conversion systems and thus often from information about its accuracy. The inclusion of internal calculation facilities obviating the tiresome manipulation of raw data or sensor outputs is now commonplace. The fact that some commercial equipment has the facility to interface with a microcomputer can further separate the user from understanding the equipment. Fault finding and maintenance can thus become a critical problem.

Non-electronic

Many pieces of non-electronic equipment may be used in agricultural research, particularly in agrometeorology, and some of these may be relatively simple. Simplicity and accuracy, resulting from an understanding of the principles of operation, leads to a more universal use and acceptance. For instance the Gunn-Bellani radiometer which is based on simple principles is routinely used in East Africa because of past work on its calibration. It is possible that other simple instruments could be used for research if the factors influencing their operation were better understood. Some examples are given later.

The developing country and equipment

It would seen axiomatic that countries or global regions that have a high risk potent. l for food production problems are the ones least able to support the research to ameliorate them. Bilateral and multilateral donors give assistance usually in the form of capital aid. By using such funds, equipment can be purchased, usually in the donor's country. In some cases they may provide local funds from which the recipient country can purchase equipment, again from the donor country, but overcoming the problems of the researcl er obtaining foreign exchange. While such funds are of obvious benefit to the recipien' country, unexpected problems can and do occur, e.g. mismatch between requirements and the eventually-supplied item, the arrival of non-functional or partly functional equipment and long time delays betwen purchase initiation and eventual receipt. We have experienced delays amounting to years, for equipment which was essentially 'off the shelf' in the donor country.

The rapid advances in electronics coupled with delivery delays can mean that newer models of the equipment may have been released in the donor country prior to receipt of the older model by the developing country. This can lead to problems in obtaining spare parts and, coupled with problems of maintenance, this can lead to equipment being shelved.

Cost and complexity of some commercial equipment can discriminate against young local researchers in developing countries. Besides having to generate a project in which equipment funding can heavily outweigh other expenses the researcher may be faced with the problems of foreign exchange regulations and future unexpected expenses when spare parts or overseas maintenance are required. The lack of sustainable back-up facilities during a project can put the whole scheme at risk. The high cost of commercial equipment will naturally limit its distribution in a developing country which in turn limits both the amount of data taken and possibly where the data are taken.

Lack of technical skills is a problem which faces developing countries. Although there may be the opportunity for both local and overseas training, 'hands on' experience in a local problem situation would seem to have many benefits. The involvement of local staff in, for example, small electronics projects or equipment function investigations raises skill levels and forms a basis for further training. The need for many measurements in agroforestry and agricultural research situations coupled with technical staff with low skill levels may necessitate the use of equipment that is both cheap and easily used. However the validity of using existing equipment may have to be researched. Such an endeavour may bring simpler cheaper equipment into use as well as train staff. Donor projects which provide training and technical 'back-stopping' in such situations can be invaluable in assuring that research and training efforts do not come to a premature end.

Endeavours to make appropriate instruments or in some cases assess the appropriateness of others can take place with reference to one or more specific requirements (Appendix). The requirements fall into three categories: (a) an actual need to make a specific measurement not provided by a piece of commercial equipment; (b) to overcome constraints such as the lack of money; (c) to produce a meaningful training exercise. It can readily be appreciated that each of these requirements will have its own set of individual problems. For instance with requirement (a) it could be that novel sensor applications may have to be investigated while in (b) cheap alternatives may be tried out. Being a training exercise, (c) is likely to involve a high time commitment. While requirements (a), (b) and (c) may be identified along with certain problems, interconnected 'spin-off' benefits occur. For instance if a novel instrument is produced (e.g., (a) above) or production is attempted to save money (e.g., (b) above), valuable 'hands on' training (c) may result. If the instrument is relatively simple, its potential construction by other users may be possible and the original constructors may then become involved in 'user-friendliness' considerations.

In most developing countries training may become an important common factor in all projects, since without elevating the skill levels, the problems of long acquisition time or prospects of more data being obtained may not be solved. Similarly, without the elevation of skills, problems with equipment imported from developed countries will eventually occur.

In the case studies that follow, three main areas of endeavour may be identified. One is the production of pieces of equipment, another is the assessment of simpler alternative methods or instruments. The third is the assessment of the functioning of existing commercial equipment. The first two could be considered appropriate instrumentation; the third, the appropriateness of instrumentation. In all these, the authors have noted a strong training component, whether serendipitous or intended.

Solar radiation

Solar radiation data have many uses and various types of data exist. Such data may be, for instance, collected from meteorological stations or from within crops or at crop

interfaces. Meteorological data in developed countries are increasingly being taken with automated electronic weather stations. Because of the level of technician training, shortage of money, etc., this approach may not be possible in developing countries.

In Tanzania non-electrical equipment (the actinograph and Gunn- Bellani) was used to collect data at various sites. The results were compared with more sophisticated equipment at the University of Dar es Salaam in cooperation with the National Directorate of Meteorology (Stigter and Waryoba 1981; Stigter, Jiwaji and Musabilha 1987; Stigter et al. in prep). This allowed the performance of non- electrical equipment to be assessed and simultaneously also allowed simple alternative electrical equipment to be assessed in terms of cost effectiveness. The skill levels of local staff were greatly increased by this project. Thus, in this case, while the central theme was to find appropriate instruments, a spin off was training.

Problems of maintenance, repair and power supply have been addressed at the University of Dar es Salaam for the integration of solar energy values (Stigter and Mabuba 1980; Stigter and Kainkwa 1983). Maintenance and repair problems were solved by local technical staff, previously trained through a Dutch University Co-operative Project, as they were able to identify malfunctioning electronic modules which could then be sent to The Netherlands or elsewhere (via the project) for repair or replacement. The problems of unreliable power supply were solved by the use of electrochemically integrating equipment. Rechargeable batteries which could be recharged using simple solar cells are an alternative and are presently used in the project.

Appropriate low-cost solar radiation intruments could be used in the large numbers required particularly in agroforestry or agricultural research. Such instruments have recently been described (Newman 1985). Large numbers of these could be conveniently 'read' using a microcomputer. The basic approach however uses existing technology in an ingenious way.

Requests for the loan of solar radiation equipment by graduate students of the University of Nairobi working at various research stations prompted an attempt to produce a cheap electrical instrument for PAR measurement. The problem such students faced was either the lack of any instrument for such measurements or the availability of non-functional commercial equipment which had proved difficult or impossible to get repaired. The construction of the initial instrument involved consideration of available sensors, linearization, cosine response, circuit design and construction, general construction techniques and calibration. During a three- month training scheme conducted by the University of Nairobi and the University of York, an Electronics Link technician (funded by The British Council) was able to 'update' this instrument from analogue to digital. This change has allowed new avenues of data storage to be investigated; for instance a circuit has been designed to allow many light readings to be put into memory and retrieved later. This would allow rapid spot measurements to be made in crops and at crop interfaces.

The appropriateness of some commercial solar radiation equipment has come into question during its use in our experiments. In circumstances common in the tropics, particularly in semi-arid and arid regions, it has been found that some of the materials used may deteriorate rapidly under the high solar loads experienced. The manufacturers are aware of the problem, though the field experimenter may not be initially aware of how quickly the deterioration occurs in some tropical conditions. One of us (CLC) found a filter in a solarimeter to break down after only 15 min exposure on the coast just south of Mombasa, Kenya.

Temperature measurement

Crop and soil temperatures have an impact on crop productivity through various physiological processes. Commercial equipment which measures temperature can have either or both of two main drawbacks. It can be expensive and it may not measure what it purports to (Coulson et al. 1986). Examples can be cited to illustrate both these situations.

Measurements on beans indicated that the leaf temperatures obtained depended on the instrument used (Coulson 1985; Coulson et al. 1988). The use of a small thermistor in a simple circuit for measuring leaf temperatures provided encouragement for the production of a simple leaf-temperature measuring device. This was constructed (Coulson and Musyoki 1986) with a view to simplicity and cheapness and to obviate one fault inherent in our commercial instrument. Considerations involved the analysis of problems inherent in contact leaf temperature measurements and calibration methods. Although an appropriate instrument was the initial consideration, cheapness and training were important 'spin-offs'.

Problems of non-contact temperature measurements using infra-red thermometers (IRT) have been addressed at the University of Dar es Salaam (Stigter, Jiwaji and Makonda 1982; Stigter, Makonda and Jiwaji 1982, 1983; Stigter Mwampaja and Kainkwa 1984). Besides the drawback of high cost, IRTs may suffer from other faults, calibration not being the least important. Using 'commonly available' equipment and locally developed techniques it was possible to improve the performance of a non-commercial Dutch IRT. Initially the thermocouples necessary for testing the IRT were made in Holland, though during the project it was possible to fabricate them at Dar es Salaam as well as to develop the methodology for the construction of the calibration surface.

Problems in making temperature measurements in the tropics may occur because of the high solar radiation levels. Problems may also occur in temperate regions with some types of equipment but they may be potentially more serious in the tropics. Uncontrolled radiation falling on the inlet tubing of an expensive imported piece of equipment was found to be a main cause of erroneous results in an experiment to examine leaf/air temperature differences (Coulson et al. 1988).

In field experiments there is a frequent need to take environmental readings over long periods of time, perhaps at frequent intervals. Data loggers are of use in such situations, especially at distant experimental sites. Although commercial data loggers are available, though at high cost, maintenance problems can limit their applicability in developing countries, except where there is adequate back-up.

This view depends on the situation of the individual researcher. The breadth of skills at a university can be expected to be greater than in many other situations; and as such may lend itself to the use of more complex instrumentation. For example, because of a previous successful attempt to use a simple technique and a cycling millivolt recorder to record temperatures (Coulson and Taylor 1984) and the wide skill base at the University of Nairobi, the development of a prototype temperature data logger was undertaken. It attempted to solve two problems. In the first case, further investigations on crop flower abscission (Kamweti and Coulson 1984) required the frequent measurement of air temperatures within a crop over a period of weeks; and secondly, a graduate student in the Physics Department of the University of Nairobi required an electronics project for his thesis research. The prototype logger (Namuye 1986) incorporated an existing microprocessor board which simplified the task.

In this endeavour it was necessary for people of different disciplines to appreciate problems outside their own. Besides the production of a piece of potentially useful

equipment, the enterprise served as an excellent training opportunity in the application of electronics, as well as inducing a great amount of local confidence. As a result of this experience, a field data logger is being developed for use in a Ph.D research on alley cropping in Machakos District.

Wind and air movement observations

Information on air movement parameters in and around crops is important. However, the two main problems are that commercial instruments may not measure the wind components that occur in and around crops; and in multi-point simultaneous sampling situations the necessary duplication of commercial equipment may be too expensive. In Dar-es-Salaam and Wad-Medani (Sudan) an investigation of simple appropriate techniques for measuring air movements was undertaken. Work was carried out to elucidate the factors affecting the evaporation of water from shaded Piche evaporimeters, since data from this instrument had been used to replace the aerodynamic term in the Penman evaporation equation (Stigter and Uiso 1981; Stigter, Uiso and Rashidi 1984). The instruments being simple and cheap could possibly be used as multi- point air movement sensors, via mass exchange observations. This work continues.

The use of naptha or moth balls as air movement indicators is currently being studied at Wageningen in relation to two ongoing agroforestry projects in the tropics involving air flow in low-density tree plantations. The Piché will also be tried out in these projects.

Soil water and crop water use

Information on water availability and use is of obvious importance in many developing countries. Unfortunately their measurement is not easy, particularly if it is necessary to make readings over long periods of time at distant sites.

We have been unable to successfully measure soil moisture in Nairobi using commercial psychrometric equipment. The initial interest by the overseas manufacturer in the problem seems to have waned leaving us with expensive but non-functional equipment. The equipment is now over three years old and is well out of its guarantee period. Its complexity, coupled with lack of circuit diagrams means that local repair is probably impossible. Special batteries are not available locally. A similar situation has arisen with a neutron probe. Following return from the manufacturer the probe functioned for about an hour and the new fault was diagnosed as an IC which the manufacturer says is no longer available.

Both of these problems illustrate the shortcomings of using complex electronic equipment in developing countries. Both might have been solved had an overseas-linked project been operative to cover the cost of equipment shipment back to the manufacturer and with an overseas contact to explain the fault to the manufacturer and keep track of the instrument during its repair and subsequent shipment back.

The use of resistance blocks may offer a cheaper alternative allowing many points to be sampled, an important point considering the possible inhomogeneity of soils and highly variable microclimatic gradients arising in agroforestry situations. The use of an AC bridge eliminates problems of the capacitance effect found with DC techniques, though the electronics of the meter may be sensitive to the high temperatures commonly found in the tropics. However, resistance blocks are not without their problems and some of these are presently being investigated at Wageningen through the TTMI project prior to their use in the field in Kenya, this being an example of the use of a linked project.

Lysimeters are large and expensive pieces of equipment. Parts of these could be fabricated in developing countries and it is possible that with the purchase of some parts from overseas a commercial equivalent could be produced. Comparison with simple 'oil drum' lysimeters could then take place locally.

Discussion

The consideration of instrumentation has been divided into the appropriateness of instrumentation and appropriate instrumentation. The former covers the functioning of commercial equipment under optimum conditions and extreme conditions. Appropriate instrumentation refers to the construction anduse of simple equipment whose maintenance and use is within the general skill levels locally available and whose accuracy is acceptable.

The cost of locally built appropriate instruments can be assessed. If the development is the first one attempted, the cost will be relatively high and the major part of this will be the development costs. These will include initial equipment such as soldering irons, multimeters, oscilloscopes, trial components; and the time spent by personnel. While hardware can be easily costed, time estimation is more difficult except in an industrial situation where the criterion is profit versus loss. One of the important initial considerations concerning the building of appropriate equipment is the cost advantage of doing so. High customs duties can increase costs so much that it could be cheaper to import a commercial equivalent. If this is the case little encouragement is given to local developments unless duty is waived and even if this is done the time taken to clear such items can be very dispiriting.

From the point of view of training, established courses can be costed; but frequently such courses, necessary as they are, lack relevant 'hands on' experience. Such experience is best gained in trying to solve real problems in the country in which they occur. In institutes of learning, training and research or development are the basis of the job and the training of one person helps others. In such a situation costing of time is more difficult. What is more important is the question of which endeavour is most profitably started with reference to perhaps numerous aims (Appendix).

Some of the difficulties that occur in the transfer of methodology and technology involve language. The developmental state of a language has important implications in this, since some languages have been able to embrace the abstract concepts associated with modern technology while others have not. Whether we are involved in the testing of commercial equipment or the building of appropriate equipment, this problem will exist. The development of a *lingua franca* is necessary and will naturally occur with the people involved in the various endeavours. (English has shown itself to be a convenient scientific language).

Unless we continue to find ways of dealing with the problems outlined, developing countries will be increasingly and adversely affected.

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Appendix:

Considerations for appropriate instrumentation (AI)

Scientific and educational requirements	AI considerations
Type of measurement required	Develops awareness of sensor applicability and specific measurement needs
Level of sophistication and accuracy	Develops awareness of minimum requirements and performance limits
Usability and durability	Develops awareness of practical aspects of equipment
Performance	Analysis of performance and possibility of improvement and tropicalization
Distribution and availability	More data required or more students using equipment simultaneously

Overcoming constraints	AI Considerations
Lack of funds	Possible cheapness of AI
Lack of foreign exchange	Possible purchase of components locally
Long acquisition time	Can be longer or shorter depending on complexity of AI
Lack of trained personnel to operate or maintain sophisticated commercial equipment	Simplification and dedication of equipment for local operation
Maintenance problems	Locally built, therefore locally maintained
Restricted distribution or access	Local production, maintenance and possible cheapness will increase distribution

Training of local staff	AI Considerations
Design and development skills Fabrication skills Maintenance skills Improvement of local confidence	Result from local investigations of commercial equipment and local production of equipment

The design and analysis of experiments to monitor agroforestry systems

S. Langton

Statistics Department
Rothamsted Experimental Station
Harpenden, Herts AL5 2JQ, England, UK

Abstract

The experimental designs available for monitoring agroforestry systems both on a large scale and for measurement of microclimate will be reviewed. These will include designs for investigating the tree/crop interface as well as conventional field plot trials. Analyses appropriate to the designs will be suggested.

Why design experiments?

A glance through the literature relating to the measurement of microclimate and other environmental variables will reveal large amounts of data which are the results of isolated observations rather than designed experiments. The usefulness of this work could be greatly improved by the use of properly designed experiments incorporating the principles of randomization and replication. Without replication it is impossible to judge whether an observation is an isolated freak result or is typical of the system being studied, and without randomization there is always a risk of bias.

Designs for agroforestry

It must be remembered that the same basic experimental designs are just as appropriate for agroforestry experiments as for other field experiments, and the same analyses are, in general, equally valid whether the variable being measured is yield or is an environmental variable. Thus the need for blocking and other devices to control the residual variation or 'error' still applies in agroforestry experiments, and the advantages of using a factorial design are just as great. Further details on these subjects may be found in any textbook on experimental design (e.g., Cox (1958), which is very readable). In addition the literature on the design of intercropping experiments is of considerable relevance to agroforestry and has been reviewed by Mead and Riley (1981).

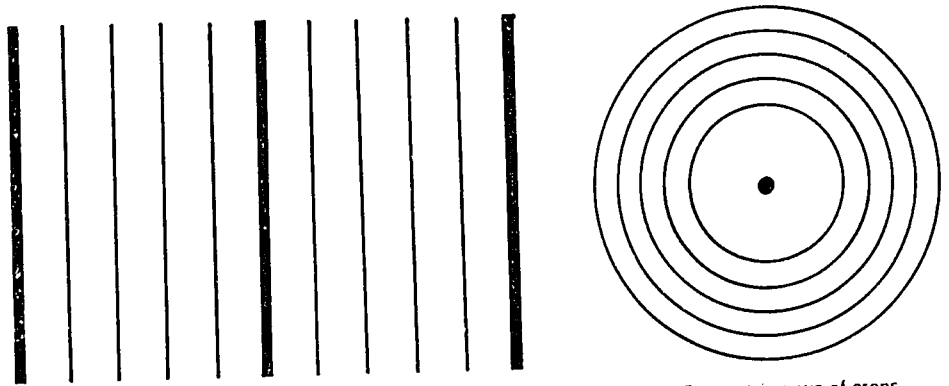
It is not, of course, possible to list the best design for every conceivable experiment. Instead I will discuss those designs which seem to have the most potential for use in agroforestry, using the following headings:

- simple designs for investigating the tree/crop (or tree/tree) interface;
- systematic designs for spacing experiments; and
- general designs for agroforestry systems.

Simple designs for investigating the tree-crop interface

Figure 1 shows two designs given in Chetty (1986) which could be used to investigate the interface. The designs should be replicated unless they are purely observational and in the case of Figure 1a the orientation should be randomized (perhaps with just two possible orientations). In both cases the analysis will involve fitting response curves describing the change in the variable measured with increasing distance from the interface. In Figure 1a, the effect of orientation could be considered and in Figure 1b, aspect (north, south, east or west).

Figure 1 Two designs for investigating the tree-crop interface:
(a) parallel rows of trees and crops;
(b) concentric rows of crops around a single tree.
Thick lines represent hedges; thin lines, rows of crops.



(a) Thick lines represent hedges, thin lines represent rows of crops

(b) Concentric rows of crops around a single tree

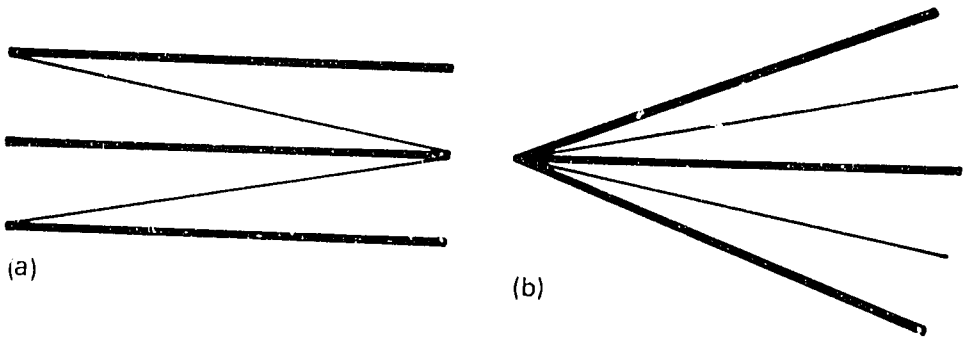
Systematic designs

Many agroforestry experiments are designed to investigate the optimal plant spacing for a particular system and in this type of experiment traditional, fully-randomized designs have a number of shortcomings. Even where the spacing of only one component of the system is to be investigated, the number of 'treatments' (i.e., different spacings) is liable to be comparatively high and, combined with the need for adequate guard areas to separate the different spacings, this results in an unacceptably large block size for a randomized complete block design. Even when an incomplete block design is used a considerable proportion of the experimental area will be taken up with the guard areas. Secondly the size of the plots needed will depend on the spacing used: closely spaced plants requiring a smaller area. This may create problems in arranging the plots in the field, unless all plots are made the same size as the largest, which again results in a waste of the experimental area.

The solution to these problems is to use a systematic design in which spacing varies in a regular fashion, thus removing much of the need for growth areas. Figure 2 shows two very simple systematic designs for a hedge-crop intercropping situation. Suitably replicated, the effect of spacing could be investigated by examining the change in yield,

or any other variable, along the length of the plot by fitting an appropriate response curve. One of the five systematic designs proposed by Nelder (1962) for use in mono-cropping situations is shown in Figure 3. The shape of the area available to each plant is constant, but its size increases radically; another of Nelder's designs varies the shape but keeps the area constant. These four designs suffer from the disadvantage that the crops are not rectangularly arranged, but lie on the arcs of circles. Bleasdale's (1967) parallel row design (Figure 4) avoids this, although at the cost of confounding the effects of area and shape.

Figure 2 Two simple designs in which spacing varies systematically. Thick lines represent hedges; thin lines, rows of crops.

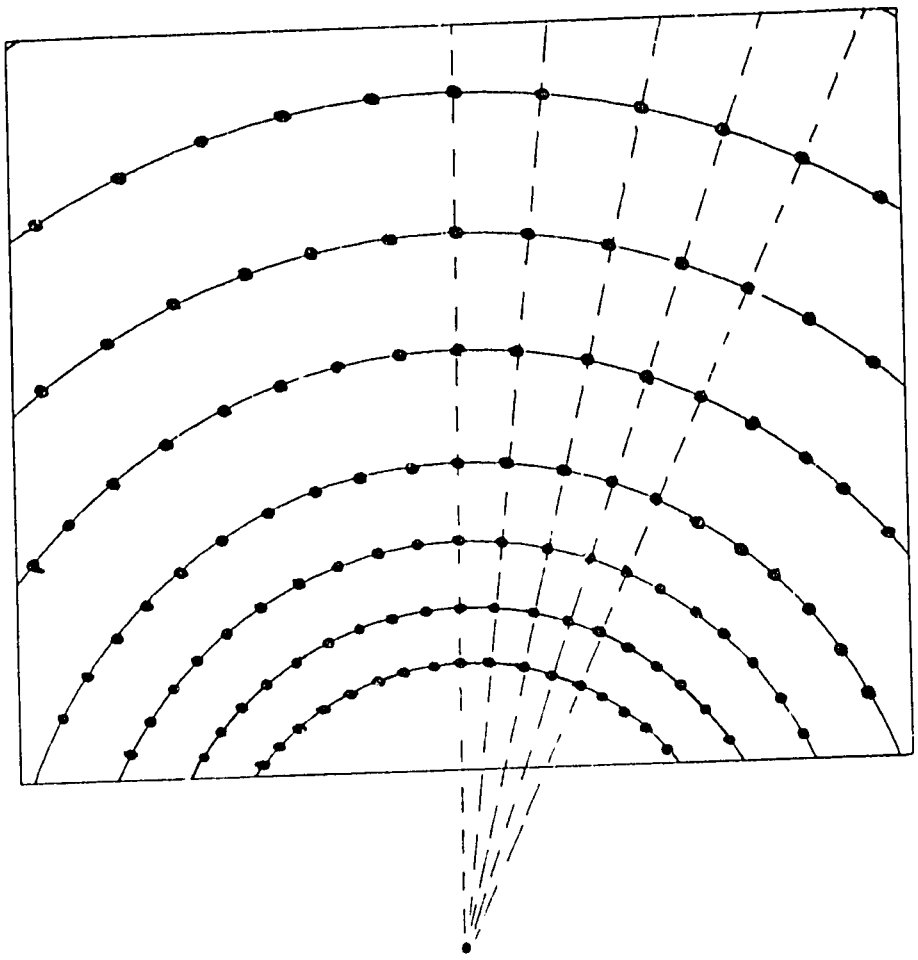


These designs can be adapted to deal with a system involving more than one species in a number of ways. Where it is desired to keep the ratio of the two species constant but vary the overall density a certain proportion of the 'spokes' (radii) can be planted with each species. Planting alternate spokes in a fan design with different crops, for example, will produce the simple design of Figure 2b (although with the within spoke density varying as well as the distance between spokes). Where the density of only one of the species is to be varied it is planted in the positions indicated by the fan design while the other species is planted on the same land at its usual spacing.

Figure 5 provides a design which allows the effect of independent variation of the densities of two crops to be examined. It consists of two parallel row designs arranged at right angles; the scale of the two designs can, of course, be different to allow for differences in size and desired density between the two crops. Analysis is again by examining response curves, but since both densities are varied, the response surface in two dimensions is now of interest. A nearest-neighbour type of analysis, which will be discussed later in this paper, may also be of use in this experiment.

Before leaving the subject of systematic designs a word of caution should be added. These designs were developed by Nelder, Bleasdale and others for use at experimental stations in Britain where the land was known to be fairly homogeneous. They should not be used on land with a trend across it, or on land that has not been studied previously, since any such trend could seriously distort the results. Even where no trends are believed to exist, the experiments should be replicated, with the replications at different orientations; this will in any case help to eliminate factors such as wind funnelling, the

Figure 3 A fan design (Nelder 1962).



effect of which depends on orientation. As long as the design is properly replicated small scale heterogeneity is less important, but will result in differences in the response curves between the replications.

Another disadvantage of the designs is that the death of one tree has an effect on the effective spacing of the neighbouring trees. It is therefore important to grow some non-experimental plants of a similar species and age nearby to act as replacements in the event of this occurring. For similar reasons systematic designs are not generally useful when thinning must be carried out during the course of an experiment. Finally it should be noted that while guard rows are not necessary within each replication, they are still needed at the edges and between the treatments where the experiment involves factors other than spacing.

Figure 4 A parallel-row design (Bleasdale 1967). Individual plants are shown only in the central section.

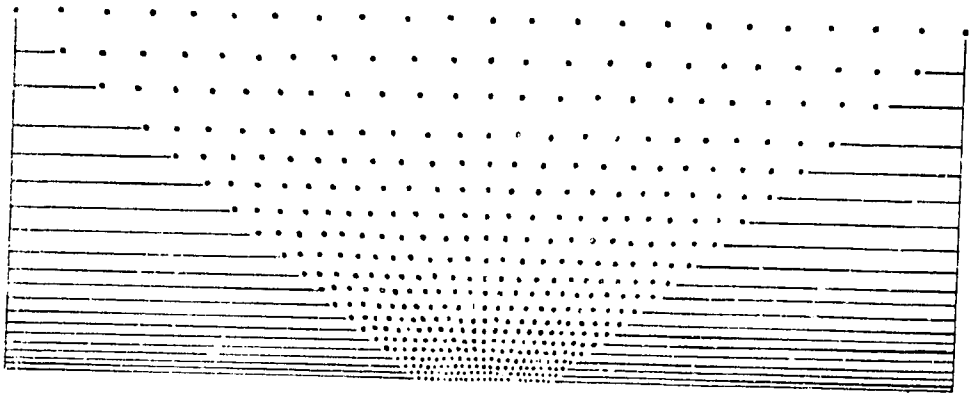
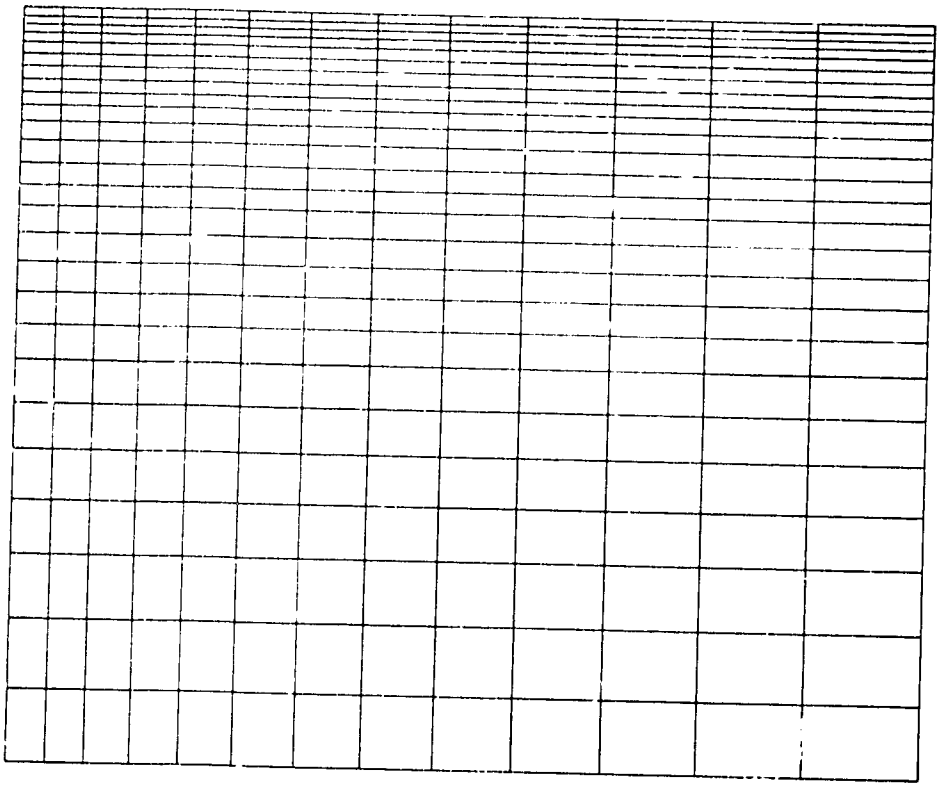


Figure 5 Two superimposed parallel-row designs. Vertical lines indicate rows of trees; horizontal lines indicate rows of crops.



General designs

As was stated above, agroforestry experiments can use the same designs that are used in single-species agronomic or forestry experiments. However, I want in this section to look at one or two more unusual designs which are particularly useful for agroforestry.

Figure 6 shows an example of a nearest-neighbour design; it can be seen that each treatment occurs next to each other treatment (i.e. to the right, left, above or below) on four occasions. Thus any deleterious or beneficial effects of one treatment on its neighbours should balance out. This may permit some reduction in the area needed for guard rows, although it is still preferable to have an adequate guard row in order to minimize such interactions. More complex designs taking account of the relative positions of the treatments are to be found in Freeman (1979). Analysis of these designs can be by the usual methods for Latin squares or special nearest-neighbour methods can be used. The latter form of analysis is still the subject of statistical research, but involves adjusting each treatment by the yield (or whichever variable is being measured) of the neighbouring plots in order to remove the effect of local heterogeneity. Nearest-neighbour analyses are of particular relevance to agroforestry since it may be possible to adjust the yields of one species in a two-species system by the yields of neighbouring plants of the other species.

Designs balanced for neighbours have also been worked out for the situation where plots are arranged in a long strip, so that only two neighbours need to be considered. These designs and their analysis are considered by Dyke and Shelley (1976).

Figure 6 A nearest-neighbour design based on a 5 x 5 Latin square.The numbers represent five different treatments.

1	2	3	4	5
4	5	1	2	2
2	3	4	5	1
5	1	2	3	4
3	4	5	1	2

Figure 7 A beehive design. The symbols o and x represent two different species. The full design consists of two hexagons, with the positions of the two species interchanged in the second one.

```
      X   X   X   X   X
    X   X   O   O   X   X
  X   O   O   X   O   O   X
X   O   X   O   O   X   O   X
X   X   O   O   O   O   O   X   X
X   O   X   O   O   X   O   X
  X   O   O   X   O   O   X
    X   X   O   O   X   X
      X   X   X   X   X
```

In most experiments plants are arranged in rows but, if the interactions between individual plants are of interest, a hexagonal grid can be useful and such arrangements have been used in competition experiments. These designs are termed beehive designs and further information about them may be found in Veevers and Boffey (1975) and Martin (1973). An example is shown in Figure 7 in which o and x represent two different species. It can be seen that different plants have different numbers of neighbours of the other species, thus allowing the measurement of competitive effects. Hexagonal designs can be easily adapted to the situation where more than two species are involved and provide a greater number of inter-specific interfaces than in a row layout.

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Sampling procedures

S. Langton

Statistics Department
Rothamsted Experimental Station
Harpenden, Herts AL5 2JQ, England

Abstract

Where large plantations are being studied it is necessary to use some form of sampling. The various methods available (eg.simple random sampling, stratified random sampling and systematic sampling) will be discussed. Particular attention will be paid to the situation where climatic variables can be used as a basis for stratification.

Why sample?

In any scientific investigation there will be situations where it is advantageous to use some form of sampling. There are three basic reasons why this may be the case:

1. Complete enumeration might take too long or be too expensive due to the large number of measurements needed; e.g., we might wish to find the average height of the trees in a 10,000 ha forest;
2. Destructive measurements: for example, the true germination rate of a batch of seeds could be found by growing them in a laboratory, but this would leave none to sow in the field;
3. In some circumstances sampling may actually give more reliable results than complete enumeration. This may arise if the smaller number of measurements allows more care to be taken over each or permits the use of more sophisticated equipment, leading to more accurate measurements.

Definitions

In everyday speech the words 'accuracy' and 'precision' are nearly synonymous, but in the context of sampling they have different meanings. **Accuracy** refers to the success in estimating the true value, whereas **precision** describes how closely clustered the values of successive estimates are. To make this clearer, consider the measurement of wind speed. If we asked four people to guess the speed and took an average of their guesses, the result might, by chance, be very accurate (i.e. close to the true speed), but would probably be imprecise (the four estimates are likely to be very different). On the other hand, if we took four readings using an anemometer which always under-recorded the speed by 20 per cent, the results might be precise, but not very accurate. The latter result could also be described as **biased**; that is, it contains a systematic error. Whether precision or accuracy is more important depends on the situation being investigated, although both properties are obviously desirable.

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In a sampling procedure the objects or sites, on which individual measurements are made, are termed **sampling units** and the **population** consists of all such sampling units. A sample refers to a group of sampling units selected from the population, on which measurements are made.

Simple random sampling

In simple random sampling not only does each sampling unit in the population have the same chance of inclusion in the sample, but each combination of n units (where n is the sample size) is equally likely to be included. This is achieved by randomly selecting each unit in the sample from amongst the whole population.

The method is best considered by taking an example. Suppose there are forty shade trees in a section of a coffee plantation and we wish to make a variety of measurements at the tree-crop interfaces of a sample of these trees. (Thus in this case the sampling units are the trees or, more specifically, the forty interfaces.) The stages in taking a simple random sample are:

1. Decide on the population. This might be all forty trees, or we might wish to exclude trees on the edge of the plantation, for example.
2. Decide on the sample size. This will depend on the equipment available and the precision required for the final estimates.
3. Select the sample by a random method (usually by using tables of random numbers). Beware of semi-random methods, such as throwing quadrats; these lead to bias.
4. Take the measurements and calculate means and standard errors.

Systematic sampling

One problem with simple random sampling is that coverage can be very uneven. Thus in the example of the last section all the trees selected to form the sample might come from the same corner of the plantation. An obvious way to avoid this is to select a regular pattern of sampling units (e.g., every fifth tree); this is systematic sampling. To give another example, in a soil survey of an area of land a grid of squares would be drawn on the map and a soil sample taken from the same position within each square. The particular systematic sample chosen must be selected at random and the simplest way of doing this, in order to avoid all risk of this, is to choose one sampling unit at random from amongst the whole population, and then to select the other units in the sample relative to it.

The advantages of systematic sampling are as follows:

1. Its even coverage will frequently lead to greater precision than a simple random sample;
2. Once the random starting point has been chosen the process is very simple to operate;
3. The information obtained can easily be used to construct a map, if desired;
4. The population size need not be exactly known at the start.

The chief disadvantage of systematic sampling is that the precision cannot be calculated and so no reliable standard error can be quoted for the mean. Approximate formulae, which give some idea of the precision subject to certain conditions, are to be found in Yates (1981) and Cochran (1977). How important knowledge of precision is

will depend on the purpose of the experiment and the nature of the variable being measured; the experimenter must weigh this against the likely advantages before deciding to adopt systematic sampling.

One situation where systematic sampling should be used with care is when there is some form of periodicity or regular variation amongst the sampling units. For example, it is obviously unwise when sampling soil on terracing 10 m wide to adopt a systematic sample at 10 m intervals (or 20 m or 30 m, etc.), since all samples will be at the same position relative to the terraces. Even when the sampling interval is not particularly close to the scale of periodicity (or a multiple of it) there is some risk of bias, especially in small samples. Unaligned systematic sampling may help in this situation (see Cochran 1977).

Stratified random sampling

Both the methods discussed so far have not exploited the structure of the population; stratified random sampling divides the units into two or more strata, grouping similar units into the same stratum. Separate estimates are then obtained for each stratum, usually using simple random sampling, and these are finally combined to give an overall estimate. Provided the sampling units in a stratum really are less variable than units in different strata, this method provides a more precise estimate than does simple random sampling. In addition the method is very useful where separate estimates are in any case needed for different sections of the population, or where it is desirable to divide the population for administrative reasons. One slight disadvantage is that it is necessary to know the sizes of the strata.

Many different factors can be used to stratify the population; for a large survey (e.g., over a whole region) it might be possible to use climatic data, where these exist. Otherwise factors such as geographic area, soil type, height above sea level, or land ownership can be used. Satellite photographs have formed the basis for stratification in some studies. On a smaller scale, any past or present knowledge of the site can be used. Where the edge of a plantation or plot is different from the centre, this can possibly be treated as a separate stratum.

Formulae for the estimates and their standard errors can be found in any of the books recommended below. These books also contain advice and formulae relating to the number of units that should be sampled from each stratum.

Discussion

In conclusion, the relative merits of the methods discussed can be summarized as follows: Simple random sampling is adequate for populations that are fairly homogeneous, particularly where the total number of units is small. Stratified random sampling, on the other hand, should be used when the population is heterogeneous, but can be divided into more homogeneous sub-populations. Systematic sampling is a good procedure to adopt when even coverage is important, but is not appropriate if exact knowledge of the precision is required, and should be used with care when there is any regular variation amongst the sampling units.

This review of sampling procedures is by no means exhaustive and the following topics would repay some study for those doing a lot of sampling; multistage sampling, cluster sampling, and ratio and regression estimators (including double sampling as a means of updating surveys, which is described in Freese (1961)).

Acknowledgement

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References and further reading

The following books are readable, and do not demand a high level of mathematical knowledge:

Freese, F. 1962. *Elementary forest sampling.* U.S. Department of Agriculture Handbook No. 232.

Freese, F. 1984. *Statistics for land managers; an introduction to sampling methods and statistical analysis for foresters, farmers and environmental biologists*. Paeony Press. (This is the same as the 1962 Freese book.)

Sampford, M.R. 1962. *An introduction to sampling theory.* Edinburgh and London: Oliver & Boyd. (This book was written for agriculturists, and is highly recommended).

Webster, R. 1977. *Quantitative and numerical methods in soil classification.* Oxford: Clarendon Press. (Chapters 4-6 cover sampling, with particular reference to soil sampling).

When further details are required the books below should be consulted. However, they are not nearly as easy to read as the above and are therefore of much less use to the beginner.

Cochran, W.G. 1977. *Sampling techniques.* New York and London: John Wiley and Sons.

Yates, F. 1981. *Sampling methods for censuses and surveys.* London: Griffin.

Finally, the following guide, which is not yet published, should be a very useful source of advice on the practical details of sampling in a forest:

Adlard, P.G. (in preparation). *Guide to the establishment, measurement and analysis of permanent sample plots.* Oxford: Forestry Institute.

The analysis of data from several sites and years

J. Riley

Rothamsted Experimental Station
Harpenden, Herts AL5 2JQ, UK

Abstract

The collection of data from different sites and/or years gives rise to a data set subject to both spatial and temporal variability caused by climatic and other variables. Any statistical analysis of the data must take into account these different types of variation; a review of the available methods with reference to agroforestry experiments is presented.

Introduction

It is common practice to extend the results of a simple experiment by repeating the trial at a number of different sites or over a number of years. Such extensive experimentation will provide information about the treatments or genotypes under a range of environmental conditions. Although sites may be chosen according to similarities of soil-type, climatic or other factors may be present that will give rise to possible differences in the results obtained. Experiments repeated over years will be subject to fluctuations in weather patterns. The analysis of data from such a range of environments permits the experimenter to determine the sensitivity of his treatments or varieties to a range of conditions and to provide recommendations about their use for a wider geographical area.

The data collected from such an experimental scheme, however, present substantial problems of analysis. Statistical analysis depends heavily upon the idea of randomness; data collected from a number of locations or from several years cannot be considered random: sites are chosen for their particular characters; and years, in terms of climate, can be considered to be correlated to some degree. Particular techniques thus need to be adopted when analysing data from treatments or varieties collected from a number of environments. Where the environments are represented by different points in time it is sometimes possible to examine the behaviour of the varieties by response curves over time with possible adjustments for seasonal effects. This is discussed in greater detail in the following paper (this Section) by S. Langton. Concentration here is on the more general data set classified according to treatments (or genotypes) and environments.

Analyses available

Much statistical research has been done on the examination of genotype x environment data sets and, since no single technique has been found for analysis, research is continuing. A summary of suitable approaches to the analysis of such data sets is given

in Freeman (1973). More recent work was presented by Silvey (1982) and by Goodchild (1982) at the XIth International Biometric Conference.

Although each data set requires analysis tailored to its structure, a common approach to the a. alysis of data collected from different environments is as follows:

1. Analysis of variance of the complete data set to determine whether genotype x environment interactions exist; if they do not exist, there is little problem but if they do exist, then interactions need examination.
2. Joint regression analysis of genotype yield on environment as described by Finlay and Wilkinson (1963) to detect genotype sensitivity to changes of environment.
3. Multivariate analysis of the genotype x environment table, possibly by one or more of the following methods:

   – principal components analysis;
   – canonical variate analysis;
   – cluster analysis;
   – principal coordinate analysis; or
   – significant rank ordering.

Analysis of variance

A most important part of any statistical analysis is to determine the questions that are to be answered. When data are collected at a number of sites, are recommendations required for each site, for groups of sites or for the one area incorporating them all? Only with this information can a relevant analysis be produced. If data are to be combined from different environments then an analysis of variance accounting for the main effects of genotype and of environment and for their interaction will determine whether any substantial interaction exists. Subdivision of the main effects and interaction into components of interest are described by Cochran and Cox (1957) together with appropriate significance tests.

Joint regression analysis

If genotype x environment interactions exist these can be examined in more detail by regressing the genotype means upon a variate of environmental indices. The sum of squares for the interaction can thus be subdivided into a component for the heterogeneity of these regressions and a remainder component. Each of these components can be subdivided correspondingly into comparisons of interest. Environmental indices can be determined in different ways. Wood (1976) examines a number of them. The usual choice of index is the mean yield of all genotypes at each environment, but others are the yield of control genotypes; climatic variables such as rainfall, altitude, temperature; environmental variables such as N% in the plant or the P content of soil; or even a combination or function of several of these external variables. The method of joint regression analysis provides useful indications of the behaviour of each genotype as external conditions vary. Response to environmental change cannot always be expected to be linear and an extreme index value for one site may well distort results. In practice it would be wise to perform such regressions for several different forms of index to avoid the use of spurious results.

Multivariate analysis

The data in the two-way genotype x environment table can be considered as a multivariate set in order to investigate the variation within it more fully. Principal component analysis can be used to identify those environments that are most influential in the production of interactions. Similarly, the technique can be used to identify groups of genotypes contributing largely to the interaction. The method is described clearly in Holland (1969); a brief outline is given here.

Principal component analysis involves the transformation of the original variates into a new set, usually of fewer variates, which are independent and which successively account for maximum proportions of the total variation. The independence property means the new variates are more easily examined by standard statistical methods; the fact that fewer variates are involved means that calculations are less cumbersome. Although principal components do not necessarily correspond to biological interpretations, Holland (1969) shows that by geometrical manipulation linear functions of the original variates can be found, having biological meaning, thus aiding more fully in the interpretation of the data. Canonical variate analysis has been used by Paterson (1974) to test whether the environments differ in their response to the treatments (-genotypes). Although the treatments are not random effects, Paterson was able to produce a satisfactory analysis, although the method appears to be of most use with large data sets.

Other methods used are cluster analysis and principal co-ordinate analysis. In cluster analysis, attempts are made to find similarities between clusters of environments using the yields from the treatments or genotypes. Various methods for calculating similarities exist and these may give rise to different clusters. Principal coordinate analysis has also been used by Shukla (1972) to demonstrate groups of genotypes making similar contributions.

A recent approach to the examination of genotype x environment interaction data is presented in Beale and Goodchild (1980). They used analysis of variance followed by a ranking process and called this significant rank order. It should be noted that this approach was suitable for the data in question, analysis of variance alone and ranking procedures alone not being used because of the nature of the variation in the data and the small number of replicates. Analysis of variance was used for the data from each environment (site) separately to provide least significant differences (LSDs). The means for the genotypes within each site were then ranked and grouped together if their difference was less than the appropriate LSD. The groupings obtained were compared from site to site. Interactions could be clearly seen through such examination. Care, however, is needed when using the LSD since its use over many pairs of means gives low precision.

Discussion

If data from many sites are required to be combined then no single method of analysis exists. Exploration of the data is necessary by several approaches: joint regression analysis to determine the response of the genotypes to site fluctuations and multivariate approaches to determine clusters within sites (environments) or within treatments (genotypes). The nature of the experiment and the form of the data will need close scrutiny to indicate which analyses are suitable and whether any further modification of the analyses is necessary; no routine form of analysis is possible, the analyses chosen depending upon the information required from the data.

Acknowledgement

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The analysis of data collected over time

S. Langton

Statistics Department
Rothamsted Experimental Station
Harpenden, Herts AL5 2JQ, England, UK

Abstract

Experiments are frequently carried out on the same experimental plots over a number of years. This poses a number of problems which will be described, together with the proposed solutions. In particular, the use of response curves for describing changes in yield over time will be considered.

Introduction

One difference between experiments involving trees and those involving field crops only is that the former generally continue for a period of years, whereas the latter often only last for one year or season. Thus in agroforestry experiments the data frequently consist of sets of successive measurements of the variables of interest, one set for each year or season, with the same treatments being maintained at each plot through the experiment (this situation should not be confused with a cross-over type of experiment, where different treatments are applied successively to the same experimental units). Such data are referred to in the statistical literature as 'repeated measurements', and the best way of analysing them has been a subject of considerable controversy.

Methods of analysis

The simplest method of dealing with repeated measurements of this sort is to sum or average them over time, and then carry out an analysis of variance on these sums or means. This analysis is perfectly correct from a statistical point of view, but provides no information regarding changes in the data with time.

One procedure that has been used to produce such information is simply to produce a separate analysis of variance for each time or season. Each of these analyses, with its associated tests of significance, is completely valid but, because results in successive seasons will almost certainly be correlated, the analyses are not independent of each other. In practice this means that, for example, significant treatment effects in five successive years in the experiment do not provide such good evidence for real differences between treatments as would significant treatment effects in five totally separate experiments. This type of analysis is not as attractive as it appears at first sight.

One common, but erroneous, method of analysis is to treat time as a factor, usually a sub-plot factor in a split-plot analysis. The first objection to such an analysis is that time can never be properly randomized; each treatment is in its second year of growth in the same calendar year, for example. Randomization is, of course, essential for a

valid analysis of variance. A further problem with the split-plot analysis is that the sub-plot error is unlikely to be homogeneous, because observations closer in time are likely to be more closely correlated than those further apart (Rowell and Walters 1976). Similar objections apply to the 'split-block' or 'criss- cross' type of analysis which is sometimes recommended.

Multivariate methods have sometimes been used for the analysis of repeated measurements (Cole and Grizzle 1966) and this approach is unquestionably valid. Unfortunately these methods are conceptually more difficult and the results are not always easy to interpret. Hence there is a strong case for avoiding a multivariate approach where there is an alternative that is statistically sound.

The fifth method provides such an alternative; it was first used by Wishart (1938) and was described in detail by Rowell and Walters (1976). It involves the analysis of contrasts over time, and is discussed below.

The analysis of contrasts over time

The hypothetical example that I will use to describe this method consists of an experiment arranged as three randomized blocks of three treatments each (Table 1). The treatments are actually three different agroforestry systems and the objective of the experiment is to compare the changes in soil moisture content between the systems. Measurements were taken every 30 days over a period of 90 days following rain; during this time there was no rain or irrigation so the soil moisture content shows a continuous decline.

Table 1 Hypothetical data for analysis

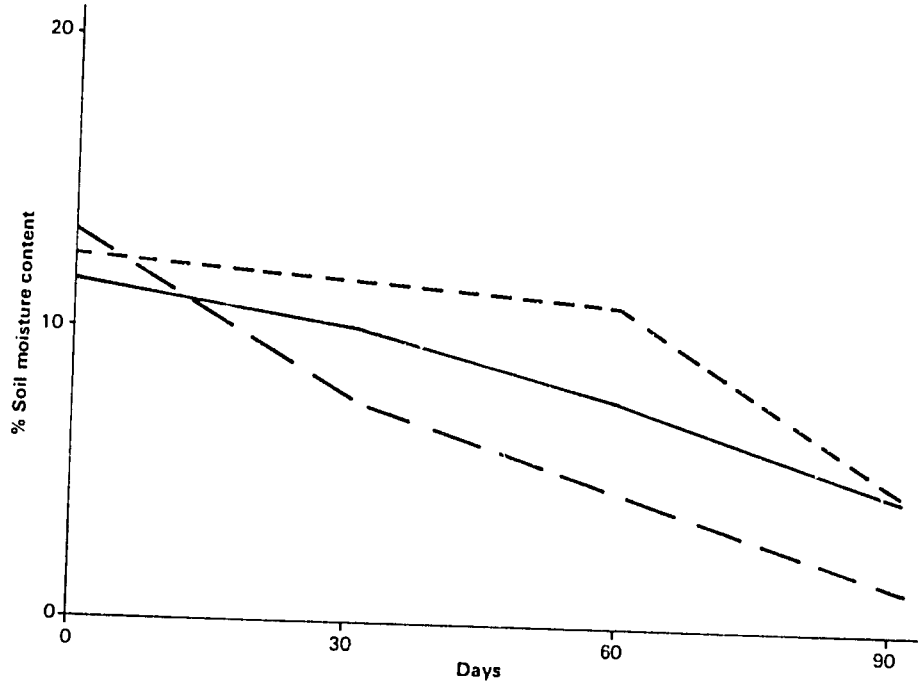
System	Day: Block	0	30	60	90
		Moisturecontent, %			
1	1	19.83	14.83	12.17	8.67
	2	20.58	14.58	11.92	9.42
	3	21.08	17.08	12.42	7.92
2	1	20.58	19.25	17.58	9.08
	2	19.33	20.00	19.33	12.83
	3	20.58	19.25	17.58	13.08
3	1	19.67	17.50	14.00	12.33
	2	19.67	17.50	15.00	11.33
	3	19.17	18.00	16.50	11.83

NB: Variables measured on a percentage scale should normally be transformed before analysis.

The first stage in the analysis is to plot the mean soil moisture content for each system against time (Figure 1). This graph clearly shows that the moisture content is decreasing

with time and, as is the case in many of these analyses, orthogonal polynomials can be used to break the change down into linear, quadratic and cubic components.

Figure 1 Graph showing the changes in soil moisture content for the three agroforestry systems (—— system 1; ------- system 2; – –system 3)



The formal analysis is best described starting with the erroneous split-plot type analysis of variance (Table 2) described in the previous section.

Table 2 Analysis of variance with split plots

Source of variation d	d.f.
›cks	2
systems	2
error (a)	4
total between plot	8
days	3
systems x days	6
error (b) (blocks x days + blocks x systems x days)	18
total within plot	27
total	35

As was mentioned earlier, the problem with this is that the within-plot error (error b) is heterogeneous; this problem is solved by splitting it into separate components for the linear, quadratic and cubic contrasts, in the same way that the time effects can be split. To carry out this split it is also necessary to divide error b into the two interactions that make it up (blocks x days and blocks x systems x days). The resulting anova table is shown in Table 3. Such a table can easily be produced using a computer package such as Genstat or can be calculated by hand by the methods described in any good textbook on the analysis of designed experiments (e.g., Cochran and Cox 1957).

Table 3 Analysis of variance with interactions

Source of variation		d.f.	s.s.	m.s.
block		2	3.500	1.750
system		2	60.577	30.288
block x system	(error a)	4	1.833	0.458
days		3	426.173	142.058
linear		1	415.538	415.538
quadratic		1	8.517	8.517
cubic		1	2.119	2.119
system x days		6	37.907	6.318
system x linear		2	16.077	8.039
system x quadratic		2	20.408	10.204
system x cubic		2	1.421	0.711
block x days		6	2.000	0.333
block x linear		2	1.644	0.822
block x quadratic		2	0.222	0.111
block x cubic	(error b)	2	0.133	0.067
block x system x days		12	16.000	1.333
block x system x linear		4	7.822	1.956
block x system x quadratic		4	6.444	1.611
block x system x cubic		4	1.733	0.433
Total		35	547.990	

The contrasts can now be compared with the appropriate component of the error variance; for example quadratic contrasts will be compared with a mean square calculated from block.quadratic and block.system.quadratic. The tabular form given in Table 4 (after Rowell and Walters 1976) is a clear way of displaying this. The days and system x days mean squares are taken directly from Table 3, but the error terms are obtained by adding together the appropriate component of the block x days and block x system x days sums of squares and dividing by the degrees of freedom (e.g., for the linear contrast:

$$(1.64 + 7.82) / 6 = 1.58).$$

Table 4 Analysis of variance of linear, quadratic and cubic components

Source of variation	d.f.	linera	quadratic	cubic
days	1	415.54	8.52	2.12
system x days	2	8.04	10.20	0.71
error (block x days + block x system x days)	6	1.58	1.11	0.31

Now by comparing the days and error rows of Table 4 it can be concluded that the overall trend is mainly linear, but with smaller quadratic and cubic components. The system x days interaction gives information about the way these trends vary between systems; it can be seen that the differences lie in the linear and quadratic components, especially the latter.

Orthogonal polynomials are not always the most appropriate form of contrast to use, and the method will work with any set of contrasts. Yates (1982) gives some alternative suggestions for a medical example where the curves are sigmoid. Rowell and Walters consider an example concerning yields of apples over a 14 year period. The graph of yield against year shows that while there is a gradual increase in yield, good and bad years alternate. Such biennial yields are best dealt with by considering sums and differences of successive years. The seven two-year totals showed the overall increase, while the seven differences demonstrated the extent of the biennial effect. Orthogonal polynomials were still used within the two analyses to reveal the changes in these effects with time.

A brief mention should be made of the number of times at which measurements should be made. Sometimes this will be dictated by other factors, but in many cases the experimenter will be free to choose. In experiments such as the soil moisture content example, where there is a regular pattern of increase or decrease, there is seldom much point in measuring at more than four or five times. Five times would permit fitting terms no high as quartic, and it is unlikely that we would be able to interpret terms higher than this, even if they were significant. Of course if there was the possibility of some more rapid change of soil moisture during the experiment (e.g., due to rain or irrigation) we might wish to make a more regular check to study this.

Other uses of this technique

Although all the literature on this method refers to measurements repeated in time, there is no reason why it should not be used for measurements repeated in space in situations where the level of correlation decreases with increasing distance apart. Examples might be where measurements of yield or microclimate are being made at different distances from a tree or where vertical profiles of CO_2 concentration or wind-speed, for example, are being compared between systems.

Acknowledgement

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Agroclimatic analysis for semi-arid climatic conditions

P.S.N. Sastry

Division of Agricultural Physics
Indian Agricultural Research Institute
New Delhi 110012, India

Abstract

Since development of Köppen's climatic classification, several indices have been used to delineate climatically homogeneous regions and some of them have been applied to agroclimatic classification in several countries. The delineated regional patterns, whether based on rainfall or climatic water balance which includes the soil factor, do not generally differ from one another and one technique can be considered as good as the other. Semi-arid regions like the Indian subcontinent being characterized by both spatial and temporal variability and advective conditions during the break monsoon periods, the effect of climate on different phenophases assumes importance. The need for a phenology-based analysis of rainfall probability for agroclimatic purposes for major crops is brought out.

Introduction

Delineation of climatically homogeneous regions has been an important aspect of agroclimatic analysis that received extensive attention since the 19th century. Mainly, such an analysis sought to explain natural vegetation-climate relationships based on rainfall, temperature and potential evapotranspiration either singly or in combination. Inclusion of soil moisture holding capacity and water balance concepts developed by Thornthwaite was considered to provide a rational basis for climatic classification. These techniques serve the limited purpose of identification of natural climatic boundaries that represent the different plant communities, soil groups and land forms in terms of numerical climatic data and bring out vegetation-climate associations.

While climatic classification is a preliminary step, it is often supplemented by rainfall reliability analysis and presented in the form of rainfall probability maps in order to meet the requirements of crop planning. The form that such a rainfall reliability analysis should take to meet specific requirements such as those of agroforestry or crop planning does not seem to have received adequate consideration. The need for inclusion of a crop parameter into such an analysis is discussed below.

Rainfall distribution and climatic indices

An examination of normal annual rainfall distribution map of India in comparison with the patterns that are obtained using several climatic indices that have been proposed from time to time – climatic types according to Köppen's system based on rainfall and

temperature, Thornthwaite's system based on moisture regime using climatic water balance (Subrahmanyam, Subba Rao and Subramaniam 1965), Meyer's N-S quotient, Lang's rainfactor, rainfall versus mean annual temperature range or potential evapotranspiration (Figures 1, Appendix) -- indicates a striking similarity in the nature of delineated zonal patterns. The regions of mean annual water deficiency (Subrahmanyam 1982), while yielding valuable quantitative estimates for purposes of long term planning of water resources of a region, do not in any way differ from the pattern that could be expected from the normal rainfall distribution map. Thus, while the individual indices evolved for different purposes have their own significance, as far as delineation of areas of climatic homogenity in general is concerned, it could be concluded that one technique is as good as the other for identifying climatic types. Except for the differences in the quantitative coefficients or magnitudes, the different indices clearly point out the dominant role played by rainfall amount and its spatial distribution in relation to the physiographic features of the region in determining the climatic types of India, which is subtropical and predominated by semi-arid climatic conditions over a large part.

Phenology-based agroclimatic analysis

In the season when rainfall is the dominant factor, its non-occurrence for a few days in the semi-arid tracts is associated with periods of high temperature and increased evaporative conditions (Sastry 1976). The Indian subcontinent is characterized by:

- break monsoon situations (induced by changes in upper air circulation) during the crop growth season prevailing for two to three weeks at a stretch causing dry spells over a large part of the country and
- early withdrawal of monsoon rains two to three weeks earlier than normal, which has been the experience during the recent decade also.

The break monsoon situations were found to bring in advective conditions (Sastry 1979) which may cause yield reduction even in an irrigated crop such as paddy (Sastry 1986) due to atmospheric stress when there is energy transfer from the surroundings to the evaporating surface. Such an effect is also reflected in the water balance in the root zone in particular seasons as shown in Figure 2 for different growth phases of pearl millet crop.

It is significant to note that because of high temporal variability, such situations occur at different crop growth stages in different years and irrespective of the total seasonal rainfall the drought severity varies from year to year, such as that illustrated for corn crop in Table 1 (Appendix). Thus the growth stage of any particular crop at which adverse environmental conditions occur in different years is of significance as this becomes an important yield determining factor. This is particularly so, since susceptibility of crops to same adverse weather conditions differs between crop species or even from one growth stage to the other. In this context, relation of rainfall reliability or water balance probabilities to growth stages of major crops can be considered to provide a better base in agroclimatic analysis. For instance, information on meteorological drought probabilities if related to phenophases of crops grown in a region would enhance its practical value in planning cropping or agroforestry systems. On this basis, using the Markov chain model, Victor and Sastry (1979) developed two different cumulative probability nomograms for dry spell runs during monsoon season at Delhi using (a) calendar months (b) growth stages of pearl millet crop.

Figure 2 Water balance during developmental phases of pearl millet crop. IARI, New Delhi.

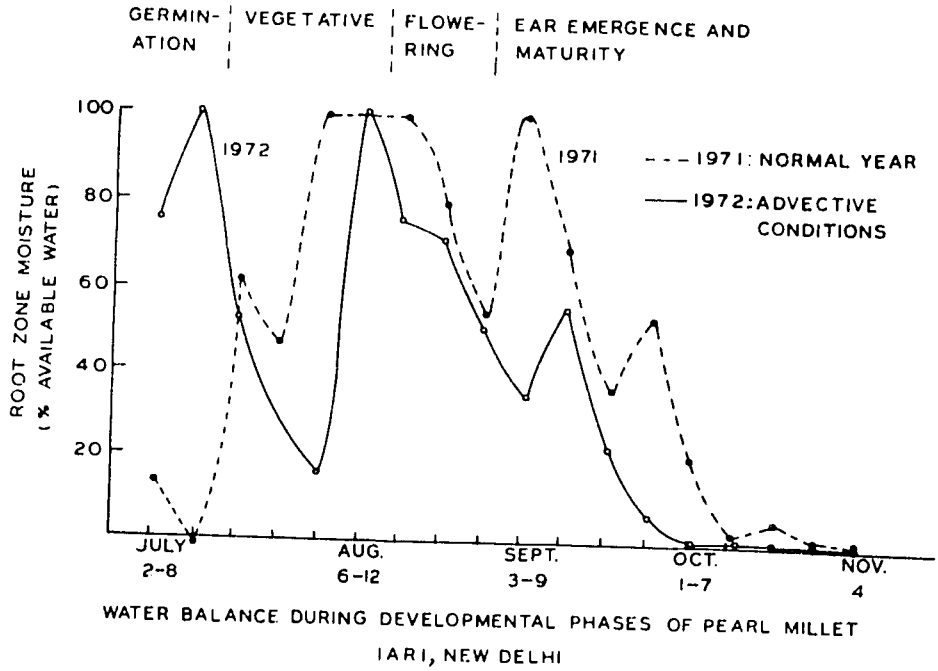
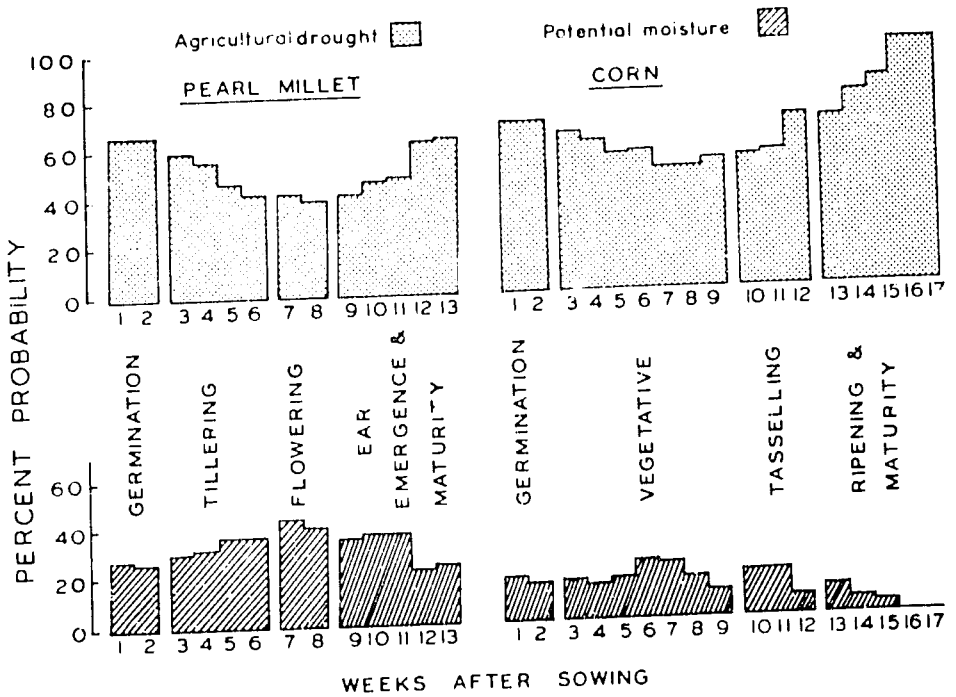


Table 1 Distribution of dry weekly periods starting July 1 in the crop phases of maize at New Delhi. (Sastry 1976)

Year	Week No. (x = dry year)																	Rainfall July-Oct mm	Drought class
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17		
1951		x	x	x		x		x	x	x		x	x	x	x	x	x	214	Disatrous
1940	x	x					x		x	x	x	x		x	x	x	x	527	Severe
1952		x								x	x	x	x	x	x	x	x	360	Moderate
1942	x					x						x		x	x	x	x	522	Light
1961	x			x							x			x		x	x	925	Unaffected
	I					II					III				IV				

I = Sowing and germination. II = Vegetative phase. III = Tasselling phase. IV = Grain filling and mature stage.

Figure 3 Probability of occurrence of agricultural drought and potential moisture conditions in the root zone during growth phases of corn and pearl millet crops at Delhi, India



Comparative statistics on rainfall reliability in the different growth stages using climatic water balance techniques can be generated to assess probability of drought proneness or occurrence of potential moisture conditions in respect of two or more crops grown in the same season. This is illustrated in Figure 3 which shows that of the two crops considered, pearl millet is better suited to the local rainfall distribution since, comparatively, probability of drought is lower and potential moisture conditions higher in the different growth stages, than that for the maize crop. Similar data generated by Victor and Sastry (1984) for five major crops grown in the Delhi region in India showed that for same climatic conditions, probability of drought-proneness increases in the order: pearl millet, sorghum, peanut, corn, and upland paddy. A point to note is that such analytical approach including a crop parameter like its growth stage period in place of calendar dates permits selection and breeding of crops tailored to rainfall distribution.

It is possible to extend such analysis to several other stations in the region to obtain climatically homogeneous areas with respect to probability of moisture adequacy based on phenophases of major crops. Evaluation of probable periods of advective conditions for semi-arid regions in the subtropics would enable selection of inter-crop combinations for provision of needed shelterbelts. Such an approach to agroclimatic analysis may be expected to lead to development of integrated agroforestry system for semi-arid regions which exhibit high temporal and spatial rainfall variability.

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Victor, U.S., and P.S.N. Sastry. 1979. Dry spell probability by Markov Chain model and its application to crop developmental stages. *MAUSAM* 30: 479-484.

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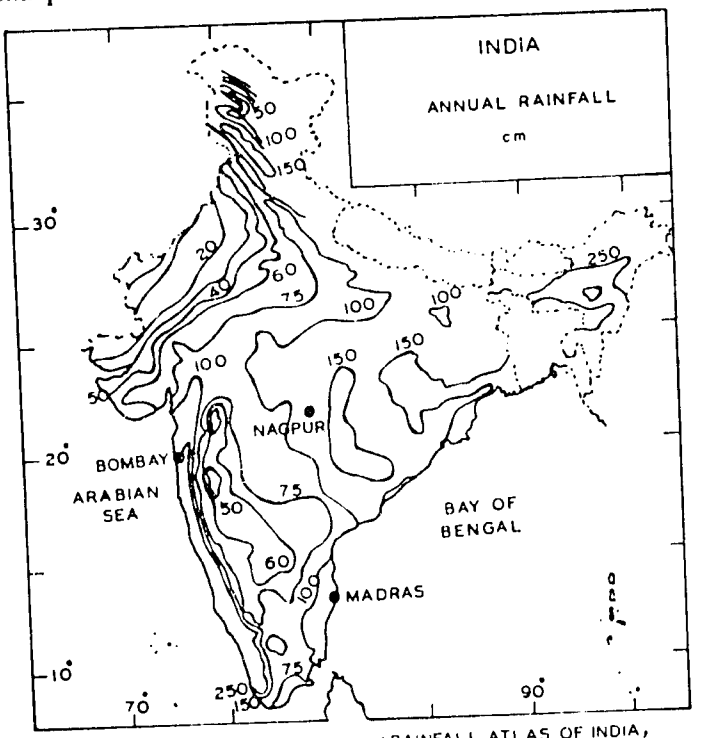
Appendix: Table 1 a,b page 342-345

Figure 1a Zonal patterns of India according to different climatic indices.



(RAINFALL ATLAS OF INDIA, IMD, 1971)

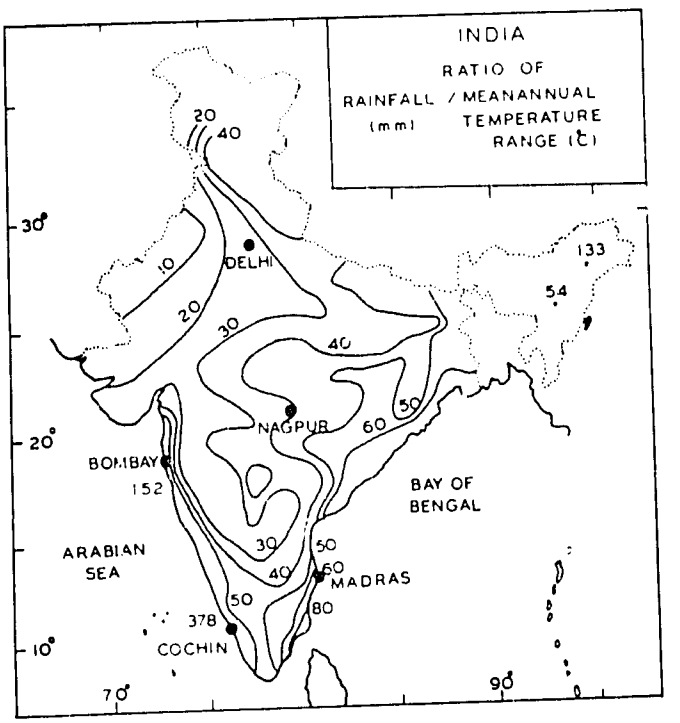
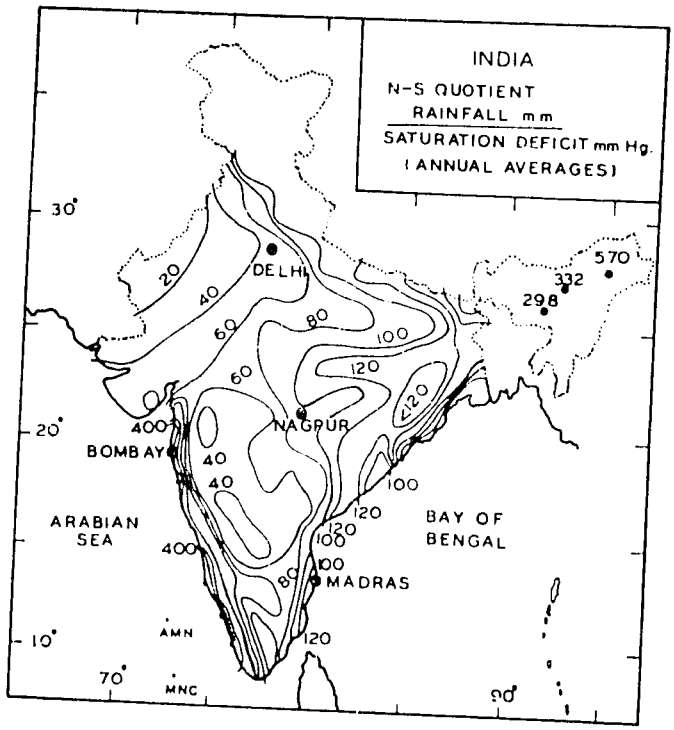


Figure 1a continued



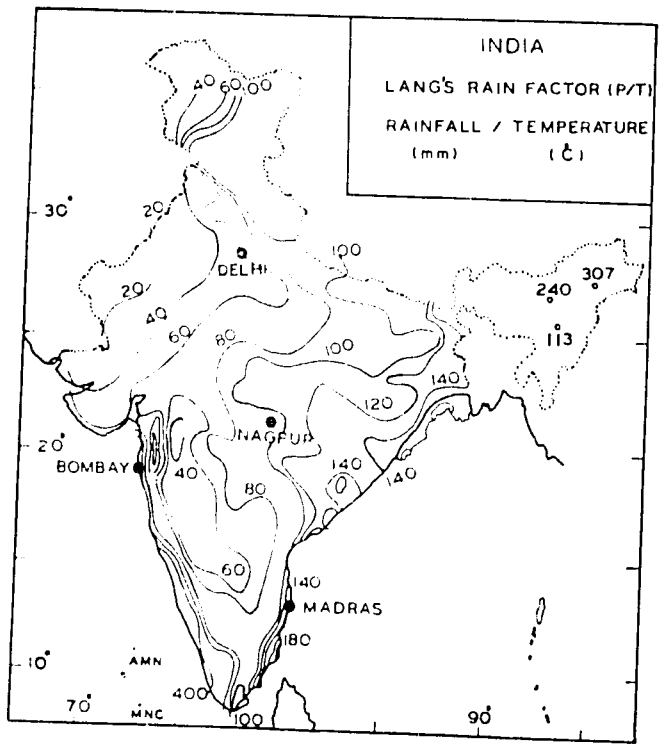
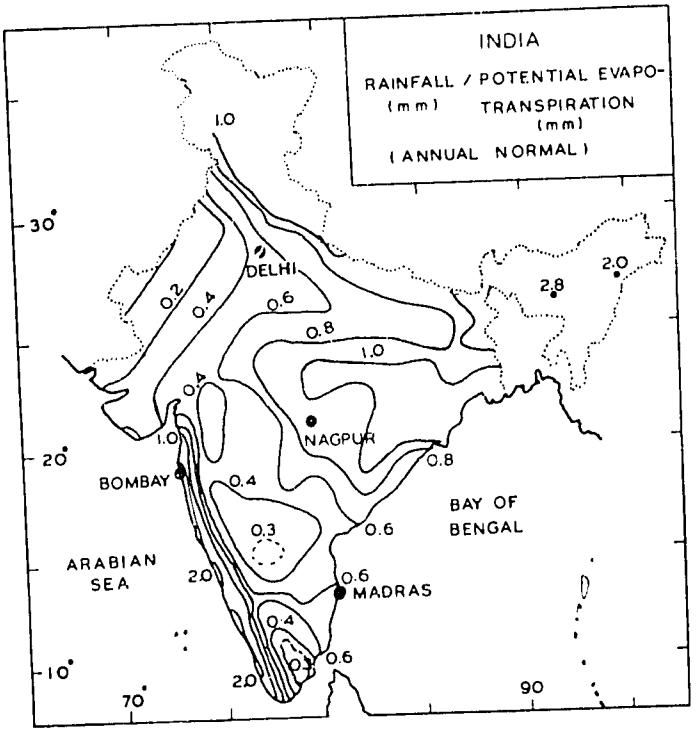


Figure 1b Rainfall/PET, climatic types of Koeppen and Thornthwaite and mean annual water deficiency patterns over India.



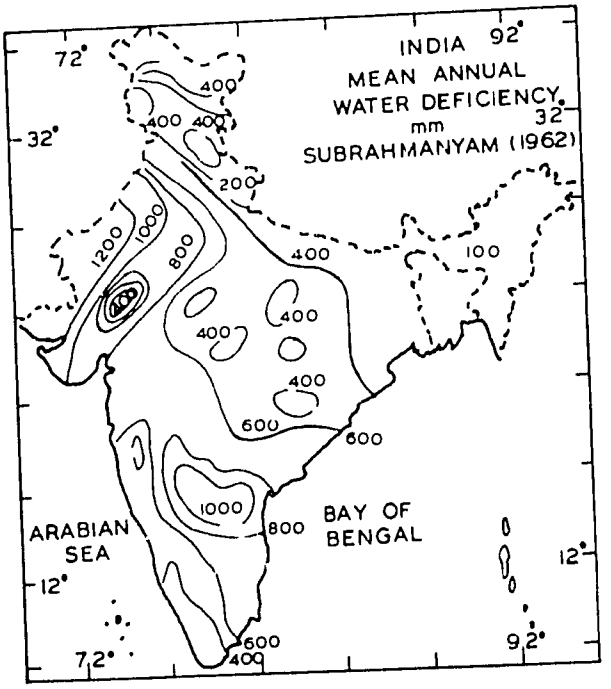
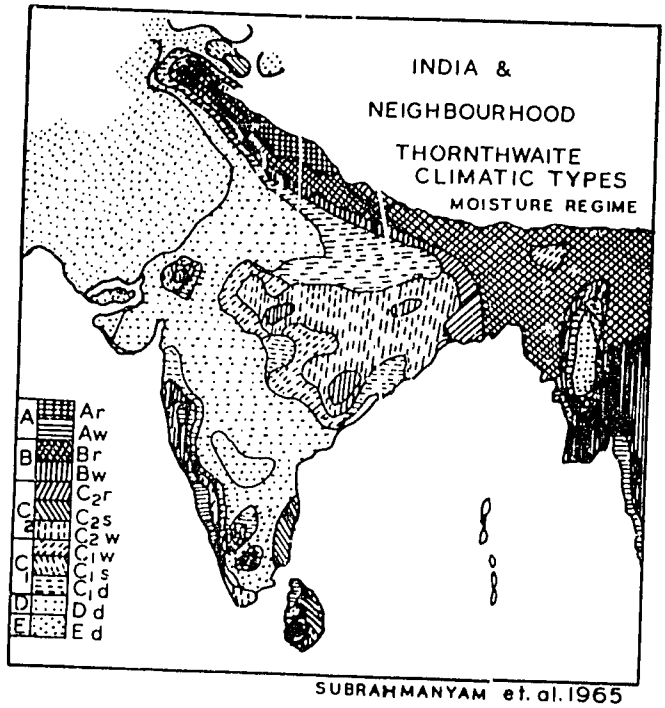
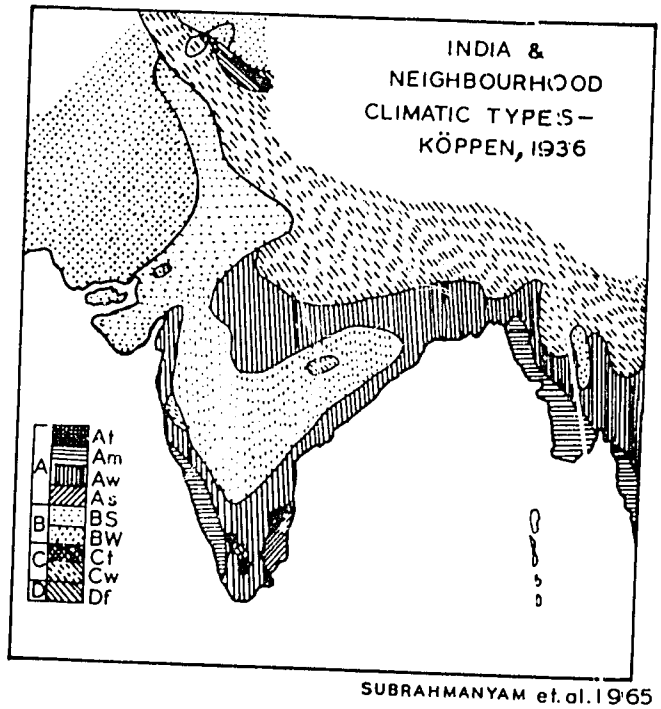


Figure 1b continued



SUBRAHMANYAM et. al. 1965



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Ecological methods for agroforestry research

S.M. Newman

Applied Biosystems, Energy Research Group
Faculty of Technology, Open University
Walton Hall, Milton Keynes, MK7 6AA, England

Abstract

A review of ecological methods that may be applied to the agronomics of agroforestry is presented. The research has focused on the use of various techniques such as phytometers, association and discriminant analysis and their application in the study of productivity and resource use efficiency.

Introduction

I define agroforestry as an activity where woody plants (usually trees) are used in more-or-less intimate association with animals and or crops in order to make use of ecological and economic interactions in the production of a wide range of materials including food, fuel, timber, fodder and chemicals. The concept underlying agroforestry then is that there may be some advantage in combining elements in an agroecosystem rather than treating them as collections of disparate single species with negligible interaction. The focus of this paper is to assess the value of certain ecological techniques in the evaluation and optimization of the interactions between the plant components in the system.

Measures of effectiveness for agroforestry

Some of the most common measures of effectiveness of agroforestry used in our research and in the literature relate to the productivity of the components in the system and the sustainability of that production within a given environmental and resource base. Some common measures of effectiveness and their context are presented below.

Total yield

Can a homogeneous single product be increased by agroforestry? This simple product includes energy, animal fodder, a chemical and so on. Here we compare the total productivity, e.g. total dry matter of the agroforestry mixture, with the highest yield produced by any of the component species grown as a monoculture.

Supplementary yield

Can a supplementary crop be added to the main crop to give supplementary products without affecting the yield or profitability of the main crop? Here we assess the species,

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density and spatial arrangement of crops that when intercropped will not depress the yield of the main crop to unacceptable levels.

Mixture yield

Two distinct crop products are required. Should they be grown as a mixture or as two discrete monocultures? Here we use a measure such as the land equivalent ratio (LER) which is the sum of the proportions of intercropped to sole cropped yield per unit area for each of the components in the system. For example, consider a given hectare of land that will produce 10 tons of walnuts per year or 10 tons of wheat. An agroforestry system of wheat and walnuts giving 6 tons of wheat and 7 tons of walnut would give an LER of 6/10 + 7/10 which is 1.3. An LER of greater than one indicates a yield advantage. In this system it could be said that the advantage is 30% as 30% more land would be required to produce the same yields from monocultures.

The ecological approach

Let us assume that we have set up an experiment to see if agroforestry results in an improved total, supplementary or mixture yield and we have a result. Likely agronomic questions are:

1. Would a different set of species perform better?
2. What is the biological basis of the yield outcome?
3. Is the result site-specific?
4. Can the spatial and temporal arrangement of the system be improved?
5. What are the limiting plant growth resources?

The conventional physiological approach to these questions would be to investigate the correlation between a single environmental variable, e.g. light, and some plant process such as photosynthesis measured by a single variable such as gas exchange. This could be carried out in the field or in laboratory situations. This approach is powerful but often requires considerable expertise, time and equipment. In agroforestry – with its inherent complexity – this approach, if it is to be comprehensive, is often not feasible. This is especially the case in many field experiments in the tropics.

The ecological approach is not a direct replacement of the above but is meant to be a complementary set of techniques to give focus to physiological investigations or to provide low cost techniques to answer physiological questions. The ecological approach attempts to use organismic responses in terms of distribution, abundance and plant process in order to factor complexes or environmental subsystems. It is inherently a multivariate approach.

The phytometer technique

A phytometer is an individual plant or population of plants used in a controlled way to indicate the importance of various environmental factors in relation to aspects of plant form or process. These can include changes in appearance, composition, process rates, fertility and longevity. Gardeners and farmers use plants as phytometers in a qualitative sense all the time as implied by statements such as 'the plant is wilting, it needs some

water'; 'brown spots on the leaves indicate a nutrient deficiency'; and 'the plant was tall and spindly due to lack of light". The use of this idea in a quantitative sense started in the 1920s when plant ecologists used transplanting techniques to determine the environmental limits to the distribution of certain species (Clements and Goldsmith 1924; Clements and Weaver 1924).

A literature review by computer indicated that the technique has not been widely used in agriculture in recent times. A search through Agricola (1970-1986) and CAB (1972-1986) databases yielded only 17 references (Newman 1984; Walton and Smith 1976; Mizuochi 1969; Leach and Watson 1968; Trlica, Child and Bauerle 1985; Yokobori 1984; Hruszka 1982a, 1982b; Nasu and Kugimoto 1981; Turkington et al. 1979; Radomski, Madany and Nozyn 1977: Inserentent and De Sloover 1976; Piotrowska and Kabata-Pendias 1974; Bonde et al. 1973; Batini 1974; Rodomski, Niewiadomski and Nozynski 1974; Kochendorfer and Lee 1973).

The most frequent use of phytometers is to separate aerial from soil factors. One can investigate the effect of the aerial environment which includes changes in microclimate or climate, light effects and pest and disease incidence or crop growth. This is achieved by growing plants in containers filled with compost or nutrient solutions and placing them in different situations.

The compost or nutrient solution is kept uniform for each phytometer so that any variation is due to aerial factors alone. This technique has been used to investigate the geographical limits to crop growth in tundra (Walton and Smith 1976; Bonde et al. 1973) and the effects of climate on the early growth of crops in Uganda (Huxley and Beadle 1964). Plants grown in containers have been used in pollution studies (Trlica, Child and Bauerle 1985; Yokobori 1984; Nasu and Kugimoto 1981; Piatrowska and Kabata-Pendia 1974) and root exudate or allelopathic research (Hruszka 1982a, 1982b).

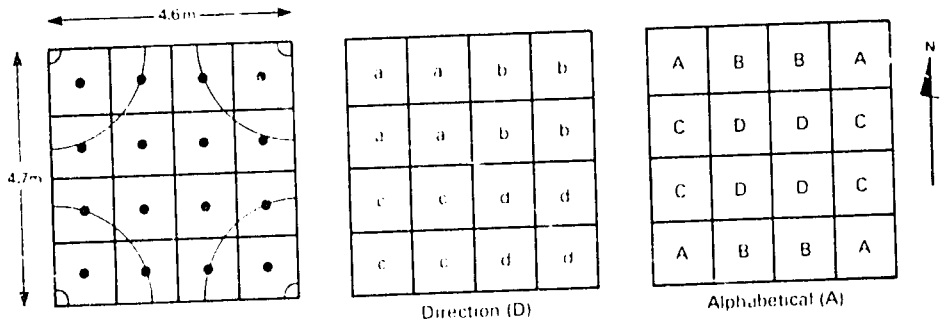
Vertical canopy structure effects on photosynthesis in field crops have been investigated using phytometers in the form of kale plants placed in glass vessels with nutrient solutions placed at different heights in the crop profile (Leach and Watson 1968). Plants grown in trenches lined with polythene sheet were used to assess the relative importance of soil versus aerial interactions in mixtures of pearl millet and groundnut (Reddy and Willey 1980). In mixed cropping it is very useful to have a mixture treatment where the root effects are kept separate by a polythene partition in order to examine the aerial interactions that take place and their effect on both LER and the balance of yield within this system. It is also important with this level of disturbance to have a monocultural control to investigate the effects of trenching with partitions so as to eliminate experimental artifacts.

Phytometers have been used recently to investigate several effects in agroforestry (Newman 1984). In this experiment the aim was to classify certain zones of aerial environment within a plantation system in terms of the responses of potential understorey crops. The performance of a range of crops – pea, carrot, radish and onion grown in pots with adequate soil resources – was assessed in various zones in a pear orchard. Some of the phytometers were placed in areas away from the influence of the trees. Others were planted in various zones in the orchard in relation to position relative to trees. With sufficient replication it is possible to classify these zones in a number of ways and test various hypotheses using analysis of variance (Figure 1). The relative performance of different species can also be assessed. Results from this kind of experiment can be used to show how close to a tree a crop can be grown and still give economic yield. It may be feasible to grow one understorey species in areas adjacent to the trees and another species farther away at the mid-point between rows. One is in effect characterizing the area of influence of the tree component.

By simultaneously growing the intercrop in the ground in positions where the phytometers are placed one can compare soil versus aerial effects and thus focus physiological investigations in the appropriate direction. It may be possible to generalize about other crops from the performance of a phytometer. For instance if the response was one in which leaf dry matter was increased in areas adjacent to trees, then a reasonable hypothesis may be that crops with leaves as the economic parts should be used. Similarly a plant with a particular form of photosynthetic mechanism or physiology may closely resemble other plants.

A crop from a particular taxonomic family may represent other members of that family. Obviously the most relevant phytometers are the candidate crops but in some situations it may not be possible to use them due to the difficulties of managing very large or slow growing crops in containers. It is important to measure many other plant response variables apart from economic yield in these studies in order to build up a rich picture of plant behaviour. Useful measures include root/shoot ratio, leaf length, leaf thickness etc. Many can be measured non destructively, e.g. leaf volume (Huxley 1971), and can be replicated throughout various growth stages. Most of the costs of carrying out the technique are related to labour rather than equipment.

Figure 1 The layout of an orchard 'plot', defined as a rectangle with a tree at each corner. Phytometers were placed at the centre of each of the 16 positions shown. These positions were then classified in various ways such as 'Direction' and 'Alphabetical' and their importance assessed by analysis of variance.



Refining the phytometer technique: the use of discriminant analysis

This can be done by using statistical analysis and a varied range of control treatments (Newman 1986). In the previous experiment the hypotheses generated were at the level of soil versus aerial environment or zones defined in terms of tree proximity or position. The technique can be refined to test hypotheses about shade, rooting depth, water, nutrients and so on.

Consider a situation where yield is depressed in an understorey in a zone of radius 3 m from a tree in an agroforestry system. The question arises, What is the ecological basis for this? One could set up a replicated experiment with plants grown in this zone with a variety of simultaneous control treatments used to simulate effects such as levels of shade, soil depth, water availability, fertility, etc.

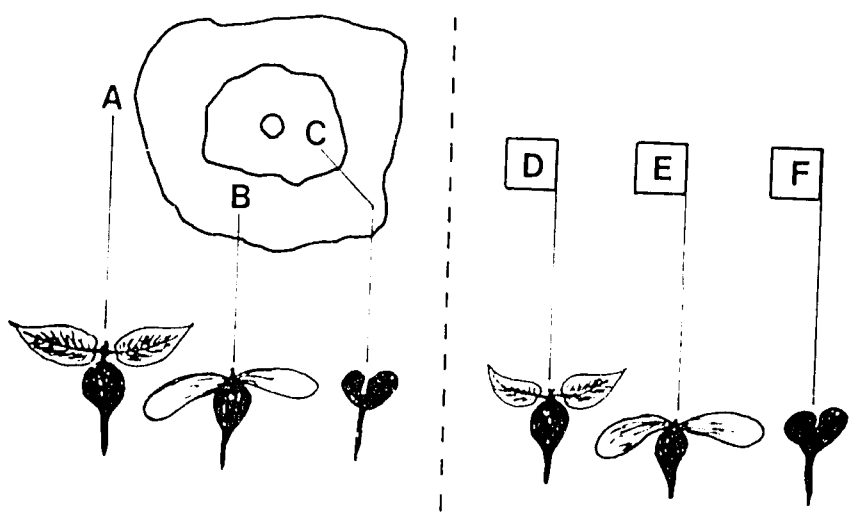
Now consider that at the end of the experiment the intercropped plants had poor yield with thin leaves, long internodes and leaves of a particular shade of green. If plants were found with a similar form and yield in a shade treatment alone, then a reasonable hypothesis would be that shade was implicated in the intercropping system. Things rarely happen so simply in reality, so statistical techniques are required in order to discriminate the most important patterns of behaviour in the system. In graphical terms one could represent the response of each plant in multivariate space with variables such as height, root/shoot ratio, etc., used as coordinates. One should look for similarity between intercropped and control response in terms of the proximity of the resulting surfaces in multidimensional space. Discriminant analysis (Klecka 1975) can be used in this form of problem and along with other multivariate techniques can aid many steps in agroforestry research (Oranga 1981).

Consider a situation where understorey crops are sampled from three zones relative to trees (Figure 2). Zone A is an area farthest away from the trees in the plantation. Zone B is an area primarily influenced by the tree canopy. Zone C is an area where the understorey is affected by the trees roots and canopy. At the same time the crop was grown in a control area with no treatments (Zone D) a shade treatment (Zone E) and a root treatment (Zone F). At the end of the experiment many variables were measured on each plant. For radish this may be leaf length, leaf dry weight, root dry weight and bulb diameter. The data are then pooled and discriminant analysis applied to find out what is the most important description of system behaviour, or more correctly, what polynomial function could best discriminate between zones. Let us assume that the best function was:

$$y = a(w) + b(x) + c(y) + d(z)$$

where a, b, c and d are parameters; w is leaf length; x is leaf dry weight and so on. The magnitudes of the parameters indicate the relative importance of the variables.

Figure 2 Possible morphological responses of understorey radish plants grown in different control areas and agroforestry zones. Zones A-C represent areas of increasing tree proximity with zones D-F representing control treatments away from the influence of trees.



A number of discriminant functions are often generated. The usefulness will depend on what percentage of the variance they account for. Consider that discriminant function 1 accounted for 90% of the variance. Each zone in Figure 2 would have a y value using discriminant function 1. Results could have values of A = 1, B = 4 and C = -4 with values D = 1.1, E = 4.1 and F = -4.2 indicating the similarity of A and D, B and E, and C and F. This would generate a hypothesis that zone A is not affected by trees; zone B is affected by shading and zone C is affected by roots. This is a rather crude and over-simplified example of this technique. The main point is that by increasing the number of plant attributes measured and devising relevant and simple simultaneous control treatments one can rapidly generate hypotheses about systems interactions. This technique has been used in this way to evaluate the potential for intercropping in a pear orchard (Newman 1986). Again no expensive measuring equipment has been used and further investigations can be focused on the important parts of the system.

Association analysis

There is a great deal of interest in the design of agroforestry systems in terms of species composition relating to the concepts of ecological combining ability. This could be defined as the combinations of species that have mutually positive interactions. An agroforestry system with high ecological combining ability would have an understorey which enhances tree growth and vice versa.

Theoretically it may be possible to trace the crop ancestors of agroforestry components and use natural associations as a basis for designing systems. One example of this is the observation that various *Rubus* specimens are often associated or found growing with *Malus* or *Pyrus* species in temperate woodlands. This would suggest that they have a high potential for co-existence and may be able to partition growth resources rather than directly compete for them. This natural association is also a common crop association in the agroforestry of temperate fruit orchards where apple and pear were often intercropped with blackberry and a number of closely related shrubs (Fekete 1958). The quantitative analysis of plant associations is a central part of plant community ecology and a vast array of techniques has been developed for its analysis (-Kershaw 1975). Some of these may be appropriate for analysing the complex semi-natural agroforests of the humid tropics where the genetic and functional properties of the crop species are not too distinct from wild ancestors.

Conclusions

In summary it appears that plant ecology has many useful techniques that can further be developed to provide answers to agroforestry problems. Techniques are available to fit understorey species with the 'niche' created by trees. Methods are available for focusing on what factors cause deviations from expected yields in many mixtures. Finally, ecological studies may provide answers to questions on the design of totally novel systems.

Acknowledgements

I would like to thank members of the technology and mathematics faculties at the Open University for constant support on statistical and experimental matters and to Sir Ralph Verney for the use of experimental areas. I would also like to thank Maureen McManus for word processing.

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Recent developments in homoclime analysis to assist species selection

T. H. Booth

CSIRO Division of Forest Research
P.O. Box 4008, Canberra A.C.T. 2600, Australia

Abstract

Two methods of homoclime analysis have been devised to assist the selection of Australian tree species for trials. Both methods use modern interpolation techniques to estimate meteorological variables at sites which may be some distance from recording stations. The first requires no biological information, but simply compares climatic conditions at a trial site outside Australia with conditions of 2795 locations in a regular half-degree grid across Australia. The second uses information from a species' natural distribution and results of its performance in trials to develop a detailed description of its climatic requirements.

Introduction

The Australian Centre for International Agricultural Research (A C I A R) is supporting studies of the potential of Australian tree species for fuelwood and agroforestry use in developing countries (Turnbull 1986).

Two methods of homoclime analysis have been developed to assist the selection of species for trials. Both methods make use of modern interpolation methods, which provide better estimates of mean climatic conditions for remote sites than techniques previously used. For example, the surfaces fitted for Australia estimate mean monthly values of average daily maximum and minimum temperature with mean errors of 1.3 and 4.1 per cent respectively. Errors associated with estimates of monthly mean precipitation are generally below 10 per cent. The interpolation methods used were devised by Wahba and Wendelberger (1980) and implemented by Hutchinson (in press), using data collected by Nix and McMahon (McMahon 1986, p. 60-63).

Methods

The first method, known as CLIMSIM (climatic similarity), allows any location in the world to be analysed, provided monthly mean values of daily maximum temperature, daily minimum temperature and precipitation are available. From the 36 monthly values, 18 climatic factors, such as annual mean temperature and driest quarter precipitation, are calculated. These are compared with the same 18 factors estimated at 2795 locations in a half-degree grid across Australia. A map is plotted which indicates the locations in Australia which have conditions most similar to the target site (Figure 1). Booth et al. (1987) describe the method in detail and use examples from Africa and South America to show how the method can assist tree species selection.

Figure 1 Locations in Africa which satisfy three main climatic characteristics derived from the natural distribution of *A. auriculiformis* in Australia.

The second method is an extension of the BIOCLIM (bioclimatic prediction) system devised by Nix, Busby and Hutchinson (see Nix 1986, p. 415; Busby 1986; Hutchinson in press). Booth (1985) used the BIOCLIM program to analyse climatic variability in the natural distribution of *Eucalyptus citriodora*. This information was then used to identify homoclime sites in Africa, which were shown to correspond to many of the areas where *E. citriodora* had proved successful in trials.

Booth et al. (in press) analysed the natural distribution of a further twelve eucalypt species, but also showed how results from trials in Africa could be used to improve estimates of the species' climatic requirements. The BIOCLIM program has recently been used to analyse climatic variability in the natural distribution of ten non-eucalypt species which have potential for fuelwood and agroforestry.

Comment

This brief note is intended to draw the attention of researchers to these recent developments. Further details, including an outline of both methods (Booth in press), are available on request.

Although the examples cited above have been carried out using Australian species there is no reason why the same methods could not be used to analyse the requirements of other species, provided the appropriate surfaces were developed for climatic interpolation.

Acknowledgements

I am grateful to The Australian Centre for International Agricultural Research (ACIAR) for financial support; Henry Nix (Centre for Resource and Environmental Studies, Australian National University); Michael Hutchinson (CSIRO Division of Water and Land Resources); and to June McMahon (CSIRO Division of Water and Land Resources) for access to programs and data.

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SECTION 5

Results of agroforestry experiments

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Tree/crop interface investigations Preliminary results with Cassia siamea and maize

P. Huxley, E. Akunda, T. Darnhofer, D. Gatama and A. Pinney

International Council for Research in Agroforestry (ICRAF)
P. O. Box 30677, Nairobi, Kenya

Abstract

The basic unit of all agroforestry systems is the 'tree/crop interface' (TCI). By studying these in small plots an understanding of the interactions involved can be developed. Such investigations are best thought of as initial, observational trials to help design more formal experiments. One such is described in which Cassia siamea *and maize were grown adjacently in a 'Y' design which enabled orientation to be investigated. The planting arrangements and assessment methods are described and the preliminary results of the first three seasons with the maize crop are given.*

Although unreplicated, the data indicate the extent to which trees, crop and trees, and crops at the interface behaved in this association, on this site. Assessment criteria for the crop, the yield profiles from the interface to the plot edge, are shown by season for both the tilled and untilled parts of the plots. The effects of orientation need further study.

The work so far has opened up many considerations of methodology and design not only for TCI experiments but agroforestry experimentation in general.

Introduction

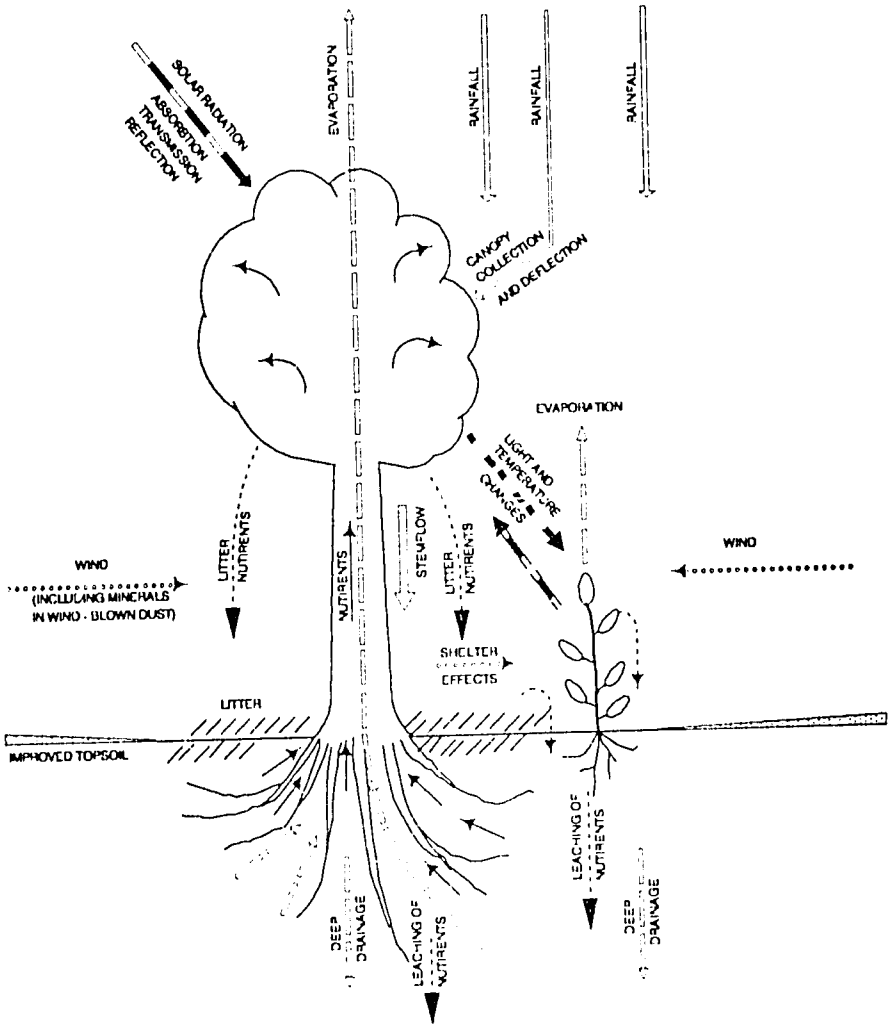
Agroforestry land use systems can vary considerably in complexity in terms of numbers and kinds of plant components, their spatial arrangements, and the various temporal sequences of natural plant growth and development patterns which occur naturally, or are managed. For research purposes, systems can be grouped into 'zonal' or 'mixed' spatial arrangements where the intimacy of associated plant components is, respectively, restricted or encouraged; or 'rotational' arrangements, where the woody perennials are completely separated from the non-woody plant components in time. Spatially-arranged systems can also be manipulated temporally, but within a seasonal time frame.

The complexities of studying spatially-arranged systems can be greatly reduced if they are considered, in the first instance, to be formed from pairs of all the associated plant components; i.e., from an appropriate number of 'tree/crop interfaces' (Huxley 1986). Here 'tree' and 'crop' mean, respectively, woody and non-woody plant components, or, in some cases components. Indeed, the choice of zonal or mixed systems, and their actual design and management options, can not be logically made until an awareness of plant-environment effects and interactions at the tree/crop interfaces are known, or better still, understood.

Because the outcome of even an apparently simple tree/crop interface (TCI) experiment is the result of all short and long-term biophysical and environmental factors at

the experimental site, it still presents an extremely complicated situation (Figure 1). The ultimate goal is that of estimating the size of the resource pools (for light, water and nutrients), and investigating the magnitude and rates of the environmental resource-sharing processes that produce – to a greater or a lesser degree – plant stress on each component. Measuring (or estimating) the results and relative importance of these stresses on plant growth and development can then, hopefully, provide sound guidelines for the manipulation of the system, both in order to improve it, and/or to provide grounds for extrapolation to other environmentally different sites. Even a more limited understanding of the resource-sharing processes can add considerably to the predictive outcome of an experiment.

Figure 1 Tree/crop interactions will result in and be a consequence of changes in environmental resource pools, shelter effects, etc. (Source: Huxley 1986).



Whatever the precise objectives may be, experience to date has shown that a careful set of observations of plant behaviour throughout the changes of season can expose a whole range of ways in which the plant components can be seen to be responding to primary or plant-induced environmental changes at the various stages of plant growth and development, e.g., germination, emergence, planting-out and so on. Such trials can also, by producing circumstantial evidence indicative of particular environmental stresses, help define precisely the experiments needed to investigate the environmental factors concerned.

Field research with woody/non-woody mixtures is a relatively new experience for most researchers with an agricultural or forestry background. It was, therefore, considered essential to carry out the kinds of detailed observations reported here before progressing to field trials. Because this investigation was to explore a wide range of responses of the plant materials, and to develop assessment methodology, the plots were not replicated as they would be under experimental conditions. Satisfactory designs for such experiments can only be achieved after sufficient has been learned about the way plants behave and interact in such associations, exactly what assessments need to be made, and when.

Tree/crop interface investigations are, therefore, as described here, probably best thought of as initial, observational trials which are a cost-effective way of 'opening-up' the problem. They will be followed by either more extensive, but well-focussed field trials, or by more precise resource-rich experiments in which selected environmental factors are investigated in depth. In their initial stages, tree/crop interface investigations can be carried out wherever they occur (as long as the conditions are fully understood and described). Alternatively, they can be conducted in small plots using either single trees or some relevant arrangement of the plant components, e.g., hedgerows (Huxley 1987).

It is important, if a regular, linear plant arrangement is used, to consider whether the effects of row orientation are to be investigated. Sun angles, wind that affects rainfall distribution (see nexr paper, this Section) and 'shelter' may influence tree/crop interface responses. If orientation is important, a 'geometric' design can be used, such as the 'Y' design used in the experiment described here. The present investigation is part of a series involving different tree/crop combinations.

Materials and methods

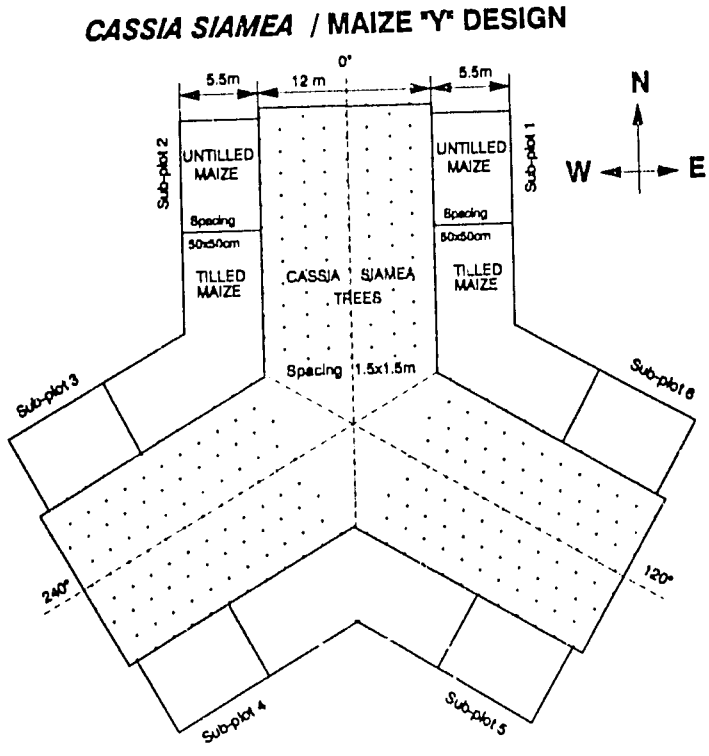
The 'Y' design used is illustrated in Figure 2, in which plot size and plant spacings are given.

Tree establishment and management

Young, nursery-grown, plants of *Cassia siamea*, were planted in April 1984, using 2 litres of diluted Aldrex (48%) in the planting hole together with two shovels of farmyard manure. No fertilizer was applied until the third crop season (see below). Plants were watered each week until the short rains started in October because it is essential in this type of design to have a complete plant stand. The area was first weeded four months after planting by scraping the surface. Subsequent weeding was done monthly at first, and then as needed under the trees as the canopy began to close.

Trees were pruned ('capped') 11 months from planting in order to regulate the biomass of each plant (larger plants were pruned more heavily than smaller ones) and to train the plants to form multiple stems and so obtain canopy closure sooner.

Figure 2 Shape and dimensions of the 'Y' design plot used in this investigation.



Pest problems started with powdery mildew at 15 months after planting. This was checked by spraying a fungicide ('Bayleton'), applied every two months during the season when the disease was most severe (i.e., at the end of a rainy period). Stalk borers were first noticed after 16 months. They were checked, but not completely eliminated, by spraying Dieldrin on the stems. Lebaycid was also applied in the damage holes, and larvae were killed with wire probes.

Subsequently, the trees were allowed to grow freely, except that the side branches were pruned vertically at the interface with the crop each sowing time. Crops were sown after the trees had grown three seasons.

Crop management

The cropped area in the outer half of each arm was left untilled and the soil in the inner half dug with a hand hoe prior to sowing (Figure 2). An adapted short-season (90-day) maize composite ('Katumani') was sown in the fourth rainy season (i.e., October 1985) in parallel rows on each side of the three arms of the 'Y' (i.e., in 6 plots). A spacing of 0.5 m x 0.5 m was used, with the first row 0.5 m from the trees. In order to produce a complete stand, three seeds were sown per hole and thinned to one plant within 12 days of emergence, during which time any essential gapping-up was done. All maize residues were returned to the appropriate plots. Plots were weeded as necessary by scraping the soil and/or by pulling. Pesticide (Dipterex) was applied for stalk-borer control when

the maize was knee high. The need to control rodents prior to sowing became apparent in the first season.

Maize was planted in every subsequent season (i.e., twice a year), as above. No fertilizer was applied in the first two seasons in order to maximize nutrient stress; but, on these relatively infertile soils (Oxisols), it was considered necessary to fertilize from season 3 on with a uniform application of N and P at the rate of 100 and 40 kg/ha, respectively, prior to sowing. Fertilizer was applied over the whole plot including the area planted with trees. Harvesting was delayed until all the maize was fully mature.

Assessment of tree and crop

Measurements were taken of the diameter of tree-stem collars (at soil level) and height of all trees at the beginning and end of every season. Maize height, date of 50 per cent tasseling, fresh and dry weight of the true stem (i.e., after stripping away the leaf bases), and cob and seed weight were recorded. In the first season this was done row-by-row, and the number of plants remaining after removing discards at the ends was recorded. In the second and third seasons these measurements were taken for every plant. It was not possible to obtain measurements of leaf area index for either the crop or tree, but photographic records were kept throughout the seasons.

Results and comments

We provide here a selection of data from the first three seasons when maize was sown. The data illustrate some of the issues that have emerged from the study so far. The work will continue for at least three more seasons.

Rainfall

Figure 3 shows the rainfall. In this region the rainfall is bimodal, usually with a 'first rains' (March-May) and a 'second rains' (October-December). The pattern over the period of observations taken here was consistent with this but some rain extended into January in both 1986 and 1987.

Cassia siamea

Figure 4 indicates the growth of *C. siamea* in height and stem collar diameter. As expected, trees at the interface were larger in both respects than those in the middle of the plot, where a fairly uniform stand was apparent. As the standard errors of the row means show, trees were more variable on the outside, i.e., at the interface.

Maize

Assessment criteria

Figures 5a and 5b show, for tilled and untilled plots respectively, measurements of maize height on three occasions during the second planting season, compared with the yield of maize cobs at harvest. Even in agricultural experiments plant height is an unsatisfactory assessment criterion, since, for any single germplasm selection, it represents the net effect of the stage of plant development, vigour of growth as affected by the plants' immediate environment, and morphogenetic effects of shading (mutual, or

Figure 3 Rainfall at the ICRAF field station, Machakos, Kenya, for the period of observations.

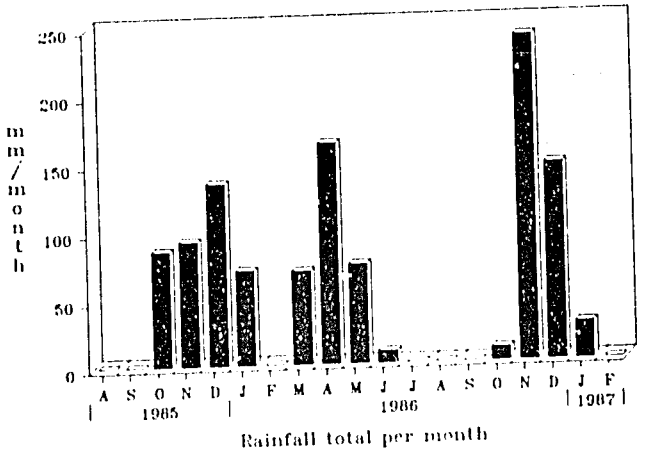
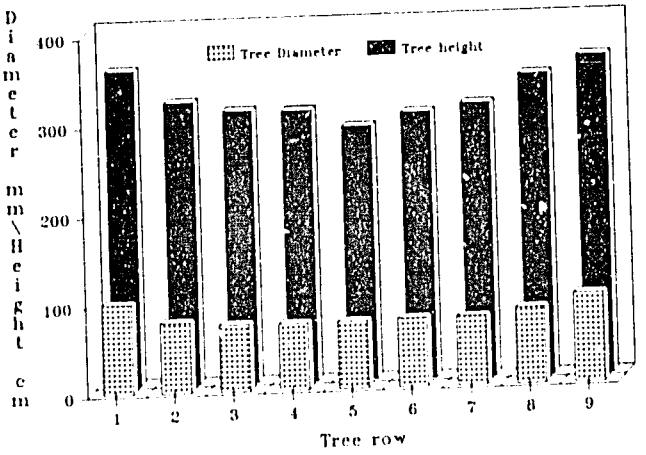


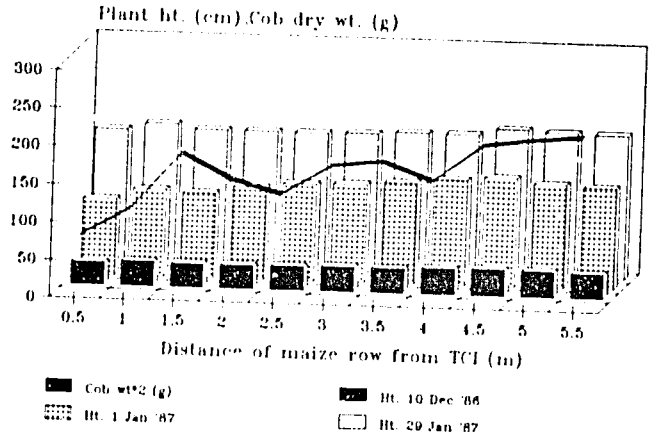
Figure 4 Tree diameter and height on 14 January 1987, at the end of the observation period. Means for three tilled and untilled arms.



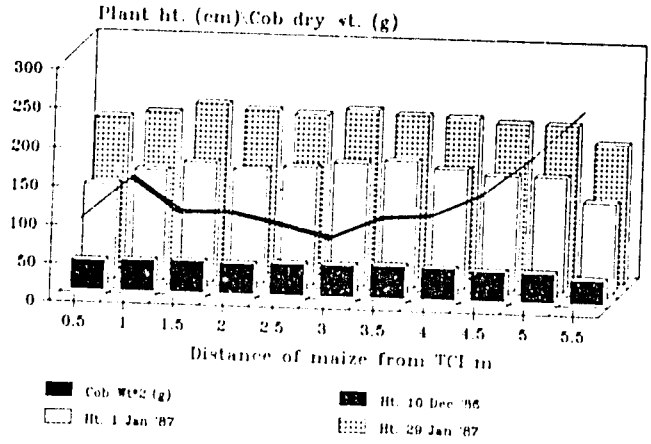
otherwise). The last is likely to be a common effect in TCI experimental plots and, as Figures 4a and 4b indicate clearly, there is a very poor relationship between the height of maize plants and their cob yield. In this third season (second rains, 1986), untilled plots produced less maize than did tilled plots, but in neither case was yield affected to any extent past the first or second row. However, there was an indication of a trend for greater yields towards the outside of the plots (i.e., away from the interface). A detailed analysis of different tree/crop interface effects awaits the results from the continuation of this work.

Figure 5 Maize height and cob dry weight by row, second rains 1986; a) means of 6 tilled plots; b) means of six untilled plots.

a)



b)



Effect of season and tillage

Figures 6a and 6b show, for tilled and untilled plots, respectively, the same maize yield trends at and away from the interface for each of the three seasons in the tilled plots. Although general yield levels varied considerably between season, the untilled plots always yielded less than tilled plots. However, there is little indication that the degree and extent (i.e., general shape) of the interface effect was different between seasons for the tilled plots. There was little change in maize yield between mid-plot and the interface for untilled plots in the last season (Figure 6b).

One reason for growing maize with and without tillage was the hypothesis that undisturbed tree plots might extend more rapidly into the untilled area and thus competitively affect adjacent maize yields more adversely than on seasonally tilled plots. A more detailed examination of interaction between tillage and season must await the results from subsequent seasons.

Effect of orientation

The 'Y' (120°) design was chosen as the simplest (and least costly) approach to observe major effects of orientation. Figure 7 shows an example of maize yields from the tilled plots in the second (short rains) season of 1985. So far no clear cut influence of orientation has been observed with this tree/crop combination on this particular site. There is some indication that emergence of maize in rows close to the interface on the 'rain shadow' side (see Section 000, this volume) can be slightly delayed. There may also be shading effects that need further investigation.

If shading and/or shelter by the trees influenced the crop, then one would expect to observe differences b when comparing rows with difference in proximity to the interface and with different orientations. Although the maize yields from the first two rows of plots 1 and 6, and 2 and 3 (refer to Figure 2) were slightly higher than in plots 4 and 5, with the sun traversing from south of east to south of west at this time of the year, and winds being predominantly easterly, there are large (and dissimilar) differences occurring in the middle of the plots. Hence even row-by-row comparisons present conflicting evidence that will require more detailed study to resolve.

Discussion

Even in its early stages, this investigation (together with those on several other layouts and tree/crop combinations which the team is studying) has provided a good deal of useful guidance for the design, assessment and data-analysis methodology for both tree/crop interface experiments *per se* and field trials with tree/crop mixtures in general. Because, in some seasons, data have been collected for maize on an individual plant basis, it is possible to use this for assessing suitable plot sizes, the extent of guard areas, etc. Indeed, it has become clear that the outside part of each plot (away from the interface) is not merely a 'discard' area but can, itself provide clues about the growth and yield of the crop growing under a more stress-free (but, perhaps more environmentally exposed) situation.

As well as assessing maize height and cob yields, we examined true stem dry weight (by removing the sheathing leaf base) and seed dry weight. True stem dry weights were not found to be useful and, in any case, required a great deal of labour to obtain. Seed dry weight, as might be expected, is highly correlated with cob dry weight for any particular germplasm source.

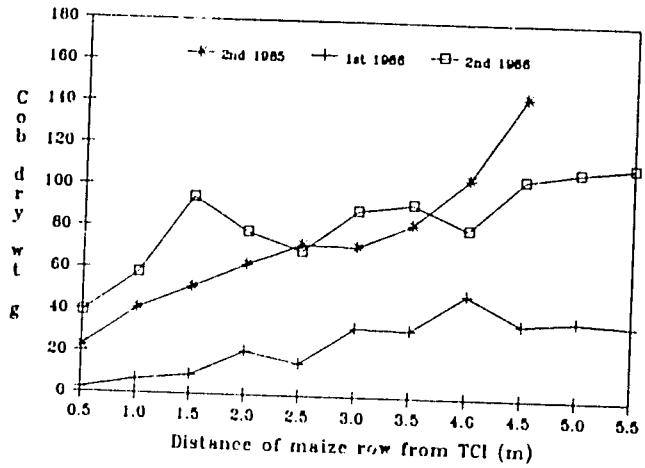
Some of the interface results obtained may well depend on below-ground competition and we intend to explore this, either by root sampling and/or by indirectly observing seasonal changes in the status of soil water profiles.

It is becoming clear that effects of orientation will need to be investigated over a larger number of seasons with different rainfall regimes, because orientation is likely to influence different stages of crop growth in different ways.

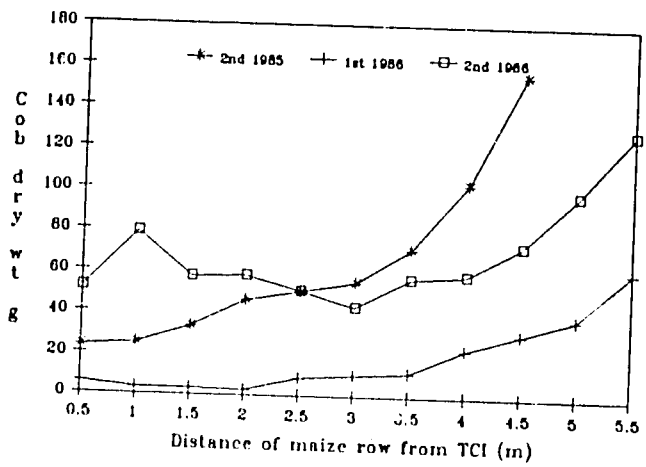
Finally, the type of crop response at the interface that we have described here is not always found with other tree/crop combinations or on other sites. If future work confirms this, then this has important implications for the design and implementation

Figure 6 Effect of season on row yields of maize (9 rows in the first season, 11 in the other two; a) means of six tilled plots; b) means of six untilled plots.

a)

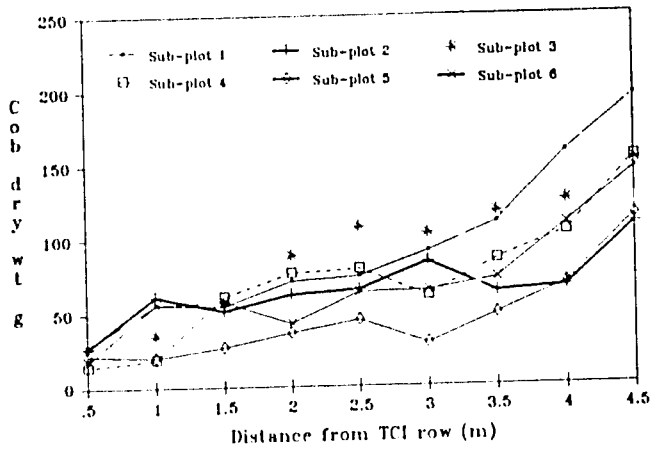


b)



of agroforestry field experiments because, even if they prove to be imposed by site and/or management. It is essential to be able to control or allow for such effects if experimental variability is to be contained.

Figure 7 Effect of orientation. Cob weight by rows for separate tilled plots in the second season 1985.



Acknowledgements

ICRAF's 'tree/crop interface' project on research methodology for conducting experiments involving woody and non-woody plant mixtures has been largely funded by the Federal Republic of Germany through BMZ/GTZ. It has been carried out at the ICRAF field station for which SIDA has provided supporting funds.

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The rainfall distribution at a tree/crop interface

T. Darnhofer, D. Gatama, P. Huxley and E. Akunda

International Council for Research in Agroforestry (ICRAF)
P.O.B. 30677, Nairobi, Kenya

Abstract

Trees in agricultural cropland change the amount of precipitation which reaches the ground in their immediate vicinity. They interfere directly, through their canopy (interception, canopy drip), their branches stems (stemflow), and indirectly by modifying the wind field. Detailed rainfall measurements supplemented by wind speed recordings, were carried out along a cross section of an agroforestry experimental design, sited to give exposure to the prevailing winds. Data reliability assessments were made, and the rain gauge readings corrected to make some small compensations for wind effects. The results for 27 storms recorded over two seasons show clear modifications of the precipitation patterns at the windward and leeward tree/crop interfaces, dependent on wind speed and direction. The effects, which were much more pronounced on the leeward side of the barrier, do not extend further than once the tree height. Some implications for field experiments involving hedges are noted.

Introduction

In agroforestry systems, trees and crops are grown together on the same piece of land in such a way that they interact with each other. In most situations this will not happen directly but through the modification of environmental factors. The area where the trees and the crops modify their bio-physical environment can be thought of as the tree/crop interface (TCI), and is where they compete for growth resources such as light, water and nutrients (Huxley 1983). Generally the interactions are complex, either positive or negative, and they can result in complementary or competitive effects. Many of the processes involved relate to the microclimatic conditions and result from modifications to the radiation regime, the heat balance, the wind regime and thus plant water use. In order to optimize the interactions in tree/crop combinations it is necessary to understand, and therefore to define and quantify, these conditions. Considering the complexity of the problems it appears justified first of all to break them down and relate them to sets of environmental variables with a subsequent impact assessment on the overall plant performance.

At the ICRAF field station near Machakos, Kenya, a number of plots have been established since 1984 to study tree/crop interactions and to develop methodologies to assess biophysical modifications at the tree/crop interface (see Huxley et al., this Section). Because in semi-arid regions water is often the most limiting factor for plant development, we decided to investigate the rainfall re-distribution at a tree/crop interface.

Objectives

Trees in agricultural cropland represent obstacles that modify the wind field; such modifications have long been recognized as affecting the rain falling in the immediate vicinity of the obstacle (e.g., Jevons 1861). Furthermore the tree itself interferes with the rainfall by holding back a part of the precipitation in the canopy (interception); by modifying the intensity and the spatial distribution of the amount that falls to ground (throughfall); and by causing another fraction of the rain to flow down the stem (stemflow).

These factors will change the distribution of the rainfall at the interface. The objective of the present study was to quantify these changes and to assess the eventual impact on the crops grown close to the trees.

Methods and materials

General climatic conditions

ICRAF's field station is situated near Machakos in the equatorial East African Highlands (1° 33' S, 37° 14' E, 1596 m asl). Rainfall occurs in a bimodal pattern. The first rainy season starts around 20 March and lasts until the end of May with an average rainfall of 300 mm; the onset of the second season can be expected around 20 October with approximately 240 mm falling by 20 December. In 1986, during which the observations for this study were made, a total precipitation of 240 mm was recorded during the first rainy season and 380 mm during the second one. Observations made since 1983 indicate that at the field station most of the rain (90 %) falls in intensities above 2 mm/h and 33% have intensities higher than 10 mm/h.

Mean monthly temperatures range from 17.2 °C in August to 21.0 °C in February and are close to 20 °C during the rainy seasons.

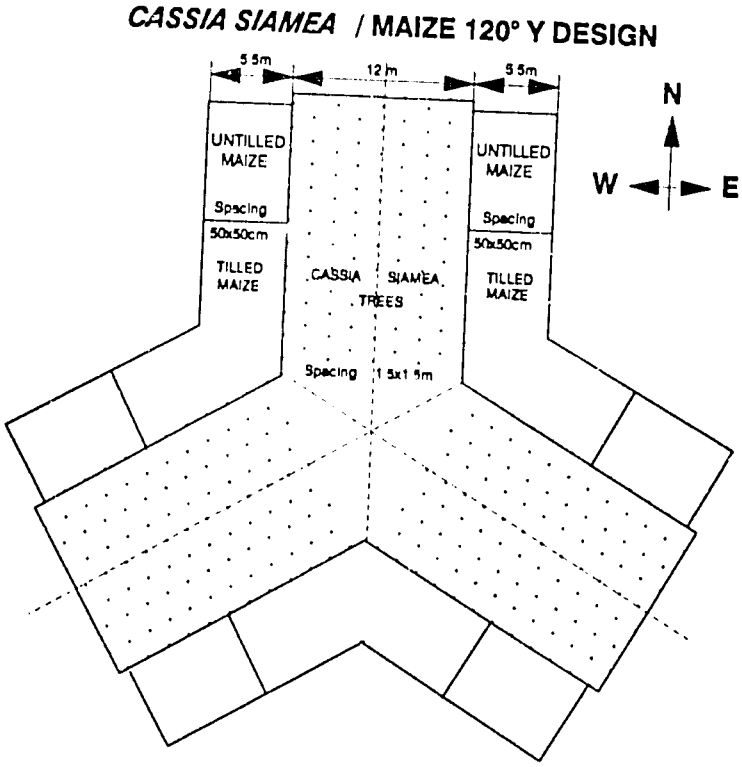
Easterly winds prevail with a high consistency (80 %), both in general terms and during hours with rainfall. The annual average wind speed at 2 m above the ground is 9.7 km/h, and is about the same during hours with precipitation whatever the rainfall intensity. There is a distinct daily variation of the wind speed with minimum values around 4 km/h in the early morning hours and maximum hourly means around 15 km/h in the late afternoon; these periods coincide reciprocally with the occurrence of maximum and minimum rainfall.

The experimental tree/crop layout

The rainfall redistribution study was carried out using an existing plot consisting of a geometric multi-row design with three arms at 120° orientation (Figure 1) planted with Cassia siamea in 1984, and first sown with an associated crop of maize in October 1985.

Each arm consisted of nine rows of 12 *C. siamea* trees planted in a staggered pattern at 1.5 m spacing, with 11 rows of maize planted immediately adjacent at a spacing of 0.5 m with a rectangularity of 1. Individual tree heights were measured; Figure 2 shows the average canopy profile just before the second season of observations. Before the planting of the maize crop, the side branches were pruned to keep the tree/crop interface vertical.

Figure 1 Diagram of experimental plot utilizing 'Y' design.



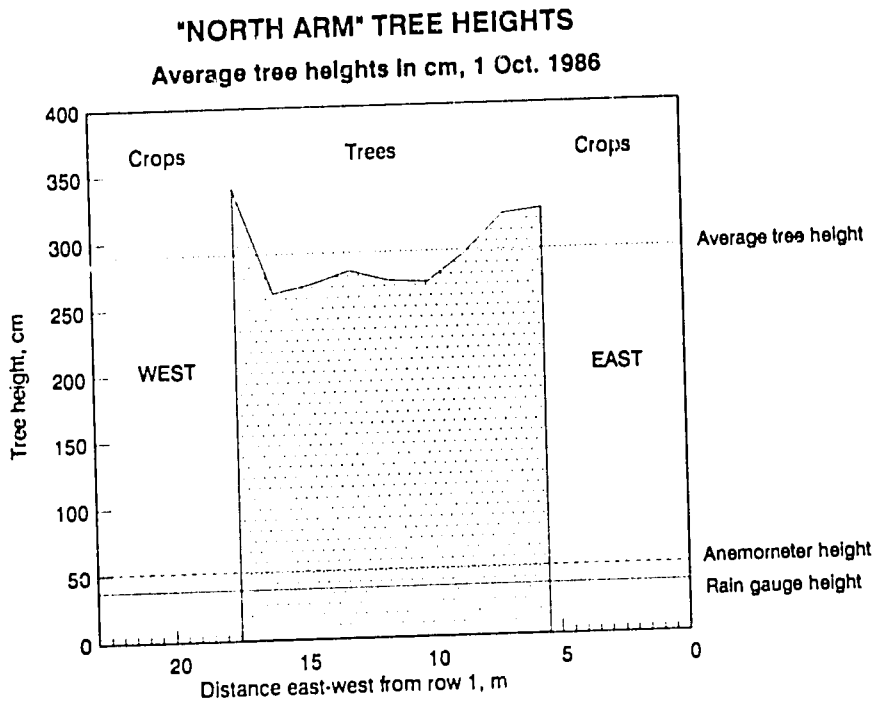
Measurements

Rainfall

Rainfall measurements are subject to a number of systematic and random errors which need to be assessed and eventually corrected. Systematic errors such as wetting losses on the internal walls of the collector, losses due to evaporation, and splash-out and splash-in from the container, are influenced by the type, frequency and amount of rainfall; windspeed; saturation deficit; and the physical properties of the rain gauge (WMO 1982). In a comparative micro-scale study these losses can probably be ignored if the same type of gauge is used, readings of all collectors are made within a short time interval and gauge rims are high enough to prevent splash-in. Random instrumental errors can be minimized by assuring uniform orifice apertures, standardized collectors and horizontal gauge rim exposure. Observational errors cannot be excluded, but appropriate training and observer continuity keep this source of data variability within limits.

An important systematic error is related to the deformation of the wind field above the gauge orifice. It depends largely on the wind speed at the gauge rim; the structure of the precipitation; and the shape of the collector.

Figure 2 Cross-section of north arm showing average tree heights.



Choice of rain gauge

To meet not only Kenyan instrument standards (KMD 1983) but also the requirement for minimum interference with the plants, we chose the Snowdon type rain gauge, with a 127 mm (5 inch) orifice diameter and a height of 37 cm, without a splayed base.

A central spike was welded onto the bottom of the outer casing, which was used to fix it in the ground. The rain water was collected in a plastic container with a capacity of 500 cm^3, equivalent to approximately 40 mm of rainfall. For the readings a measuring cylinder graduated to an accuracy of 0.1 mm was used.

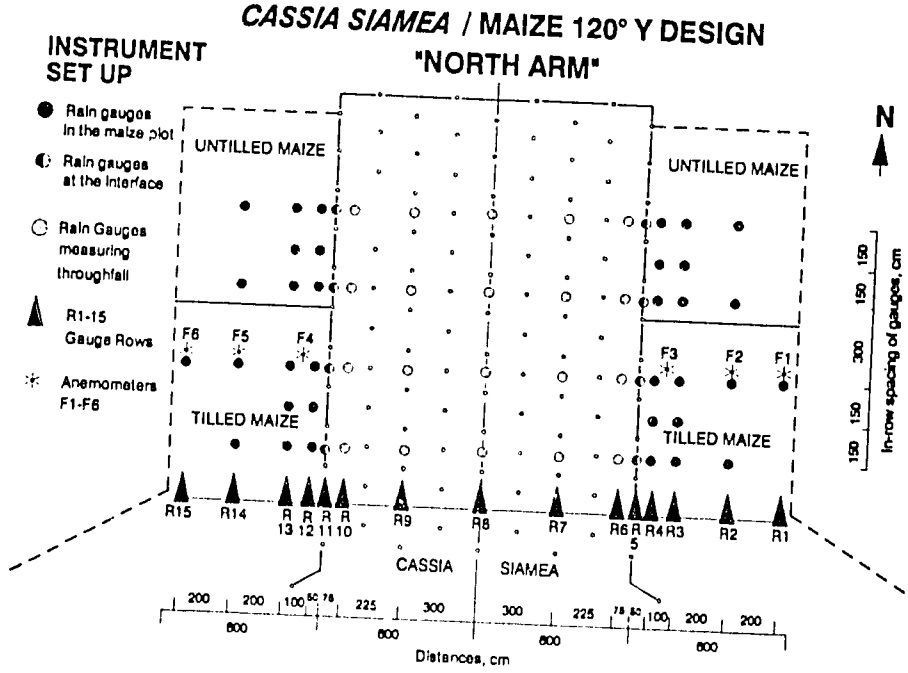
The turned brass gauge rims were manufactured to Kenya Meteorological Office specifications (KMD 1983); the coefficient of variation of the aperture areas of the 62 gauges used was found to be 0.32% with maximum deviations of 0.48%.

For the recording of rain intensities and precipitation times, a tipping-bucket gauge with an eight-inch orifice (324 cm^2) and connected to a datalogger, was available at the station climatological site, approximately 60 m from the experimental plot. The datalogger provided one-minute and hourly totals.

Placement of raingauges

Considering the predominantly easterly winds, we decided to instrument only the northern arm of the design, as maximum re-distribution effects could be expected under this exposure. Five rows of gauges running north-south were set up in the crop plots on either side of the *C. siamea* plot, including one directly in the line of the first tree rows (Figure 3). An increase of variability in the amount of rainfall caught by gauges closer

Figure 3 Arrangement of rain gauges and anemometers in north arm.



to tree/crop interface, due to modifications of the wind field and direct tree interference, was expected. Thus we varied the number of gauges per row from 1 (R1) to 6 (R4, near the interface) and reduced the between-row distance.

To monitor the throughfall inside the treed area, another 5 rows with 4 gauges each were installed. A total of 62 rain gauges were installed.

Measurement procedures

Forms based on Figure 3 were used for field data recording and immediate checking of the readings. Gauge readings were made for every storm with 3.5 mm of rainfall or more. To avoid errors due to evaporation and wetting losses, storms below this threshold were disregarded and the gauges emptied without measurements. Once the maize crop reached the rim height of the gauges no further rainfall readings were taken, but since the maize was planted late, nearly all storms were included in the analysis, a total of 27.

Wind

Wind is likely to be one of the major factors affecting the rain distribution and the catch of a rain gauge in the vicinity of a tree/crop interface. Wind speed was measured along the cross section. Wind speed and wind direction were also measured at the climatological station 60 m away.

Anemometer distribution

Three-cup anemometers (CSI Met-One 014A, the same as at the climatological station) were installed on either side of the north arm along a cross section (Figure 3). The distances from the first tree row on either side was 550, 350, 100 cm for anemometers F1/F6, F2/F5 and F3/F4 respectively. An anemometer cup height of 50 cm, which was 13 cm above the rain gauge rims, was chosen to allow measurements without leaf interference during the period that rainfall readings were made. The sensors were connected to a datalogger which was programmed to record every minute and calculate hourly mean wind speeds.

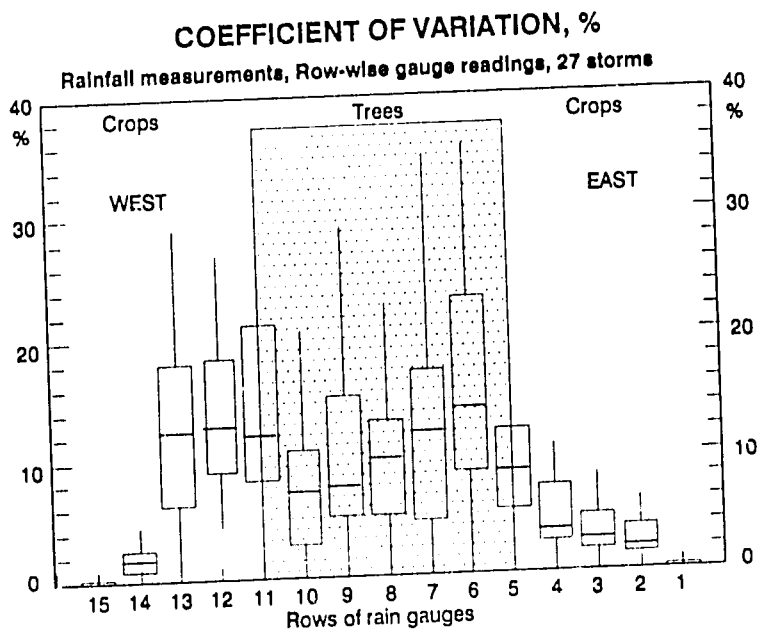
The manufacturer's specifications indicated that the threshhold was 0.46 m/s. A comparative calibration of the anemometers showed that at speeds above 1.4 m/s (5 km/h) the differences between the anemometer readings did not exeed 1%. However, at lower wind speeds (0.3 - 1.0 m/s), differences in the hourly readings of up to 15% indicated that the anemometers varied considerably in starting threshholds.

Data analysis

Rainfall

To obtain a cross-sectional view of the rainfall distribution, gauge readings were averaged row-by-row for each storm. To assess the reliability of these averages, the coefficient of variation of the gauge readings for each row and every storm was calculated, except for rows R1 and R5 which were unreplicated (Figure 4).

Figure 4 Coefficient of variation of rainfall measurements within rows for 27 storms. The boxes cover the middle 50% of the values between the lower and upper quartiles with the central line representing the median. The lines extend to 1.5 time the interquartile range.



Within-row variability of the rainfall readings was small for rows R2, R3 and R4 but increased significantly at row 5 at the tree/crop boundary. The wide range of data inside the tree plot (R6 - R10) is related to the effects of the canopy on throughfall. The relatively high variability of the amounts caught in rows R11 (tree/crop boundary) through R13 are most likely caused by turbulence on the lee side of the tree plot and irregular interception and canopy drip effects.

Detailed storm descriptions were obtained from the datalogger records (see Table 1 for sample description). They included: time of rainfall occurrence, hourly precipitation total, mean wind speeds at the climatological station and at the 6 anemometer sites, and the prevailing wind direction. Rainfall intensities were assessed from datalogger printouts of minute totals.

Table 1 Details of storm 22 on 2 December 1986.

MM	dd	hh	RR	FFM	DD	F1	F2	F3	F4	F5	F6
Dec	01	13	1.00	12.3	90	7.1	7.3	6.9	6.9	3.0	2.6
Dec	01	14	2.75	9.4	104	6.4	6.4	5.5	5.5	2.3	2.2
Dec	01	16	0.75	9.3	79	5.7	5.7	5.4	5.4	2.4	2.1
Dec	01	20	1.25	11.7	97	6.3	6.4	5.8	5.8	2.6	1.9
Dec	01	21	8.00	7.5	82	4.6	4.6	4.3	4.3	2.1	2.0
Total/Avg.			13.75	8.4		5.0	5.1	4.6	4.6	2.1	1.8

MM,dd,hh	Month, date, hour
RR	Hourly rainfall totals in mm, climatological station.
FFM	Mean hourly wind speed in km/h, climatological station.
DD	Mean hourly wind direction (vector resultant).
F1...F6	Mean hourly wind speeds in km/h at the TCI cross section, anemometers F1....F6.

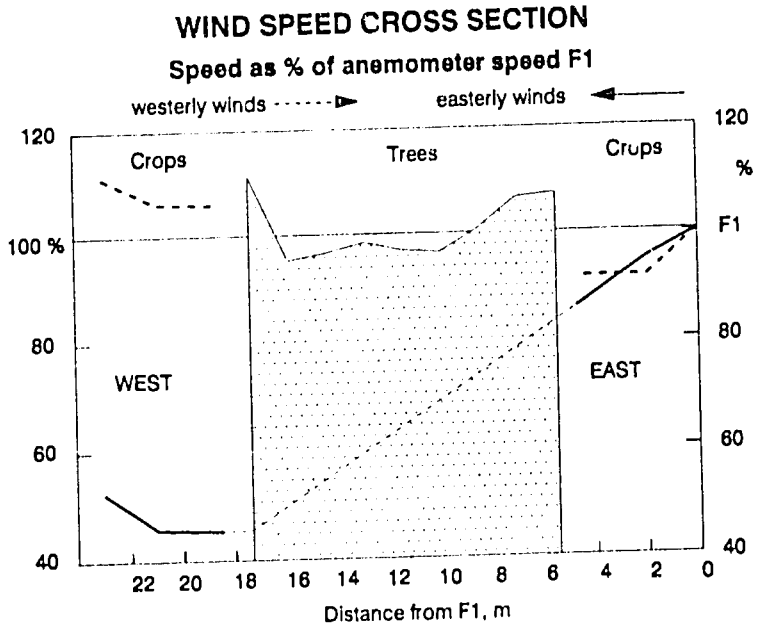
Wind speed

Average wind speeds were calculated for the anemometers F1 to F6 and are plotted in Figure 5 for easterly and westerly winds. From these data windspeed modification factors were derived for various distances from the tree/crop interface as a function of the speed at anemometer site F1, and used to estimate the wind speeds at the rain gauge rows. Missing 'F1' records were estimated from the anemometer at the climatological station, using the following regression equation derived from data collected during periods of simultaneous observations:

$$F1 = 0.4717 \times FFM + 1.03 \qquad (r^2 = 0.84)$$

where F1 is wind speed at F1 (km/h); and FFM is wind speed at the climatological station (km/h). This, and wind records from the climatological station, allowed the classification of the storms by prevailing wind direction and provided the necessary data set.

Figure 5 Average wind speed across north arm, as percent of wind speed at F1.



Correction of rain gauge measurements for wind effects

A method described by the World Meteorological Organization (Sevruk 1982) was used to standardize the variation of catch for gauges exposed to different wind speeds. Correction factors (k) indicating the ratio of precipitation measured in a sheltered gauge to that measured in an exposed gauge, were calculated as a function of the wind speed at the gauge rim, and rainfall structure parameters (N). The latter were derived in accordance with a method proposed by Bogadanova (1966) using rainfall intensity measurements. With easterly winds on the windward side of the tree plot, rain gauge measurements had to be adjusted by 1.2% to 1.4%. On the lee side, k was always smaller than 1.01 with an average value of 1.006. When westerly winds prevailed during rain storms, it was of course the west side that required higher adjustments. Nevertheless, differences on the lee side were less pronounced as was apparent from the average wind profile.

Results and discussion

Rain gauge data for all 27 storms were grouped by rainfall amounts for storms with easterly winds (Figure 6). Data for storms with westerly winds were pooled (Figure 7). Figure 8 displays the distribution of the total rainfall amounts across the plot.

Rainfall amounts with easterly winds (60° - 130°) generally decreased very slightly (1%) from R1 to R2 (significance of $P < 5\%$ using the one sided sign test) followed by an insignificant increase to R3. (Figure 6) From R3 to R4 a small (2%) but significant ($P < 1\%$) increase was observed. At the tree/crop boundary, (R5) there was, on average a 4% higher amount of water collected in the gauges than in R4, but as for the

Figure 6 Average rainfall distribution across north arm for individual storms with easterly winds. a) light storms; b) medium storms; c) heavy storms.

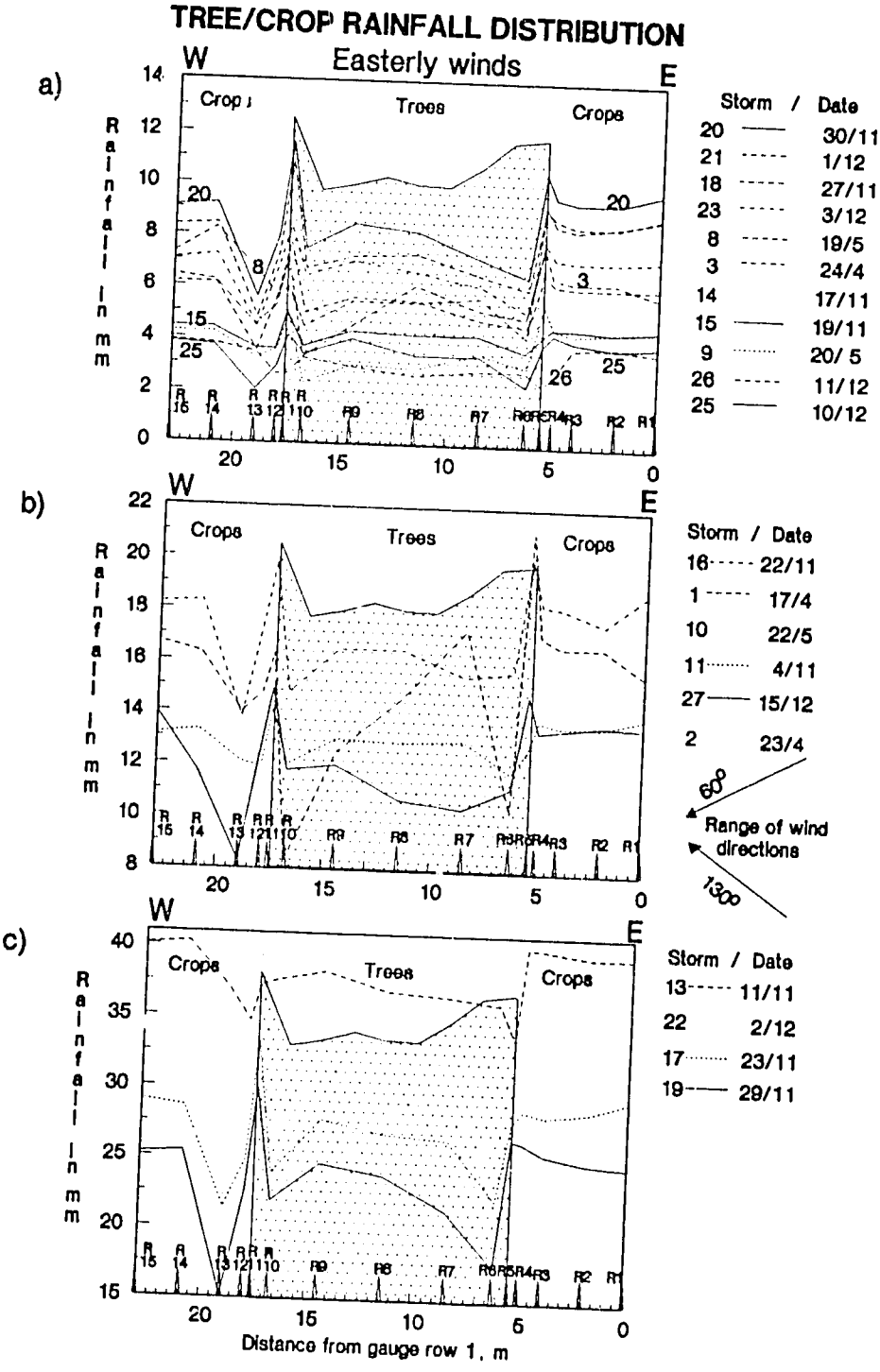
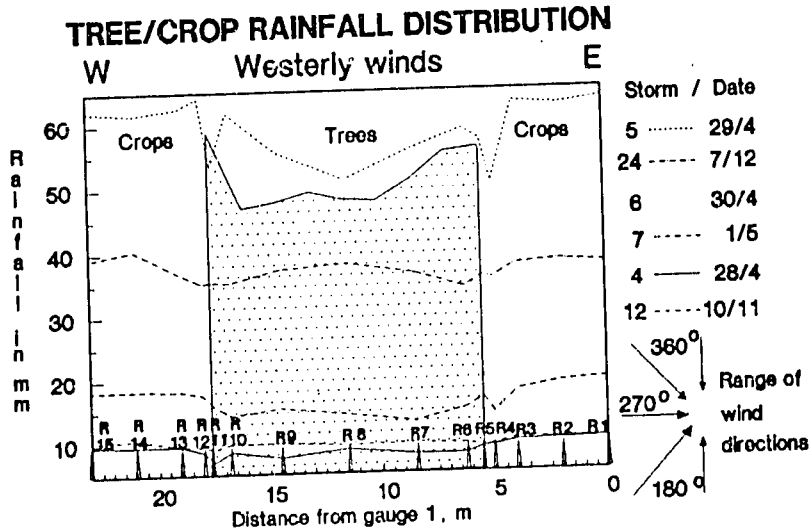


Figure 7 Average rainfall distribution across north arm for individual storms with westerly winds.



storms 11, 13, 15, 17, 25, 26 the situation was actually inverse, the significance parameter remained below 5%. Applying a paired t-test, only the increase fron. R3 to R4 yielded significance at 5%.

The initial decrease of rainfall caught in the gauges is difficult to explain. It may be that the uplift of the airflow when approaching the tree barrier kept some of the rain out of the gauges. It may be an artefact of the inherent randomness of gauge catch. At any rate, the amount of the change is very small.

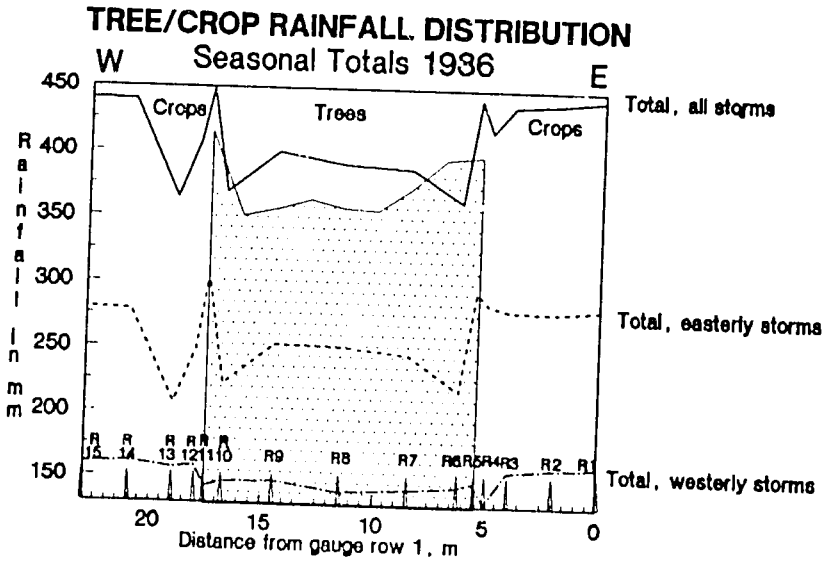
At the windward (eastern) tree/crop interface, the rainfall caught by the gauges was greater than that at the reference R1 by an average 4%; and on the leeward TCI, 8%. Values for individual storms varied from 65% to 138% and 67% to 125% at the two sides, respectively.

The higher rainfall recorded close to and at the tree/crop interface is caused by direct interference of the trees. Earlier studies of the rainfall distribution under trees (-Linskens 1951) have shown that precipitation at the outer end of the tree canopy, consisting of throughfall and large drops running off leaf tips and branches, can be 10% to 20% higher than in the open. The vertical pruning of the *C. siamea* at the tree/crop interface would have sited this canopy drip area close to first stem row.

Throughfall measurements inside the tree plot indicate that on average some 15% of the rainfall in the open is intercepted by the canopy or reaches the ground as stemflow. For storms with a total amount of less than 10 mm, this value increases to 21% while the proportion of interception and stemflow for storms above 20 mm is only 11%. Although not completely regular, the distribution pattern of the throughfall reflects the density of the canopy. Although this was not measured, it was observed to be much denser on the outer rows than in the center of the tree plot.

The relatively high precipitation at the tree/crop interface on the lee side of the plot (R11), 8% greater than at R1, can again be explained by the canopy drip effect, which was most likely reinforced by the especially dense foliage of the taller outer tree rows.

Figure 8 Average rainfall distribution across north arm for all storms.



The leeward area adjacent to the western tree/crop boundary experienced a sharp decline in the amount of water received during storms with easterly winds. At R13, a distance of 1.5 m from the last tree row, an average of 73% of the total rain in the open (at R1) reached the ground. This rain shadow effect varied considerably, however, and is clearly dependent on the wind speed. Between 50% and 60% of the precipitation recorded under undisturbed conditions was measured at R13 when the reference wind speed at the climatological station during the hours with maximum rain was greater than 10 km/h (e.g., storms 25 and 18). At wind speeds lower than 5 km/h (e.g., storms 11 and 13) the maximum rain shadow effect gets closer to the interface and was already apparent at 0.5 m distance with a decrease in the rainfall amount of only 15% and 12%, respectively. The distance over which adjacent crops would be deprived of rain was small. For example, at 3.5 m from the trees, a distance equal to their height, the precipitation was nearly back to undisturbed conditions; and at R15 (about 1-1/2 tree heights from the interface), the total amounts do not on average differ more than one or two percent from the ones at R1 on the windward side of the tree plot.

The rainfall distribution patterns under conditions with westerly winds (Figure 7) show less distinct features, which can probably be attributed to the wider directional range of the winds (180° - 360°). The rain shadow effect on the lee side can however be seen on the rainfall cross-sections for the storms 5, 6 and 7 which had reference wind speeds from 5 to 13 km/h during the hours of maximum rainfall, even if this effect extends only to a distance of 0.5 m from the trees.

A detailed analysis of the maize crop data (see Huxley et al. this Section) did not reveal a negative influence of this rain shadow on growth or yield, suggesting that the indicated reduction of precipitation did not limit the water availability for plant development in absolute terms during these two seasons. Under conditions where the general precipitation patterns did impose growth limitations these might, however, be reinforced by such modifications of the rainfall regime adjacent to the tree/crop interface.

Indeed, in such circumstances, a relatively close-planted barrier can be expected to influence rainfall redistribution similarly; e.g., with hedgerows or boundary tree lines, and on the edge of plots of tall crop plants. Even if the distances over which such effects are manifested are small, an understanding of them can help with the interpretation of yield data from agroforestry field experiments carried out under similar conditions.

Conclusions

With our experimental set up, the rainfall regime was clearly modified at the tree/crop interface. The main factors were the wind speed and its direction relative to the tree/crop interface, and the tree canopy. As expected, the leeward side of the tree plot received less precipitation than the undisturbed windward side; but, surprisingly, not much less. The area suffering from rainfall reduction was greater on the leeward side and was dependent on wind speed and wind direction, but did not exceed a strip wider than the height of the trees. Reductions of up to 50% were been observed at a distance of less than half the tree height; the average for storms with the same wind direction was 27%. Considering storms with winds from all directions, the same area experienced a total rainfall deficit of only 18%.

Precipitation caught in the gauges at the tree/crop interface was increased. This increase could not only be attributed to wind effects but was also influenced by the canopy; direct interception of the rain above the gauges, by leaves and branches, was balanced by or exceeded by the drip from the entire canopy.

Acknowledgements

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The influence of rainfall distribution on the yield of maize under Leucaena leucocephala alley cropping at Mtwapa, Coast Province, Kenya

K. Reshid and A. Getahun

Energy Development International
P.O. Box 62360, Nairobi, Kenya

B. Jama

International Council for Research in Agroforestry (ICRAF)
P.O. Box 30677, Nairobi, Kenya

Abstract

The study conducted at Mtwapa, Coast Province, Kenya, during the long rains of 1985 and 1986 on the influence of rainfall distribution pattern on the yield of maize under Leucaena leucocephala *alley cropping showed that rainfall distribution pattern had significant effect on the yield of maize even though the total rainfall for both years was the same (1130 mm and 1128 mm for 1985 and 1986, respectively). Maize yields for both years were also consistently higher under high Leucaena densities than under low densities or the sole crop. Yields of maize were very low in 1986 as a result of the heavy rains during the early crop growth stage (vegetative) (91%) and little during the pollination and grain-filling stage (reproductive) (9%) as compared to 1985 where rainfall distribution was relatively uniform whereby 58% of the total rainfall fell during the vegetative growth period and 42% during the reproductive period. As the result yield of maize in 1986 was reduced by about 60% as compared to that of 1985.*

Introduction

In the tropics, crop yield fluctuates significantly from year to year, more so because of the variable distribution of rainfall than from the total received. High rainfall at the beginning of growing periods and its absence at later stages of crop growth and development could significantly reduce yields, even when the total rainfall during the growing seasons is normal and adequate for high crop yields. Reduced crop yields under alley cropping in such poorly distributed rainfall could result nutrient leaching and from competition for the same moisture at later crop growth and development stages. This report illustrates the effect of rainfall distribution on the yield of leucaena alley-cropped maize for two consecutive years, the 1985 and 1986 long-rain seasons at Mtwapa, Coast Province, Kenya.

Materials and methods

Leucaena leucocephala K-28 was planted in May 1982 in a parallel systematic design (Bleasdale 1967) comprising 3 between-hedgerow- row spacings (2, 4 and 8 m) and 4 within-row spacings (0.5, 1, 2 and 3 m). It was cut back to height of 0.5 m on March 1985 after a growth period of three years. The leaves and small twigs were incorporated into the soils during weeding after fresh weights were recorded. Maize (Coast Composite variety) was intercropped at a spacing of 90 x 30 cms on April 1985 and April 1986. Triple superphosphate (TSP) was applied at the rate of 150 kg/ha during planting. Calcium ammonium nitrate (CAN) was applied at the rate of 50 kg/ha twice during growing period.

Due to the vigorous coppicing of the leucaena, two additional prunings were made in April and May. The leaves and twigs less than 5 mm in diameter were incorporated into the soils during weeding. The maize was harvested on 20 August, 125 days after planting.

Similarly, during the 1986 long-rains season, maize was planted as an intercrop with leucaena on 1 April. The leucaena was coppiced at the end of March, April and May. All green leaf manure (GLM) of the three cuttings was weighed and recorded before being incorporated into the soils of their respective plots. TSP and CAN were applied as in the 1985 cropping season. A control plot with five replications was also planted with the same rate of fertilizer application during the cropping seasons of both years. The plots were left fallow between experimental periods. The maize was harvested on 18 August, 138 days from planting in 1986. Data on rainfall distribution of the two years were obtained from the agromet station of the Coast Agricultural Research Centre, Mtwapa, where this study was conducted. A statistical analysis was performed with rainfall distribution in the two years and leucaena spacings as independent variables; and grain yield and green leaf manure as the dependent variables.

Results and discussion

Maize yields under leucaena hedgerows were significantly higher in 1985 than in 1986 even though the total rainfall for the two years was essentially the same, 1130 and 1128 mm, respectively (Table 1 and Figure 1). However, during both years maize yields were significantly higher than those of the sole maize crops.

The reason for the lower yield of maize in 1986 appears to be the poor distribution of rainfall in that year: 91% during the two- month vegetative growth period and 9% during the pollination and grain- filling period. In the previous year, the same amount of rainfall was more evenly distributed: 58% in the first two months, 42% in the second period. We believe that the early heavy rains in 1986 caused excessive leaching of nutrients such as N and K which were then unavailable to the maize crop. Nutrient leaching rates are high in the coastal sandy soils (Anon 1984). A single rain has been reported to have the ability to move nitrates from the soil surface to a depth of 6 cm in 24 hrs (Thompson and Troeh 1979). Vittum, Lathwell and Gibbs (1968) also found that 54 kg/ha of K was leached as a result of adding 10 cm supplementary irrigation per year. Although this experiment was in the temperate zone (New York), they suggested that the observed leaching approximated the loss in tropical humid regions.

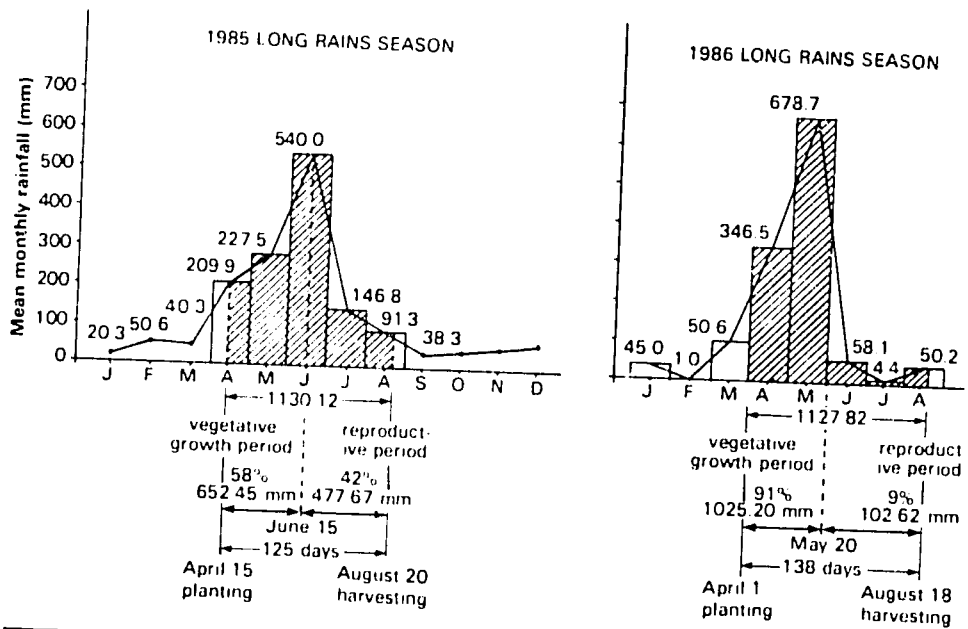
On the other hand, the small amount of rain that fell during the next two months of reproductive period (103 mm) was likely to inhibit pollination and grain filling due to moisture stress. Water stress caused either by low soil potential or high transpiration demand has consequences that involve physiological functions ranging from primary

Table 1 Maize yield (kg/ha) of 1985 and 1986 under leucaena alley cropping.

Between row spacing m	Year	Within-row spacing, m 0.5	1.0	2.0	3.0	Mean
		Yield, kg/ha				
2	1985	4,000	3,600	3,600	2,500	3,425a
	1986	2,598	1,752	1,988	1,608	1,986
4	1985	3,400	2,675	2,363	3,683	2,780b
	1986	1,302	1,330	1,382	1,076	1,292b
8	1985	3,100	2,475	3,100	2,033	2,677b
	1986	786	856	746	686	789
Mean	1985	3,500	2,917	3,021	2,406	2,961
	1986	1,561a	1,312a	1,372b	1,123b	1,342b
Sole maize (control)	1985	2,600				
	1986	475				
SE		a = 87.38		b = 107.02		c = 123.58
CV		31.4				

Means followed by different letters differ significantly from each other when tested with Duncan's Multiple Range Test (DMRT) at 5%.

Figure 1 Rainfall distribution patterns of 1985 and 1986 long rains seasons.



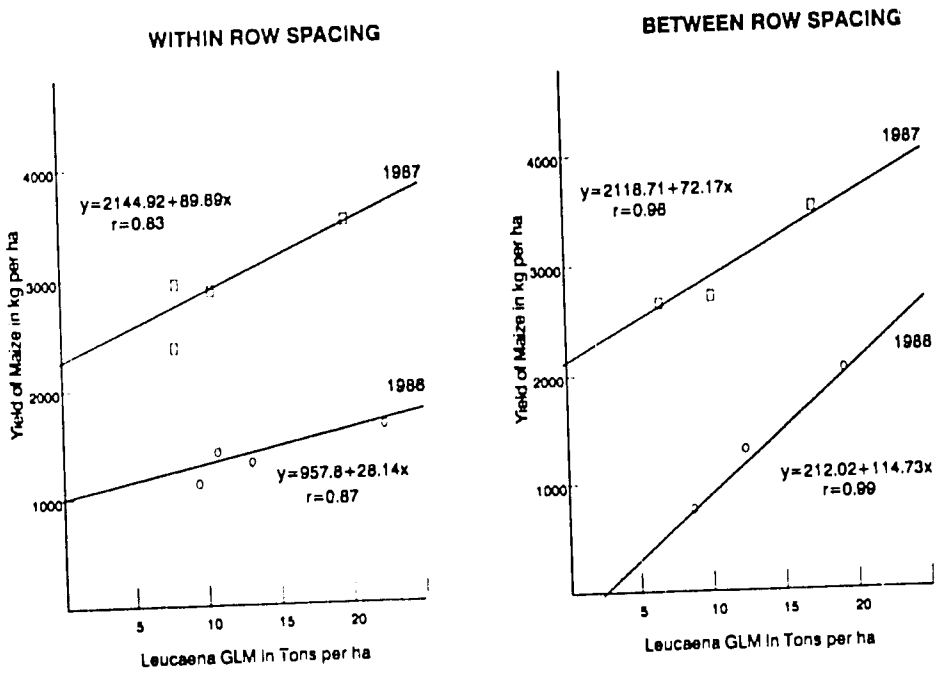
biochemical processes to effects on whole-plant physiology (Crafts 1968; Kozlowski 1968a, 1968b, 1972, 1976, 1978).

Though the main effect of water stress on photosynthesis is attributed to the opening mechanism of the stomatal aperture, there is some evidence that an inhibition of photosynthesis also occurs as a result of water stress in the cells (Salisbury and Ross 1969). This moisture stress could have been aggravated by competition from the leucaena hedgerows which coppice vigorously after every pruning.

Maize yields from narrow leucaena hedgerows has been observed to be significantly lower than under wider hedgerows, all other factors being equal (Kedir and Bashir 1986). This showed that under moisture stress, leucaena could also compete with the food crop. Under the conditions of the present experiment, however, higher yields of maize (4000 and 2598 kg/ha for 1985 and 1986 respectively) were attained by intercropping with high density leucaena hedgerows as compared with yields obtained with the lower-density hedgerows (2500 kg/ha and 475 kg/ha in 1985 and 1986, respectively) and the sole maize crop during both years (Table 1). The reduction in yield of maize in 1986 was about 35% in the 2 x 0.5 m plots when compared to the maize yield reduction of the sole maize crop that had a reduction in yield of 82% from 1985 to 1986.

The positive correlation between maize yields and amount of GLM incorporated into the soil during both years (Figure 2) showed that the higher yield of maize in the high density leucaena hedgerows (e.g., 2 x 0.5 m) was also associated with the high GLM pro-

Figure 2 Correlation between maize yield and green manure incorporated into the soils during the long rains seasons of 1986 and 1987.



duced (Table 2). Conversely, maize yields were consistently negatively correlated with increase in hedgerow spacing (Figure 3) which produced decreases in GLM yields.

In the higher density leucaena hedgerows (2 x 0.5 m), the effect of high evaporation rates and wind velocity that are characteristic of the coastal area might have been reduced as a result of the high density hedgerows serving as a windbreak. Also partial shading of the soil could have created a favourable microclimate of stable humidity for the development of the intercrop under high leucaena density plantings.

As is the practice in alley cropping systems (Kang, Wilson and Lawson 1984), the leucaena hedgerows were left to grow during the dry season and develop a dense canopy. This controls the growth of weeds and protects the soil from the intense heat of the sun. The high yields of GLM that were obtained from the three cuttings of the high- density leucaena hedgerows, and the extensive root system of leucaena, could have added more nutrients and organic matter to the soil. This may have substantially increased the moisture retentive capacity of the sandy soils. Thus, nutrients and moisture would be more readily available to the crop than in lesser leucaena hedgerow densities and sole maize crop (Table 2).

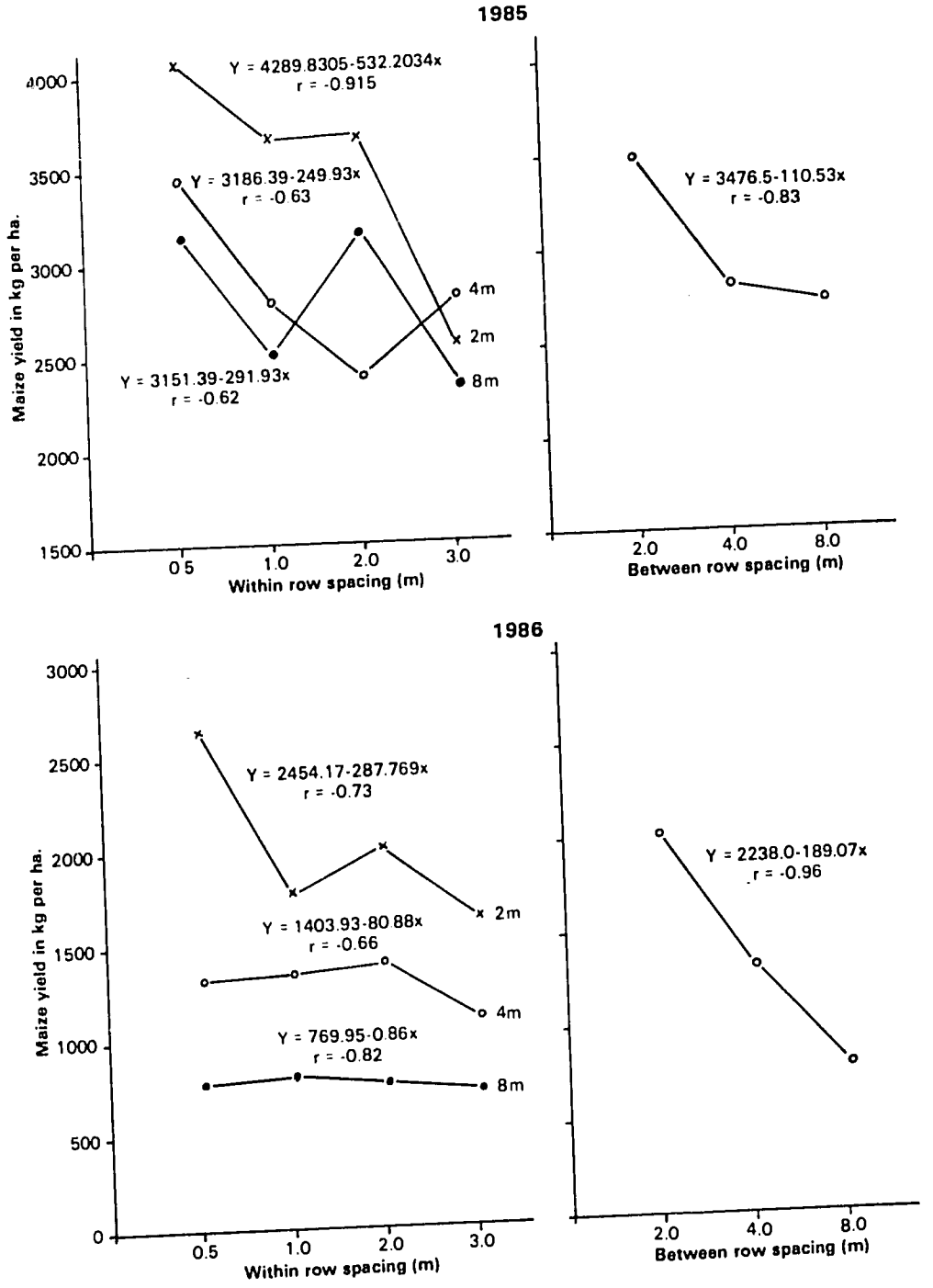
Agriculture in the coastal strip of Kenya is currently characterized by predominantly tree-based systems in which trees such as coco palm, cashew nuts and mangoes are intercropped with cassava and/or maize, with or without associated livestock grazing. Our results indicate that under the conditions of uneven rainfall distribution, high evaporation rates, high wind velocities and weeds that occur in the coastal strip of Kenya, alley cropping may be a useful alternative farming system. This should ameliorate the high leaching rates of the soils and reduce the need for chemical fertilizers.

Table 2 Leucaena green manure yield (t/ha) of 3 prunings for 1985 and 1986 long rains seasons.

Between row spacing m	Year	Within row Spacing m 0.5	1.0	2.0	3.0	Mean
		Yield, t/ha				
2	1985	28.3	17.4	13.9	11.3	17.7a
	1986	32.2	16.9	14.1	14.06	19.0
4	1985	18.3	8.6	6.5	8.2	10.4b
	1986	20.4	11.5	11.2	7.6	12.0
8	1985	121	62	46	48	69.0c
	1986	12.9	9.7	6.7	6.7	9.0
Mean	1985	19.5a	10.7b	8.3b	8.2b	11.33
	1986	21.8a	12.7b	10.7b	9.4b	13.0
SE	a = 0.4310		b = 0.49		c = 0.86	
CV		9.62%				

Means followed by different letters, significantly differ from each other when tested with DMRT at 5%.

Figure 3 Correlation between maize yield and spacing during the 1985 and 1986 long rains seasons.



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Light availability at the tree/crop interface

J.E. Jackson and J.W. Palmer

Institute of Horticultural Research
East Malling, Maidstone, Kent ME19 6BJ, UK

Abstract

The tree x crop interface with respect to competition for light in an agroforestry system can be defined as the proportionate area of crop-producing ground on which the trees cast shade (F_{max} – the fraction of the land area which would be shaded if the trees were non-transmitting). The actual proportion of the available light which is received by the crop (T) is governed by the equation:-

$$T = T_f + F_{max}\, e^{-KL'}$$

where T_f is the fraction of available light which misses the trees altogether, L' is tree canopy LAI divided by F_{max} and K is the light extinction coefficient within the tree canopy.

Where the trees form a continuous upper canopy in a multi-story system T_f is zero, F_{max} is 1 and the light received by the under-tree crop is a function of tree canopy LAI and K. If tree LAI is uniformly distributed so will be the light received by the crop.

In tree-row x crop-alley system T_f is controlled by the dimensions and orientations of the rows and alley-ways and also by latitude and time of day and year: these last three factors determining solar altitude and azimuth. Where the rows are N-S the lower the latitude the greater the relative irradiance of the alley. If the ratio of tree height to alley width is more than 1:1 the irradiance over the alley is remarkably uniform. With E-W rows, there are strong interactions between time of year, latitude and shading pattern. In equatorial regions, for example, at certain times of year the alleys would be able to produce crops requiring high light intensities irrespective of tree height whereas alley irradiance at 30° N is never quite as good and is optimal at quite a different time of year.

Young trees intercept relatively little of the incident radiation. It was shown experimentally that crops of strawberries growing between 2- and 3-year-old rows of apple trees at normal commercial spacing did not reduce the apple yields and, in themselves, yielded as much as when grown in the open.

Introduction

In previous papers (Jackson 1983 and this volume, Section 2) simple general method of determining the proportions of the available light which will be intercepted by the tree-crop and ground-crop components of agroforestry systems was discussed. The possibility of maximizing overall productivity by combining trees of high transmissivity but high light requirements for development of their economic product with ground crops with lower light requirements was also considered.

In this context the area of crop-producing ground which can be shaded to any extent by the trees is considered as a tree/crop interface. For convenience, although trees may

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bear crops themselves they are, in this paper, simply referred to as trees unless their economic product is specifically being considered and the term 'crop' is used for the ground-cover crop beneath or between the trees.

In order to optimize the integrated agroforestry system it is essential to know the proportion of the total light which will be available to the ground crop(s) and its distribution over the cropped area. It may well be preferable to have the entire crop surface irradiated as uniformly as is possible, or to have a system with more shade-tolerant ground crops planted nearest to the trees.

Trees, however, take a long time to grow. Moreover, the number of potential combinations of tree and ground crops is large, the arrangements in which they could be combined is almost infinite and the size of factorial experiments on agroforestry systems such as to limit the number of combinations which it is practicable to test. A modelling approach to the effects of different arrangements and densities of tree canopies on the light penetrating to the 'agroforest' floor thus has many advantages.

The results of such modelling of light distribution in agroforestry systems can then be used in conjunction with experimental data on shade responses of the different crops, their seasons of growth and cropping etc, as a guide both to the direct planting of agroforestry systems and to further experimentation on these.

Calculation of light distribution over the crop in agroforestry situations

The general equation that defines the proportion (T) of light transmitted to the crop is:

$$T = T_f + F_{max}\, e^{-KL'} \qquad (1)$$

where T_f is the fraction of the available light which misses the trees altogether and would reach the crop even if the trees were totally non-transmitting (i.e., solid and opaque); F_{max} is the fraction of the available light which would be intercepted by the trees if they were non-transmitting; L' is tree LAI (m^2 leaf per m^2 total ground surface) divided by F_{max}; and K is the light extinction coefficient of the tree canopy.

This equation can be applied to an agroforestry system of any level of complexity. Here it is used in relation to three distinct types of system, the first two being defined in their extreme forms:

1. **Multi-storey systems** in which the trees form a closed canopy through which light penetrates to the crop beneath. Separation between tree and crop is thus primarily in the vertical dimension. The term T_f in equation (1) is zero, F_{max} is 1 and light transmission to the crop will be controlled by vertically-summed tree LAI and the relevant light extinction coefficient K.
2. **Row-and-alley systems** in which rows or belts of trees which are so dense that no crop can grow under them are separated by clear alley-ways in which crops can be grown. In this case $T = T_f$, because there is effectively no transmission through the trees. The light energy available to the crop is a function of the pattern of (solid) shadows cast by the belts or rows of trees which, in turn, is dependent on tree height, latitude, row orientation and time of day and season. Scattered, very dense trees casting 'solid' shadows provide a variant of this type.
3. **Intermediate systems** in which transmission to the crop is both of light which by-passes the trees altogether (T_f) and light which passes through the tree canopies (T_c)

which is calculated as $F_{max}e^{-KL'}$ as in equation (1). Almost all multi-storey systems and row-and-alley systems are likely to be intermediate systems in their early years before the tree canopies grow together (multi-storey systems) or become so dense that crops can only be grown in the alleys (row-and-alley systems).

Multi-storey systems

The key question in such systems is likely to be whether they are indefinitely sustainable as agroforestry systems, ie whether light transmission will not ultimately become too low for crop production under the trees. If the system is not indefinitely sustainable the question becomes that of the age at which either the canopy has to be thinned or cropping under it changed to more shade-tolerant crops or abandoned. For calculation of these limits it is essential to measure K for the tree species (see Jackson 1980, 1983), the rate of increase i . LAI and to know the light requirements of the under-tree crop.

Row-and-alley systems

A computer program to calculate cast shadows from non-transmitting hedgerows of varying size, geometry and orientation at different latitudes was used in relation to orchard system design (Jackson and Palmer 1972) and subsequently modified to deal with transmission through the canopy (Palmer 1977). Methods were also described in these papers for calculating diffuse light interception in row-and- alley systems. These programmes enable calculation of the light intensity at any point on the 'floor' of a hedgerow orchard or a row- and-alley agroforestry system at regular intervals each day throughout the year, anywhere in the world, given the appropriate input data. This includes tree dimensions and shape, alley-way width, latitude and date (from knowledge of which solar altitude and azimuth throughout the day can be determined).

If the shadows are not effectively solid, information is also needed about canopy density and the light extinction coefficient for the canopy. These latter can be treated simply in terms of leaf area or in more detail separating out effects of branches and fruits as light-intercepting structures. Where there is a close relationship between leaf area and the dimensions of branches etc, which is often the case, then calculations based on leaf area and extinction coefficients determined *in situ* in relation to measured leaf area are likely to be satisfactory.

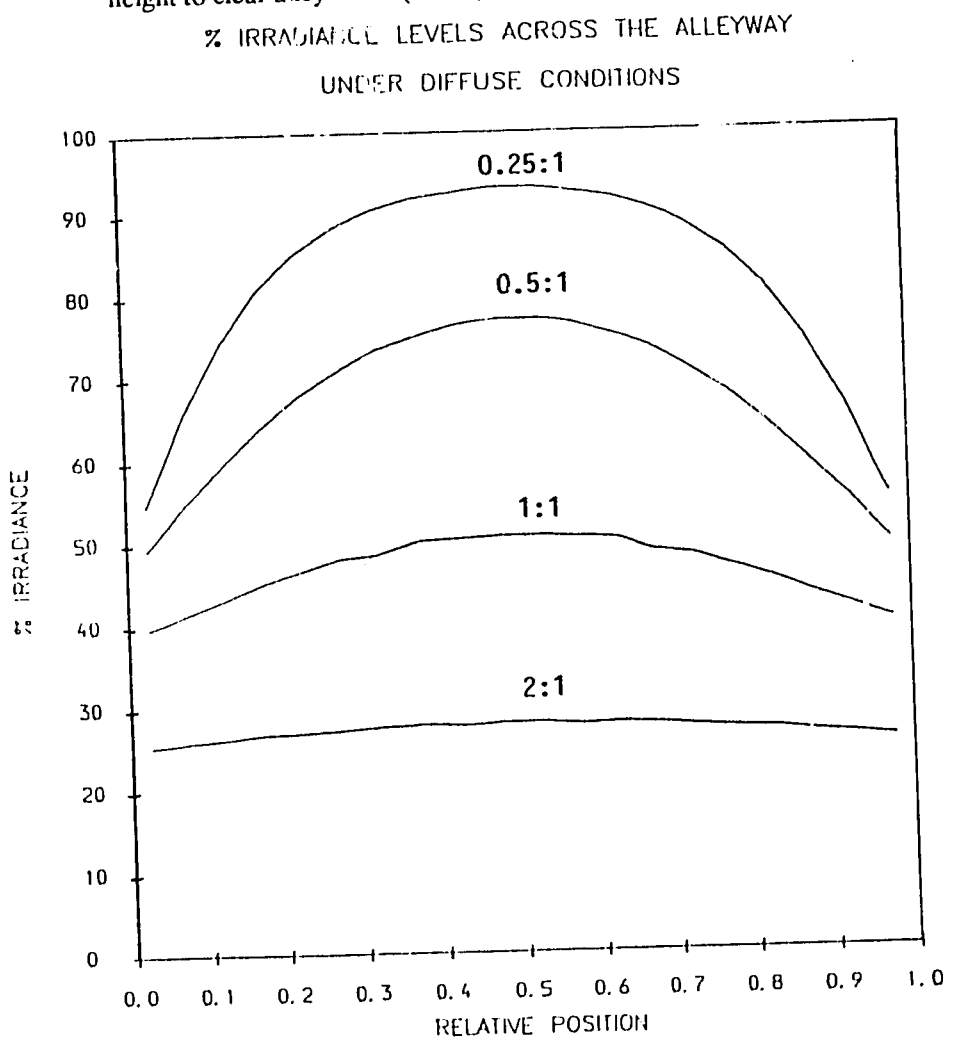
Whereas the light penetrating through a continuous upper-storey canopy is little affected by latitude, solar altitude and azimuth, these factors are very important with respect to T_f in the discontinuous canopy, row-and-alley situation and interact strongly with row orientation. As an illustration, the effects of all combinations of the following were investigated, assuming non- transmitting belts of trees with vertical sides where they abut on the alleys:

1. Ratio of tree height to width of clear alley between adjacent belts of trees:- 0.25:1, 0.5:1, 1:1, 2:1;
2. Row orientation:- N-S, E-W, SE-NW;
3. Time of year:- 21 June, 21 September, 21 December;
4. Latitude:- 0 (equator), 30N, 50N.

For latitudes in the southern hemisphere the data for 21 June and 21 December must be reversed: a SW-NE row orientation gives similar results to the SE-NW orientation. Light levels across the alley were first calculated for totally diffuse conditions, assuming a Standard Overcast Sky, and then integrated over the day for clear, sunny conditions using the levels of diffuse and direct light in relation to solar altitude given by Monteith (1969) and calculating cast shadows on the assumption that the tree rows or belts were flat-topped and vertical-sided, i.e, of rectangular cross-section. The computer programme assumes that the diurnal pattern of irradiance is symmetrical about true solar noon.

Figure 1 gives the variation in light levels across the clear alley-way under diffuse conditions. The term 'clear alley-way' is used to indicate the alley between the (assumed vertical) edges of the tree canopies, not the distance between tree trunks on each side

Figure 1 Irradiance at different positions across the alley surface between two hedges, bordering the alley at 0 and 1 respectively, with 4 ratios of hedge height to clear alley width (0.25:1, 0.5:1, 1:1 and 2:1). Diffuse light only.



of the alley. As the ratio of tree height to alley-way increases not only does the relative irradiance received on the alley-way decrease but there is much less variation across it.

Figures 2, 3 and 4 give the patterns of irradiance across the alley-way under clear, sunny conditions for the three row orientations for each latitude and time of year combination. The patterns for the N-S rows show little effect of time of year.

The effect of latitude is not very great but is consistent, the lower the latitude the greater the relative irradiance received on the alley and the greater the proportion of it irradiated to above any particular percentage of full daylight. At a ratio of tree height to alley width of 1:1 or greater, the irradiance across the alley is remarkably uniform, light levels adjacent to the trees being but little lower than those in the centre of the alley. This suggests that an alley crop which does not have too high a light requirement could be produced to a uniform standard under these conditions. Where the above-

Figure 2 As in Figure 1, at 3 latitudes and 3 times of year. Full sun; hedgerow orientation E - W.

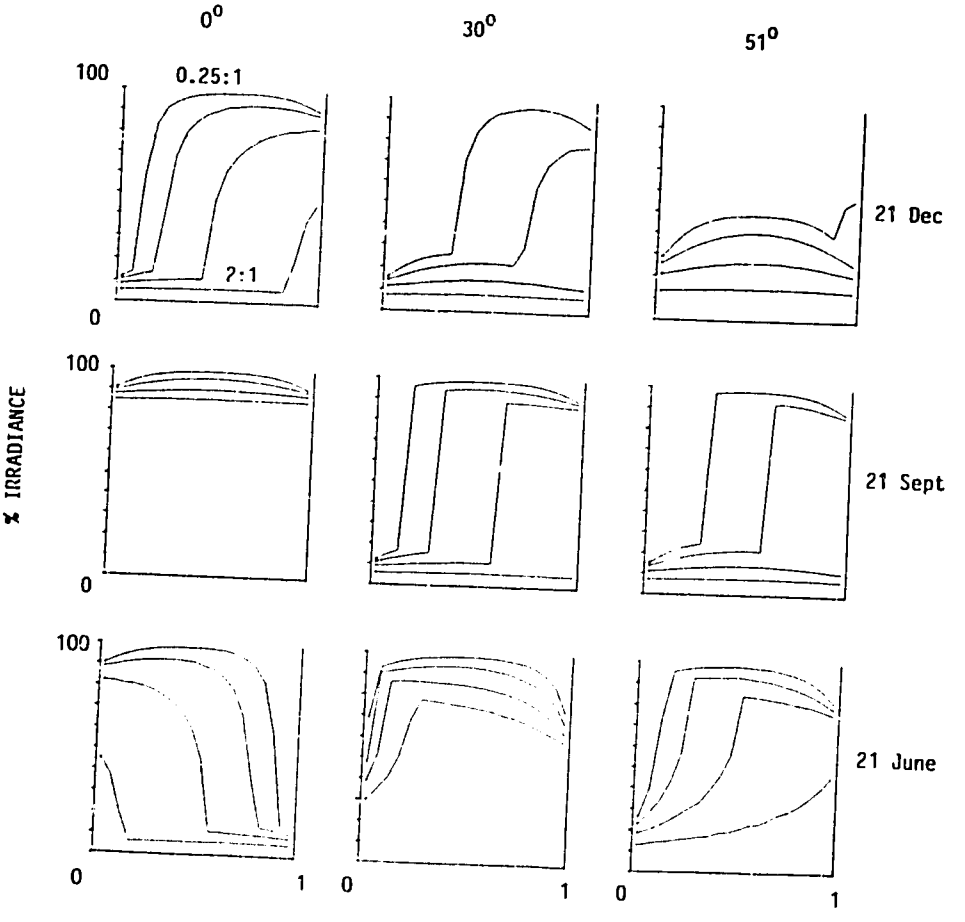
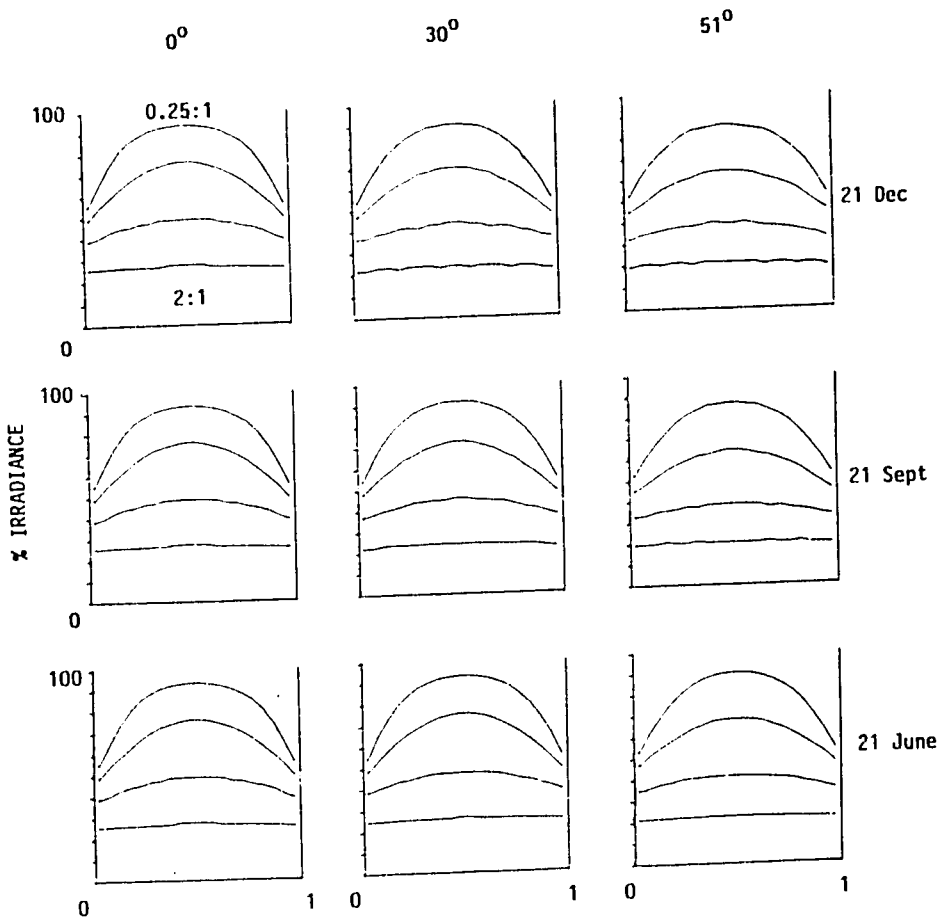


Figure 3 As in Figure 2. Full sun; hedgerow orientation N -S.



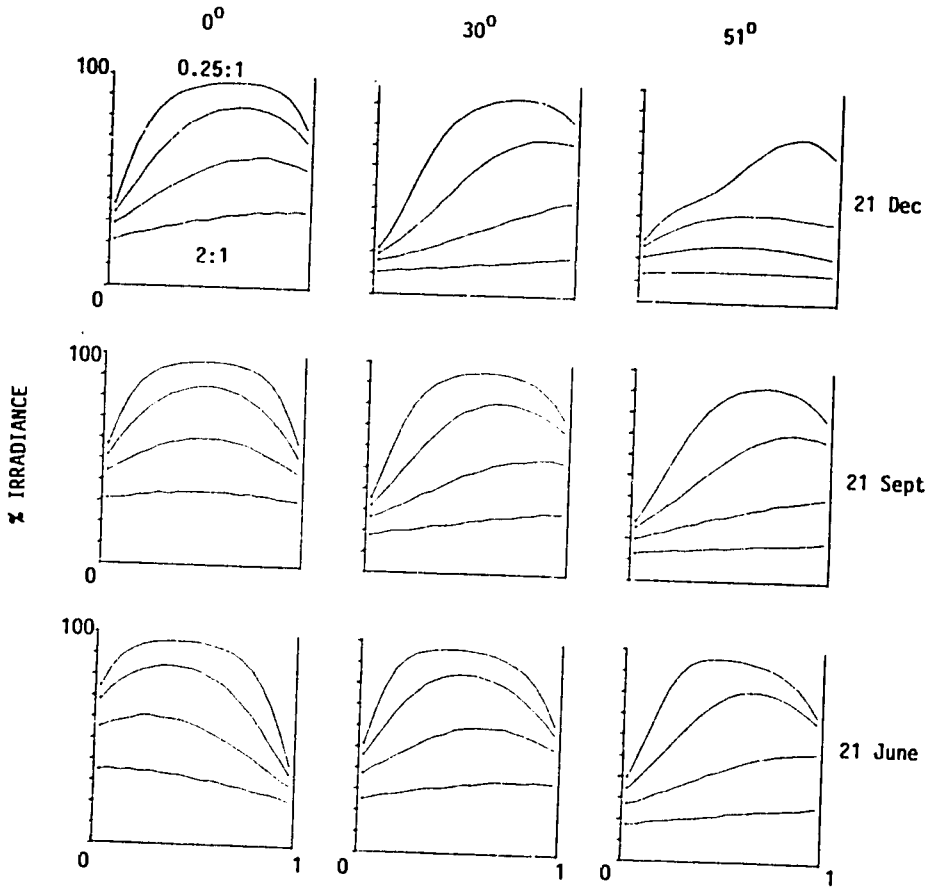
canopy irradiation levels are high the alley-way levels should be such as to produce good crops of shade-tolerant plants such as tropical beans and cassava (Jackson 1988).

With E-W rows, the pattern is altogether more complex, depending on latitude and time of year. In equatorial regions there is obviously a short growing season around 21 September when the entire alley width is highly irradiated, with half of it being well irradiated from June to September and the other half of it from September to December even when row height equals clear alley width. This opens up obvious possibilities for growing even high-light-requirement, short-season grain crops over half of the alley in row- and-alley systems as long as water supply is adequate.

Rows oriented SE-NW are intermediate in their effects on light distribution on the alley. As shown in Figure 4, it is only in a limited number of cases that uniform light conditions obtain over the greater part of the alley.

These computer-model results are essentially illustrative. The assumption that the trees are non-transmitting is a 'simplest case' assumption which is effectively true for some tree canopies which have high LAI values and dense habit (e.g., many windbreaks),

Figure 4 As in Figure 2. Full sun; hedgerow orientation SE - NW.



but much less so for others. Transmission through the canopy would increase the light incident on parts of the alley but would not, except in very extreme cases, influence the basic pattern of variability with latitude, time of year and tree and alley dimensions. This variability is such that it is obvious that a much more detailed analysis is needed before decisions are taken about row orientation and spacing for individual situations. In particular there would be need to:

1. Investigate a wider range of tree height to alley-width ratios;
2. Examine row orientations which might be favoured, for example, for reasons of contour terracing;
3. Define the local radiation climate and take into account the actual ratio of diffuse to direct light and features such as the prevalence of mid-day or afternoon cloud which could affect the relative irradiance from different sections of the sky; and
4. Carry out the calculations for each day, or a day in each week, of the year.

The tree/crop interface - an example of minimal competition

In orchards producing apples for commercial sale, the trees are now generally managed so as to maximize the yield of well-coloured, large fruits rather than total yield. Such fruits can only be produced under conditions of high irradiance on the actual fruit surface and on the nearby spur leaves. The level required varies from variety to variety but the minimum light requirement for good quality fruits ranges from 30 to 50% of full daylight. The ultimate target of orchard design when the trees are mature therefore places a high value on the orchard and the trees not being too dense. Even in mature apple orchards the trees seldom intercept more than 70% of the available light. For the first few years after planting light interception is much lower than this, because the trees have not yet attained their full size or canopy density. Typically, a productive modern 5-year-old orchard may intercept only 30% of the available light (Jackson 1980) and a 3-year-old orchard planted as a very intensive 3-row-bed system intercepts a similar amount (Jackson and Middleton 1987).

In most apple-growing countries the trees are grown in hedgerows; the tree-row being maintained free of competing grass and weeds by the use of herbicides while the alleys are grassed.

Benefits and problems arising from elimination of the grass in the alleys are discussed elsewhere but there would seem little reason why a crop could not replace grass in the alley-ways since the grass is cut only for management reasons and not harvested as a crop. In an experiment planted in 1982 a comparison was made between the yields of apples (grown in hedgerows) with herbicided, grassed, or strawberry-cropped alley-ways and between strawberries in these alley-ways and in the open.

Apple and strawberry intercropping experiment

Experimental details

The trees (cv Cox's Orange Pippin on M.9 EMLA rootstock with James Grieve pollinators every fourth tree) were planted in the spring of 1982 as two replicates of a 3 x 3 latin square with three treatments: overall herbicide, grass alley-ways, or strawberries (cv Cambridge Favourite). The trees were 3 m apart within rows 4.5 m apart and the strawberries were grown as three rows 1.1 m apart centred in the middle of each alley-way. This enabled the wheels of the tractor to pass between the rows of strawberries to apply the spray chemicals. The ground immediately under the trees was kept clear of grass, strawberries and weeds by herbicides: this herbicide strip being approximately 1.2 m wide.

Apple fruit yields and quality.
Results are given in Table 1.

Table 1 Effects of alley cropping on the yield and fruit quality of Cox's Orange Pippin apple.

Year	'Crop' in alley			
	None (overall herbicide)	SED Strawberries	Grass	6df
1983				
Yield (t/ha)	2.62	2.11	1.98	0.472
Yield Class 1 (t/ha)	0.81	0.60	0.90	0.240
Mean fruit size (g)	142.00	138.00	139.00	4.710
% wt fruit C1 1 colour	99.00	99.00	100.00	0.810
% wt fruit C1 1 russet	31.00	26.00	29.00	8.190
1984				
Yield (t/ha)	9.52	8.47	8.41	0.447
Yield Class 1 (t/ha)	5.53	4.96	5.32	0.399
Mean fruit size (g)	134.00	122.00	123.00	6.240
% wt fruit C1 1 colour	85.00	92.00	90.00	2.140
% wt fruit C1 1 russet	71.00	64.00	72.00	2.010
1985*				
Yield (t/ha)ha	4.31	5.59	6.06	0.994
Yield Class 1 (t/ha)ha	1.98	2.79	3.08	0.552
Mean fruit size (g)	182.00	173.00	170.00	10.400
% wt fruit C1 1 colour	92.00	93.00	92.00	2.420
% wt fruit C1 1 russet	51.00	53.00	55.00	5.250

*The strawberries and grass in the alleys were treated with herbicide in spring 1985 so the yields in that year show residual effects only.

The only significant effect on total yield was in 1984 when total yield was lower with grassed alley-ways than with overall- herbicide treated alleys, but this effect was not seen in the yield of Class 1 fruit due to the improvement in fruit colour under the grass treatment. This improvement in colour was not evident as a residual effect in 1985 after both the grass and the strawberries were killed by weedkiller.

The effects on the market quality of the apples indicates the potential complexity of intercropping effects. The higher proportion of well-coloured (Class 1 colour) apples when grown with strawberries or grass in the alley-way was probably due to competition by these for soil nitrogen: it being well established that high soil nitrogen reduces fruit colour and that 'grassing down' improves it by lowering nitrogen levels. The reduction in the percentage of top quality apple fruits with respect to skin-finish (% Class 1 russet) in 1984 when apples were intercropped with strawberries represents skin damage resulting from the chemical spray programmme used for strawberries.

Strawberry yields
There were no significant differences between strawberry yields in the open and those in alley-ways between trees. The trend was in favour of strawberries in the open in 1983 but this was reversed in 1984 (Table 2).

Table 2 Effects of growing Cambridge Favourite strawberries in the alley-ways of a young apple orchard as compared with in the open.

	Strawberry yields (t/ha)		
	Open-grown	In orchard alleys	SED 36df
1983			
Dessert fruit	5.13	4.86	0.202
Total fruit	6.99	6.49	0.254
1984			
Dessert fruit	9.86	10.68	1.145
Total fruit	14.98	15.86	1.223

These results should not be taken to simply that apple trees and strawberries cannot compete with each other which certainly occurs when the trees are planted close together and the strawberries are grown under them (Atkinson 1975). It does, however, show that when grown with the degree of spatial separation implicit in row-and-alley systems with herbicide use within the tree row the effect of young trees on the alley crop and of the alley crop on young trees can be minimal.

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Light and water availability in fields with and without trees. An example from Nyabisindu in Rwanda

I.F. Neumann

Emerson College
Forest Row RH18 5JX, Sussex, UK

P. Pietrowicz

GAT/GTA
P.O. Box 47051, Nairobi, Kenya

Abstract

Trees integrated into fields may compete with the crops for light and water and therefore can reduce yields. In Nyabisindu (Central Plateau in Rwanda, 1700 to 1900 m, approximately 1500 mm of rain p.a.) it was found from experience that in this place the shading effect is more important in normal years.
The effects of arrangement of trees in the field, tree spacing, and pruning of the canopy on light interception were tested in casestudies in agroforestry systems with up to 8 year-old Grevillea robusta. *Shading effects can be controlled efficiently by planting the trees in rows in east-west direction leaving a 'light channel' of 8 to 12 m width in between. 250 to 350 trees per ha may lead to an average light extinction of over 50% in comparison to the open field. By pruning the lower branches of the crown, light extinction can be reduced to about 35%. This degree of shading was tolerated by maize-beans mixed crops.*
Well maintained rows of trees on the sides of fields (E-W direction) had no significant effect on the humidity of the soil as measured by tensiometers. However, the potential evaporation in the middle of the field was reduced by 36% in average. Plants in the open field showed signs of temporary wilting in hot afternoons, whereas this was normally not the case in the field with trees. The reduced light availability was probably over-compensated by the gain in time for active photosynthesis.
In a drought season, water competition between trees and crop was observed and the drought effects were more severe in the shaded field and close to trees than in the open field.

Introduction

Natural and human environment

Nyabisindu is located in the Central Plateau region of Rwanda, at an elevation of approximately 1700 - 1900 m asl. The soils of the hilly landscape have a moderate-to-

poor natural fertility. In normal years about 1000 - 1200 mm of rain may be expected during the humid period from September to June (Pietrowicz 1985). This permits two crops per year: the (so called) first or short rains allow cultivation of beans or an early maize (e.g., Katumani compound) while the second or long rains are adequate for a longer-maturing crop. Traditionally Sorghum bicolor is the preferred crop during this season.

The Nyabisindu region is inhabited by approximately 400 persons per km^2, of whom more than 90% are small-holder farmers producing almost exclusively for their own consumption (Dressler 1984). The traditional forms of land use (shifting cultivation and extensive pastoralism) are no longer likely to provide enough food for the further growing population (Miniplan 1983; Delapierre 1985). Soil degradation and erosion reach alarming dimensions. Also the supply of fuelwood, obviously as important as food crops, is becoming short (Stebler 1983).

A low-input system for sustainable agriculture

These complex difficulties are not easily resolved. However, a precondition to any positive development will be an intensified, ecologically sound, sustainable agriculture that utilizes the locally available resources in an optimal way. We are convinced that diversified low-input systems are superior to agronomic systems with a higher capital turnover, at least under the prevailing local conditions. An improved farming system was developed on the basis of:

1. the natural climax vegetation (i.e., tree savannah in the drier east and semi-deciduous forest in the west);
2. autochthonous farming practices; and
3. experiences gained elsewhere under similar ecological and socio- economic conditions.

This diversified farming system includes agroforestry techniques, intercropping, rotations with green manuring and lays, erosion control, and intensive cattle rearing with minimum grazing, and so forth (Ludwig 1976; Egger 1982; Pietrowicz 1983).

The role of trees in a low-input farming system

The systematic integration of trees into agricultural fields implies material for fodder and mulch or compost, demarcation and stabilization of erosion control stripes (PAP 1984), protection of soil and crop from wind, heavy rains, and excess sunshine, etc. (Neumann 1983; Pietrowicz 1983). However, trees integrated into fields may not have only positive effects but also negative impacts. Competition between tree and crop for light, water, and nutrients is probably the most important limitation to agroforestry.

Under given site conditions the degree of competition will be dependent on the age or size of the tree; the species and its characteristics such as crown shape and density; the shape of the root system; and, last but not least, the density and the arrangement of the trees in the field (Neumann and Pietrowicz 1985; PAP 1984, 1985). Whereas the characteristic properties of a tree species make it more or less suitable for agroforestry use, the management of tree stands plays a decisive role on the performance of an agroforestry system.

Effect of trees on light availability in fields

In demonstration fields with up to eight-year-old *Grevillea robusta* trees, some management-dependent factors were tested. They included the arrangement of trees in the fields and the modification of the crown shape by pruning.

When the plots were established, trees were planted densely along terrace borders and contour lines separating the 8 - 10 m-wide field strips. It was then observed that crops, especially maize, performed much better in strips oriented east-west than in those oriented north-south. It appeared that this was due to differences of light availability depending on the orientation of a field strip. In the equatorial tropics the sun moves from east to west with little deviation from the zenith. Thus the center of east-west oriented strips received full sunlight throughout the day; while in strips oriented north-south, direct sunshine was limited to a few hours around noon; for most of the day, the fields were shaded by the trees.

Approximately half of the trees were cut. The light interception (as measured with a light meter)* was reduced from 47% to 17% as a result of the cutting. In practical terms, maize scarcely grew under the pre-thinning condition, while it performed well after the thinning.

However, if the contour lines and hence the field strips follow the east-west direction, an average light interception of up to 50% may be tolerated. This average value comprises the area of permanent shade under the trees (up to 80-90% light interception on a sunny day) and the inner field which receives full sunlight throughout the day (center of field: less than 10% light interception). Maize grows well in the inner field, but not under the trees.

Size and shape of the crowns also have important effects on the light availabile to crops grown in adjacent fields. The effects of pruning may be exemplified by a field heavily shaded by *Grevillea robusta* at a stand density of 634 per ha. The trees were up to 8 years old and unpruned, resembling a forest more than a field. Removing the branches from the lower quarter of the crowns reduced light interception from 72% to 54%. Subsequently a quarter of the trees were felled to obtain an even distribution of 480 trees per ha, resulting in an average light interception of 47%, averaged over the field (Table 1).

Table 1 Sequential opening of a field shaded very densely by *Grevillea robusta* (634 trees per ha, age up to 8 years, tallest tree 15 m, tree rows in north-south orientation, crowns freely developed); light extinction in % of full light.

Treatment	Light Extinction %
control	72
lower branches cut off: 29% of crown depth of trees 10 m high	
26% of crown depth of trees 10 m high	54
thinned to 480 trees per ha	47
light channels in E-W direction opened, approx. 50% of trees felled	17

Source: Neumann & Pietrowicz 1985

* Light interception was calculated from lux values determined simultaneously in fields with and without trees. No data are available on the radiation relevant for photosynthesis.

In well-spaced and maintained agroforestry stands with 250 to 350 trees per ha of variable age, the average light extinction varies between 20% and 50%, depending on the orientation of the slope and the rows in the field. This degree of shading is tolerated by maize- beans mixed crops.

Effect of trees on water availability in fields

Soil moisture and potential evaporation were compared in fields with east-west oriented, well-maintainewd rows of trees and neighbouring open fields.

Although trees had no significant effect on the moisture status of the soil as monitored by tensiometers, soil moisture tension appeared slightly higher in shaded fields and closer to the trees.

Trees reduced the effective rainfall by interception. Even the open center of the field received an average of 10% less rain than the open fields. In normal seasons water concurrence between trees and crops was not expressed. During a drought season, however, distinct water concurrence could be observed. The drought effects were more severe in shaded fields and close to the trees than in open fields.

The rows of trees in the agroforestry plots reduced the potential evaporation considerably. In the center of the field, which received sunshine throughout the day, the potential evaporation was reduced by 36%, compared to open fields. During the observation period (49 weeks in 1983) the average weekly evaporation was 25.5 mm in the open and 18.8 mm in the shaded field. This finding is supported by phenological observations of the crops. In the open fields plants showed temporary wilting signs in hot afternoons, whereas this was normally not the case in the fields with trees.

Effect of trees on crop yield

The average harvests obtained in this experiment over five growing seasons are summarized in Table 2. The data are for mixed crops, i.e., maize and beands in the first rains; and maize, soy beans and sweet potatoes in the second rains. While the harvests of maize, beans and sweet potatoes were significantly higher in the agroforestry treatment, soy beans and particularly the weeds suffered from the shade.

Table 2 The effect of tree integration on the harvest of mixed crops (average over five seasons)

Crop		Harvest w/trees	open kg/ha	Difference %
Maize	(grain)	1476	1204	23 **
Bean	(grain)	885	798	11 *
Soy Bean	(grain)	244	312	22 *
Sweet Potato		3375	2439	39 *
Weeds (dry weight)		1680	2210	32 **
Green manure		15270	14560	5 ns

Source: Neumann and Pietrowicz 1985.

Conclusions

The case study confirmed that spatial arrangement and management of tree stands are decisive for the performance of an agroforestry system. To limit light interception to a degree tolerated by crops, trees must not shade the agricultural land permanently. On level land, this can be achieved by planting trees only in east-west-oriented rows. On slopes, where this is not possible due to the need for erosion control, trees should be placed at cross points of contour lines (e.g., terrace borders, erosion control ditches) and thought lines in east-west direction leaving open 'light channels.' Also, pruning the lower branches of trees can reduce light interception considerably.

The higher harvest obtained in well-maintained agroforestry plots indicate that slightly reduced light availability (approximately 15-20% in this case study) can be compensated for by a gain in time with active photosynthesis.

The optimal density of trees (number per ha) and the degree of shading of a field is probably very site-specific. The most important determining factors include species, age, size and shape of the trees grown, exposition of the field, light and water requirements of the crops to be grown, temperatures and moisture availability during the growing season; and probably also the nutrient status of the soil.

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Soil erosion as influenced by rainfall erosivity under different agroforestry systems

R. Gopinathan and C. Sreedharan

Department of Agronomy, College of Horticulture
Vellanikkara, Trichur 680654, Kerala, India

Abstract

An experiment on 'Agrotechniques for soil conservation in taungya systems' was conducted at the Instructional Farm, College of Horticulture, Vellanikkara for a period of two years from May 1984 to April 1986. The main objectives of the experiment were to assess the runoff, soil and nutrient losses as influenced by the important taungya practices and to evolve economically and ecologically viable agroforestry measures for soil conservation.

Eucalyptus, the main tree component, was intercropped with the usually-cultivated taungya crops of cassava and rice. The efficiency of cassava planting on ridges, grass farming and grass stripping was also investigated. There were seven treatments replicated thrice in randomized block design. Daily runoff and soil loss were quantified by installing multi-slot devices consisting of 47 slots and brick masonry settling tanks specifically designed for the project.

*Various rainfall characteristics were reloted vis-a-vis runoff and soil loss. It was found that runoff was highly correlated with the amount of rainfall (r = 0.930**) closely followed by kinetic energy (r = 0.912**) and AI_m (r = 0.848**). Soil loss showed maximum correlation with EI_{15} (r = 0.977**). A comparatively lesser correlation of runoff with soil loss (r = 0.790**) indicated that erosion was more influenced by rainfall characteristics than runoff.*

Cultivated fallow plot produced the highest runoff of 1259 mm (53 per cent of the total rain) and soil loss of 352 t/ha/yr. Mound planting was very much deleterious irrespective of the cassava population. Rice taungya was comparatively harmless. Grass farming was more efficient than ridging in controlling soil erosion and runoff. It accepted more than 96 per cent of the rain and eroded only 0.40 t/ha of soil in the second year. Replacing 10 per cent of the cassava population with grass strips reduced soil erosion by 41 per cent as compared with the maximum cassava treated plot within one year. Tree planting alone could reduce the soil erosion by 87 per cent in the second year.

The eroded soil was, in general, more clayey and contained more nutrients than the soil matrix especially during the initial months. Cultivated fallow plot had lost 416, 116, 680, 242, 878 and 229 kg/ha of N, P, K, Ca, Mg and S respectively. Such losses were 395, 120, 697, 183, 717 and 213 respectively in eucalyptus + five cassava on mounds.

Grass farming, irrespective of high fertilizer application, effectively reduced the above nutrient losses respectively to 4.0, 0.40, 4.0, 2.0, 0.70 and 0.10 kg/ha. Ridge planting of cassava was also comparable to grass farming in controlling nutrient drain.

Mound planting of cassava cultivation affected the soil physical characteristic while grass, rice and zero cultivation improved them. Appreciable chemical changes were not manifested between treatments during the investigation period.

The most robust trees were observed in the eucalyptus-alone treatment. The weakest trees were seen with eucalyptus + five cassava on mounds. The highest net income of Rs. 10,120 / ha produced by eucalyptus + grass combined with the complete control of soil erosion in the second year make this treatment the most ideal. However, the absence of a subsidiary food crop limits its adoption on a wide scale. When acceptability, profitability and sustainability are taken into account, the treatment eucalyptus + cassava + 10 per cent grass strips seems to be a better system.

Introduction

Soil erosion is universally recognized as a serious threat to man's well being. An alarming majority of farmers especially in the tropical developing world suffer from devastating effect of soil erosion and consequent low crop productivity. Current conservation techniques of contour embankments, check dams, retaining walls and terraces are characterized by their high cost and impracticability. This inevitably prevents the hill slope farmers from adopting them to any measurable extent.

Proper crop management is more effective in reducing erosion than conservation practices such as terracing and contouring. This is mainly due to dissipation of the rainfall erosivity by crop cover. Shaxson (1981) argues that vegetation is so effective that more effort should be made to integrate crop cover with other soil conservation practices. Unfortunately the research on the effect of crop cover in reducing erosion is inadequate to serve as a basis for conservation planning.

Agroforestry is a sustainable system of land management suited to the fragile and brittle ecosystem of the tropics where soil erosion is a major problem. Most of the research results now available are from temperate zones; and a knowledge of the mechanism in tropical climate, soil and ecosystem is rather inadequate (Kanwar 1982). Environmental conditions and farming systems need to be taken into account when transferring technology from one country to another. Therefore, soil conservation planning must necessarily be country-specific and sometimes region-specific or even economic-sector-specific.

Kerala, the southernmost state of India experiences a tropical humid climate and receives intense seasonal rainfall leading to severe soil erosion. Almost half of the cultivated area is on sloping lands not suitable for agriculture. The farmers are forced to cultivate cassava, the most important subsidiary food crop of the state on these steep slopes due to acute pressure on arable land. Cassava is, however, a highly erosion- permitting crop. But low cost of cultivation, quick returns and lesser incidences of pests and diseases make this an inevitable component of subsistence farming. It is important, therefore, to develop conservation techniques that incorporate the protective ability of tree crowns and crop canopies against rainfall erosivity. This paper gives the details of a two-year field experiment on runoff and soil loss as influenced by eucalyptus-based agroforestry on a steep sloping farm in Kerala.

Materials and methods

The experiment was conducted at Kerala Agricultural University, Vellanikkara, Trichur, from May 1984 to April 1986. The site was situated at 10° 32' N and 70° 10' E at an altitude of 22 m asl. The soil was a deep, well drained, moderately acidic, sandy clay loam oxisol fairly rich in organic matter. The plot had a slope of 25 percent facing north.

The experiment was laid out in uniform runoff plots of size 24 m x 4 m, arranged lengthwise facing north.

The following seven treatments were replicated thrice in a randomized block design.

T_1 – Eucalyptus alone.
T_2 – Eucalyptus + five plants of cassava on mounds in between four trees.
T_3 – Eucalyptus + four plants of cassava on ridge across the slope taken in between four trees.
T_4 – Eucalyptus + one cassava on mound in between four trees (Present taungya practice allowed by Government on hill slopes).
T_5 – Eucalyptus + congosignal grass.
T_6 – Eucalyptus + upland rice.
T_7 – Cultivated fallow.

In the second year, T_7 was changed to eucalyptus + cassava on mounds as in T_2 + 10 per cent of the area inter-stripped with congosignal grass.

Daily runoff from each plot was collected in a runoff- collecting device comprising a brick masonry tank and a multi-slot device with 47 slots, specifically designed for the purpose. Settled and suspended sediments were measured separately and total soil loss was calculated. Splash erosion in each treatment was determined by installing splash collection assembly as suggested by Verma (1984). Rainfall interception was assessed by measuring the throughfall under the canopy cover with ordinary rain gauges. Canopy cover index was calculated from the canopy cover of each crop and each treatment.

An automatic recording rain-gauge installed at the experimental site provided details on specific rainfall events. Various characteristics of the rainfall, viz., amount, duration, intensity, kinetic energy, EI_{15} (total k.e. x maximum rainfall intensity in 15 minutes / 100), EI_{30} (total k.e. x maximum rainfall intensity in 30 minutes / 100), and AI_m (amount x intensity maximum factor) were determined (Wischmeier 1975; Hudson 1984).

Results and discussion

Splash erosion and rainfall interception as influenced by canopy cover

Data on splash erosion and rainfall interception are provided in Table 1 and Table 2, respectively. Figure 1 depicts the monthly combined canopy cover index.

In the first year the cultivated fallow plot, T_7, recorded the highest splash erosion and T_5 the lowest. T_6 immediately preceded T_5. Among the cassava intercropped treatments, T_3 gave the maximum value followed by T_4 and T_2. T_1 recorded lower value than the cassava intercropped treatments.

The second year showed almost the same trend. T_7 registered a lesser value than T_3 and T_4. In grass plot T_5, annual splash erosion was significantly less and even registered zero values in some months.

Table 2 reveals that, in the first year, grass and rice plots recorded maximum interception. T_1 registered the lowest interception. Other treatments gave intermediate values. The same trend was followed in the second year.

Splash erosion is a measure of the detachability of soil particles by the impact of rain drops. The highest splash erosion observed in T_7 of the first year is due to the impact of the un-interrupted rain on the cultivated bare fallow plot. Soil detachment due to

Table 1 Splash erosion (g/m^2)

Month	Treatment							
	T_1	T_2	T_3	T_4	T_5	T_6	T_7	Mean
1984								
May	10.46	11.94	13.49	11.19	10.96	9.84	12.49	11.48
June	60.63	66.92	69.61	60.62	23.29	21.63	65.52	52.59
July	49.66	62.67	72.15	64.07	4.33	8.79	72.19	47.69
August	11.23	15.42	15.08	18.18	0.18	0.84	18.91	11.41
September	11.96	7.84	13.87	19.57	0.41	2.91	27.64	12.03
October	14.79	8.75	10.46	15.20	1.46	9.00	27.41	12.44
Mean	26.46	28.92	32.44	31.45	6.77	8.83	37.36	
C.D. (0.05)	a = 1.78		b = 1.32		c = 3.55		d = 3.48	
1985								
May	6.22	10.27	7.76	10.16	1.48	6.81	10.99	7.67
June	65.60	83.34	95.47	81.35	10.53	18.60	83.29	62.59
July	24.97	29.88	39.80	42.73	1.43	2.21	30.99	24.57
August	8.60	9.16	12.01	15.14	0.11	0.48	9.00	7.79
September	0.30	0.21	0.20	0.18	0.00	0.18	0.18	0.15
October	4.86	5.21	8.82	10.11	0.21	4.82	4.75	5.54
December	1.07	0.87	1.10	2.10	0.00	0.81	0.91	0.98
Mean	15.95	19.85	23.59	23.11	1.97	4.82	20.01	
C.D. (0.05)	a = 0.93		b = 0.69		c = 1.91		d = 1.84	

a = CD for treatments
b = CD for months
c = CD for months between treatments
d = CD for months within treatments

Table 2 Rainfall interception (%)

Month	Treatment							
	T_1	T_2	T_3	T_4	T_5	T_6	T_7	Mean
1984								
May	0.00	0.00	0.00	0.00	0.00	0.00		0.00
June	0.65	4.57	3.24	1.16	17.04	18.36		7.50
July	2.81	18.82	17.04	7.32	35.25	28.96		18.37
August	9.06	24.56	23.49	15.55	39.86	40.75		25.55
September	13.93	26.73	25.98	18.13	39.61	33.60		26.33
October	16.03	31.16	30.27	21.57	44.39	9.40		25.47
Mean	8.50	21.17	20.00	12.75	35.23	26.22		
C.D. (0.05)	a = 1.73	b = 1.44	c = 3.52	d = 3.51				
1985								
May	23.18	14.46	13.05	14.09	12.82	14.71	0.00	13.19
June	25.52	23.63	22.83	24.66	34.41	39.00	15.36	26.49
July	26.00	32.00	34.96	30.20	41.39	45.85	31.03	37.65
August	32.67	42.03	40.10	40.71	56.42	50.85	33.09	42.27
September	35.70	48.58	40.63	41.17	39.12	29.05	36.43	38.67
October	31.37	41.20	39.89	34.18	34.93	18.90	33.89	24.58
Mean	27.90	33.22	31.59	30.54	33.64	30.71	25.54	
C.D. (0.05)	a = 1.14	b = 1.18	c = 3.08	d = 3.12				

a = CD for treatments
b = CD for months
c = CD for monthsbetween treatments
d = CD for months within treatments

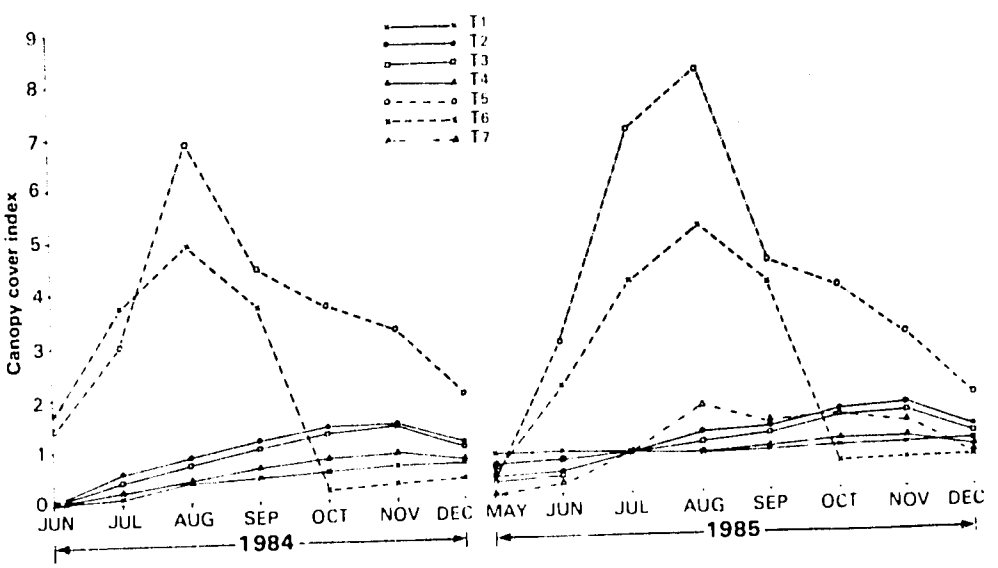
impact of rain is mainly determined by the energy with which individual raindrop hits the soil surface (Mutchler and Young 1975; Hudson 1984). When the rainfall characteristics of maximum intensity, average intensity, kinetic energy, EI_{15}, EI_{30} and AI_m were correlated with splash erosion, higher positive correlations were seen with AI_m ($r = 0.932^{**}$) and EI_{15} ($r = 0.923^{**}$). There was no canopy to intercept the rainfall during first year in T_7.

The lowest annual splash erosion and zero values observed during some months in T_5 are indicative of the very high protective ability of dense vegetal cover, the energy-dissipating power of which has been established by many workers (Hudson 1971; Meyer et al. 1975; Hussein and Laflen 1982). The rainfall interception data provided in Table 2 explain the extent to which the vegetal cover of each treatment protected the soil from the direct impact of raindrops. T_5 and T_6 registered higher interception values in all the erosive months, exceeding 50 per cent in some months of the second year. Depth of rainfall showed maximum positive correlation with kinetic energy ($r = 0.975^{**}$) followed by AI_m ($r = 0.909^{**}$), EI_{15} ($r = 0.859^{**}$), maximum intensity ($r = 0.714^{**}$) and duration ($r = 0.712^{**}$).

As rainfall interception increases, throughfall decreases with a corresponding decrease in erosivity. This explains the lowest splash erosion of T_5 where the combined canopy reduced erosion to about one-eighth that of bare ground (Figure 1). In T_6, though the canopy cover index went below 1.0 consequent to rice harvest, the canopy offered some protection in all the erosive months and registered values comparable with those of T_5.

The variations seen in the cassava-intercropped treatments, were to a great extent proportional to the amount of canopy except in T_3 where ridging was practiced. The reduced rate of splash erosion seen in T_2 as compared to T_4 towards the end, substantiates this. But all the cassava-treated plots showed significantly higher throughfall, no

Figure 1 Monthly combined canopy cover index.



matter whether the population of cassava was minimum as in T_4 or maximum as in T_2. The initial slow growth of cassava, severe soil disturbance due to mound planting, large exposed area and possibly the high energy of leaf drips (Finney 1984; Noble and Morgan 1984) are the probable reasons. Comparatively lower values seen in T_7 towards the end of the second year are indicative of the protective ability of grass stripping. Lower values of splash erosion during second year in T_1 are attributed to the undisturbed nature of soil and stabilization effect of trees.

Runoff

Table 3 provides details of monthly and annual runoff observed in different treatments. During first year, T_7 gave the highest value and T_3, the lowest. Towards the end of the year, T_3 and T_5 became comparable. In the second year, T_5 gave significantly lower runoff than all other treatments. T_1, giving higher annual runoff in the year showed lesser values than T_6 in some months of the second year.

The protective ability of each treatment is probably responsible for differences in runoff. The maximum runoff in T_7 during the first year is attributed to the decreased infiltration rate. Direct, continuous and uninterrupted impact of raindrops may puddle the soil surface and plug the macropores with fine soil particles (Hudson 1984).

The effects of vegetation and ground cover are noticed in other treatments. Canopy cover increased the rainfall interception, reducing throughfall and runoff. In the grass plot, the highest infiltrability coupled with transpiration might have reduced the runoff. The grass plot even surpassed T_3 in accepting almost 96 per cent of rainfall during

Figure 2 Runoff as a function of treatment.

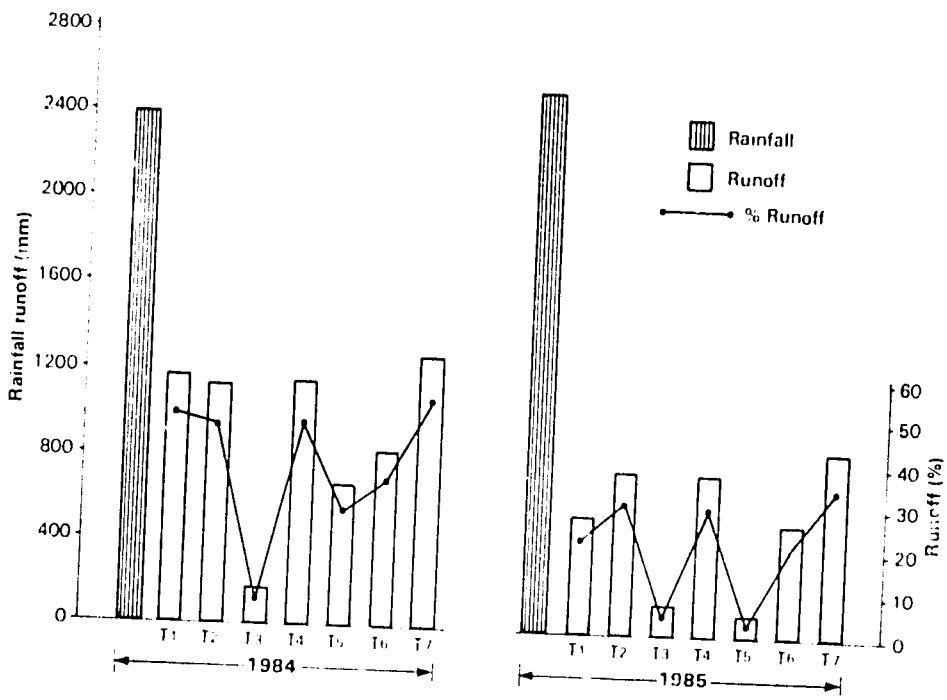


Table 3 Monthly runoff (mm)

Month	Treatment							
	T_1	T_2	T_3	T_4	T_5	T_6	T_7	Mean
1984								
May	117.22	114.07	8.25	117.50	84.30	93.32	11.41	93.43
June	434.94	422.67	81.53	436.58	270.77	320.94	45[illegible]3	344.48
July	375.73	381.32	41.86	375.59	260.55	305.61	417.63	308.33
August	53.69	47.12	9.31	46.36	14.03	35.54	63.09	38.45
September	61.77	56.09	9.29	61.45	8.77	14.57	68.56	40.07
October	126.63	100.98	16.35	109.38	18.36	45.07	136.88	79.09
Mean	195.00	187.04	27.77	189.48	109.46	135.84	209.84	
C.D. (0.05)	a = 2.53		b = 1.86		c = 5.03		d = 4.91	
1985								
June	260.09	352.24	58.60	356.31	48.64	263.92	423.40	251.89
July	222.66	306.50	53.06	276.72	36.20	228.76	324.11	206.86
August	42.31	63.69	17.32	63.00	15.18	15.12	74.47	41.59
September	0.81	1.30	0.40	1.14	0.81	0.79	1.29	0.93
October	18.71	42.37	10.28	52.07	9.98	21.62	44.33	28.48
December	2.82	2.26	0.87	2.42	0.99	1.69	2.22	1.90
Mean	91.23	128.06	23.42	125.28	18.63	88.65	144.97	
C.D. (0.05)	a = 2.95		b = 3.84		c = 7.51		d = 7.64	

a = CD for treatments
b = CD for months
c = CD formonths between treatments
d = CD for months within treatments

second year (Figure 2). The benefit of grass was manifested clearly even when 10 per cent of the area was grass stripped. This suggests that grass once established is more effective in reducing runoff than ridging.

Rice also controlled runoff to a significant extent and in effect behaved similar to grass. The mound method of cassava cultivation seems to accelerate soil runoff. Even though increased rainfall interception was noticed in T_2 there was no appreciable difference in runoff between the cassava-cropped plots.

The stabilization effect of the treatments consequent to tree cropping is worth noting. Even though there was more rainfall in the second year, all treatments recorded comparatively lesser runoff. This was more evident in T_1 which maintained robust trees. Undisturbed soil consequent to zero cultivation might have aided in reducing runoff.

Soil loss

Loss of soil as settled and suspended sediments in each treatment is presented in Tables 4 and 5 respectively. Annual total soil loss (settled + suspended sediments) is depicted in Figure 3. The largest quantity of both settled and suspended sediments is observed in T_7 in all the months recording an annual total of about 350 t/ha, a value many times higher than the tolerable limits of erosion. As there was no protective cover, the soil detachability of falling raindrops and transportability of the runoff were very high. Even though T_5 recorded some soil loss in the initial months, soil erosion was almost completely controlled by the end of the second year (0.4 t/ha). This was even less than T_3 which recorded 1.22 t/ha in the same period. The moderating effect of grass and its

Figure 3 Soil loss as a function of treatment.

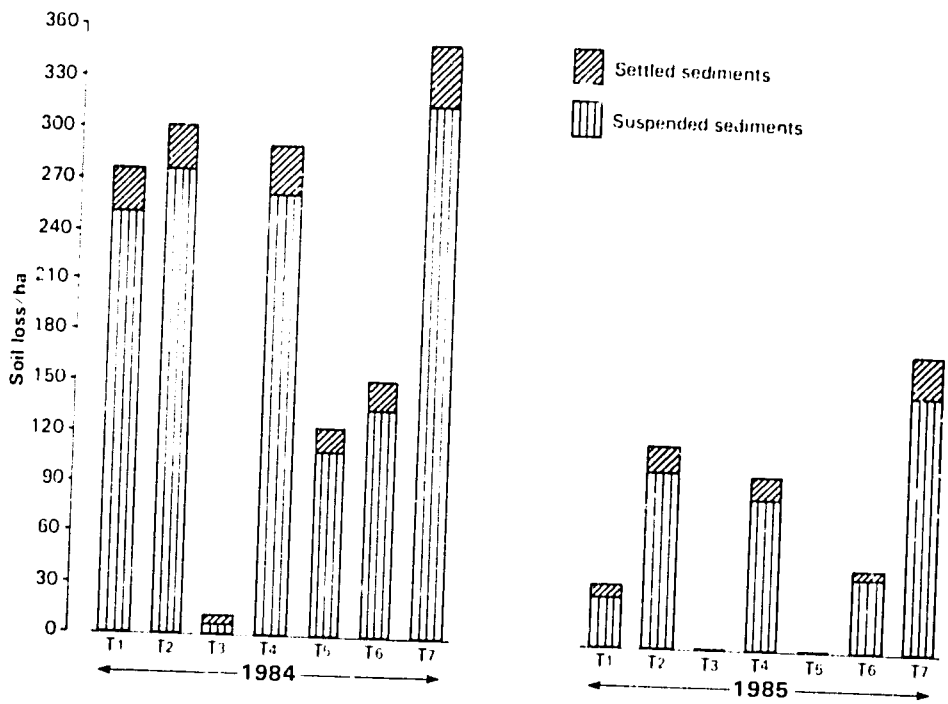


Table 4 Monthly settled sediment loss (t/ha)

Month	Treatment							
	T_1	T_2	T_3	T_4	T_5	T_6	T_7	Mean
1984								
May	44.99	46.85	2.30	46.93	34.19	38.21	49.99	37.64
June	122.53	142.37	4.53	125.73	62.30	71.91	146.27	97.26
July	41.07	57.64	0.15	55.20	13.02	23.49	62.58	36.17
August	5.61	7.04	0.01	7.12	0.05	0.43	7.83	4.01
September	20.36	13.45	0.00	16.55	0.10	0.23	31.04	11.68
October	10.93	5.52	0.00	9.81	0.07	0.74	17.85	6.42
Mean	41.91	45.48	1.15	43.56	18.29	22.38	52.59	
C.D. (0.05)	a = 1.22		b = 0.78		c = 2.17		d = 2.06	
1985								
June	23.84	64.18	0.58	55.11	0.16	32.77	100.30	39.56
July	6.81	33.50	0.04	30.00	0.03	4.90	48.48	17.68
August	0.36	2.79	0.00	2.67	0.00	0.00	4.25	1.44
September	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
October	0.03	1.12	0.00	1.40	0.00	0.00	0.36	0.45
Mean	6.26	20.32	0.12	17.84	0.04	7.53	30.68	
C.D. (0.05)	a = 1.52		b = 0.92		c = 2.49		d = 2.43	

a = CD for treatment
b = CD for months
c = CD for months between treatments
d = CD for months within the treatment

Table 5 Monthly suspended sediment loss (t/ha)

Month	Treatment							
	T_1	T_2	T_3	T_4	T_5	T_6	T_7	Mean
1984								
May	3.54	3.67	0.20	3.53	2.19	2.71	4.54	2.91
June	9.94	13.05	1.17	12.61	4.67	6.67	15.58	9.11
July	6.36	7.75	0.15	7.33	1.18	3.30	11.10	5.45
August	0.34	0.48	0.01	0.45	0.02	0.11	0.93	0.33
September	0.44	0.55	0.00	0.68	0.01	0.12	0.96	0.38
October	1.08	1.34	0.00	1.62	0.00	0.15	2.87	1.01
Mean	3.62	4.47	0.25	4.37	1.53	2.16	6.00	
C.D. (0.05)	a = 0.19		b = 0.15		c = 0.40		d = 0.40	
1985								
June	2.98	9.44	0.58	9.01	0.15	2.60	14.52	5.61
July	1.30	5.45	0.04	5.44	0.03	2.09	7.89	3.18
August	0.05	0.57	0.00	0.73	0.00	0.03	0.93	0.33
October	0.20	0.18	0.00	0.35	0.00	0.04	0.29	0.15
Mean	1.13	3.91	0.16	3.88	0.05	1.19	5.91	
C.D. (0.05)	a = 0.27		b = 0.13		c = 0.37		d = 0.34	

c = CD for treatment
b = CD for months
c = CD for months between treatments
d = CD for months within treatments

fibrous root system are probable contributing factors. The protective ability of grass was apparent even when 10 per cent of the area was stripped of grass in T_7 in the second year. T_7 lost only 177 t/ha of top soil in the second year which was 41 per cent less than that of T_2 in first year.

Observations in T_2 and T_4 reveal that mound planting – irrespective of the number of cassava accommodated – produced high erosion rates. The down-flowing water formed rills, quite often encircling the newly formed mounds, probably causing the increased soil loss.

Tree planting alone (T_1) reduced erosion by 87 per cent in the second year. Damaging effect of interculturing and consequent land disturbance are avoided in this treatment. All the treatments showed notable reduction in soil loss in the second year as compared with the first year in spite of high rainfall. This can be attributed to the protective ability of eucalyptus. These findings suggest that with proper agrosilvipastoral systems, sloping lands can be used for cultivation without causing severe erosion problems.

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Microclimatic modification in intercropping and alley-cropping systems*

J.E. Corlett and C. K. Ong

International Crops Research Institute for the Semi-Arid Tropics
Patancheru P.O., 502 324 Andhra Pradesh, India

C. R. Black

University of Nottingham, School of Agriculture
Sutton Bonington, Loughborough LE12 5RD, U.K.

Abstract

Modification of microclimate is one facet of agroforestry where potential exists for favourable interspecific interaction, but where few data are available. Studies of the possible beneficial microclimate modifications in agroforestry systems may usefully draw upon the detailed data already amassed for sole crops and some multiple cropping systems. Data are presented from rain-fed experiments carried out at ICRISAT (Hyderabad, India) during the 1985 and 1986 rainy seasons. In both years millet (BK 560) and groundnut (R33-1) were grown as sole crops and as an intercrop with a row ratio of 1:3 (millet:groundnut) and row spacing of 30cm. Instrumentation was installed in sole and intercrop plots. In 1986 millet (BK560) was grown as an alley crop between one year old Leucaena leucocephala *hedges. The hedges were spaced at 3.4m intervals in sole leucaena and alley crop plots while millet row spacing, within the alleys and in sole plots was 47cm. Instrumentation was installed in sole and alley crop plots. In each experiment light interception, wind speed, saturation deficit, soil and leaf temperatures were routinely monitored. The microclimatic characteristics and their effects on yield in the two systems are compared. Additional data are presented from the agroforestry trial indicating how competitive interactions below ground may negate any beneficial changes in microclimate.*

Introduction

Many workers have attributed to agroforestry a capacity for the beneficial modification of microclimates (Huxley 1983; Brunig and Sander 1983). Microclimates have already been studied in some systems such as shelter-belt plantings (Guyot, this volume, Section 7) but measurements in systems containing both trees and crops are rare. At ICRISAT, studies on microclimatic modifications in conventional intercropping systems have been in progress for several years (Marshall and Willey 1983). The investigation of microclimates in agroforestry systems was a logical extension of this research.

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Monteith et al. (1981) observed that limitations in the study of microclimate often rest not in the collection of data but in the choice of appropriate forms of analysis. It is important not only to quantify changes in microclimate but also to relate them to plant responses. In order to predict the effect of changes in one component of the microclimate on the rate of specific plant processes, it is frequently necessary to resort to data already collected in controlled environment studies.

In this paper we present results from rain-fed stands at ICRISAT (Hyderabad, India) during the 1985 and 1986 rainy seasons which allow comparisons to be drawn between intercropping and alley- cropping systems. Although these experiments were not specifically designed for this purpose, they demonstrate similarities between the two systems and serve to illustrate methods of analysis which relate microclimatic variables to growth and development.

Theory

Temperature and thermal time

In order to describe the response to temperature of crop developmental processes many workers have used the concept of thermal time or accumulated temperature (e.g. Gallagher (1979) for wheat; Garcia-Huidobro et al. (1982a,b) for pearl millet; Leong and Ong (1983) for groundnut). This concept can be illustrated using the example of leaf appearance in pearl millet. The rate of development may be expressed as the reciprocal of the time (t) between the emergence of successive leaves from the whorl of the preceding leaf.

This rate (leaves per day) is a linear function of temperature given by:

$$1/t = (T - T_b)/\tau \qquad [1]$$

where temperature (T) exceeds the base temperature (T_b), below which no development occurs, but is less than the optimum temperature (T_o), above which increasing temperature reduces the rate of development. The The thermal time for the process, τ, can be expressed as day degrees (C d) per leaf. Ong and Monteith (1985) have provided evidence that Tb and To are conservative over many developmental processes for a particular variety.

Thermal time may be calculated from hourly or daily mean temperatures, although the latter should only be used in cases where T never exceeds To during the diurnal cycle. In the tropics, temperatures at mid-day often exceed To, in which case:

$$1/t = [(t_1/t)(\overline{T}_1 - T_b)/\tau_1] + [(t_2/t)(T_m - \overline{T}_2)/t_2] \qquad [2]$$

(Garcia-Huidobro et al. 1982b), where some fraction of the process is completed at a mean temperature $\overline{T}_1$ below T_o and in a time t_1 and the remaining fraction is completed at a mean temperature $\overline{T}_2$ above T_o and in a time t_2. Tm is the maximum temperature beyond which the rate of development is zero. τ_1 represents the degree-days above T_b, and τ_2 the day-degrees below Tm necessary for completion of the process under consideration.

In our analysis accumulated thermal time during different periods of growth has been calculated from the equation:

$$\tau = t_1(\overline{T}\,T_b) + t_2(T_m - \overline{T}_2)\,\tau_1/\tau_2 \qquad [3]$$

If the cardinal temperatures for different processes are similar, the τ values may differ from process to process but the ratio τ_1/τ_2 will remain constant.

The saturation deficit factor

Saturation deficit is a frequently measured microclimatic variable because of its importance in determining potential evaporation and plant water-use-efficiency. However it is a difficult quantity to relate directly to plant growth and development owing to its linkage with rainfall, temperature and soil moisture. Monteith (1986) used a relation between photosynthetic rate and vapour pressure deficit developed from laboratory studies (El Sharkawy et al. 1984). In this analysis actual net carbon exchange (N) is related to actual vapour pressure deficit (D) by the linear relation:

$$N = N_m[\,(1 - (D - D_o)/(D_m - D_o)\,] \text{ for } D > D_o$$

$$\text{and} \quad N = N_m \qquad \text{for } D \leq D_o \qquad [4]$$

where N_m is the maximum net carbon exchange, D_o is the vapour pressure deficit below which $N = N_m$ and D_m is the deficit at which net carbon exchange becomes zero.

In our analysis we have calculated a saturation deficit factor, Z, from the equation:

$$Z = 1 - [\,(D - D_o)/(D_m - D_o)\,] \qquad [5]$$

(Monteith 1986, but with D = saturation deficit) for evaluating the possible effects of changes in saturation deficit on growth. It is assumed for this purpose that all other microclimatic factors remain constant, especially leaf temperature and soil moisture. If the microclimate was modified so that mean canopy temperature increased while saturation deficit decreased, the vapour concentration gradient between leaf and air might increase, decrease or remain constant depending on the balance between these two quantities.

Experimental details

In the 1985 and 1986 rainy seasons at ICRISAT (Hyderabad, India) pearl millet (*Pennisetum americanum* (L.)) Leeke var. BK 560) and groundnut (*Arachis hypogaea* L. var. Robut 33-1) were grown as sole crops and as an intercrop with a row ratio of 1:3 (pearl millet : groundnut) and a row spacing of 30 cm. In the 1986 rainy season, pearl millet (BK 560) was grown as an alley crop between hedges of one-year-old leucaena (*Leucaena leucocephala* (Lam.) de Wit). The hedges consisted of a double row of leucaena with 60 cm between the two rows and 25 cm between trees within each row. These hedges were spaced at 3.4 m in sole leucaena and alley-crop plots, while the pearl millet row spacing was 47 cm within the alleys (5 rows in each alley) and in the sole plots.

At harvest, crops were sampled row by row and dry matter (DM) yields calculated on a 'row area' basis from the equation:

$$\text{DM (t ha}^{-1}) = \frac{\text{row sample DM (g)}}{\text{length of row (m) x row spacing (m)}} \times \frac{1}{100} \qquad [6]$$

Grain yields were calculated in a similar manner. In each experiment the length of row sampled was 6 m. In the alley-cropping experiment the hedges were cut to 70 cm prior to sowing the millet, at 30 days after millet sowing, and again after millet harvest.

At each cutting, 28 sample trees were measured for dry matter production in prunings and as dry matter increment in stems. Stem dry matter increment was calculated using an experimentally-determined regression of stem dry weight on stem volume and field measurements of stem volume. Tables 1 and 2 summarize the details of the intercropping and alley-cropping experiments, respectively.

Table 1 Details of intercropping experiment, ICRISAT Center, rainy seasons 1985 and 1986.

Planting	27th June 1985 and 8th July 1986.		
Soil	Medium/deep Alfisol.		
Design	Randomized block design, 5 treatments, 3 replications.		
Plot size	12 x 30 m.		
Treatments	(only 3 of the 5 treatments are considered)		
	SM - Sole millet (BK 560), row spacing 30 cm.		
	SG - Sole groundnut (Robut 33-1) row spacing 30 cm.		
	MG - 1:3 millet/groundnut intercrop row spacing 30cm.		
Rainfall	1985	millet	273 mm(crop duration = 80 days)
		groundnut	371 mm(crop duration = 100 days)
	1986	millet	419 mm(crop duration = 80 days)
		groundnut	419 mm(crop duration = 115 days)

Table 2 Details of alley-cropping experiment, ICRISAT Center, rainy season 1986.

Planting	Trees planted in August 1985
	Millet planted on 24 June 1986
Soil	Shallow Alfisol
Design	Randomized block, 6 treatment, 3 replications
Plot size	10 x 22 m (sole millet 30 x 22 m)
Treatments	(only 4 of the 6 treatments are considered)
	SM - sole pearl millet (BK 560, row spacing 47 cm
	SL - sole leucaena (KB), double rows spaced at 3.4 m
	ML - alley-cropping, leucaena as in SL with 5 rows of millet in alleys.Millet row spacing 47 cm
	MLP- alley-cropping with vertical polythene barrier separating millet and leucaena root zones to a depth of 50 cm

In each experiment wind speed, saturation deficit, leaf temperature, soil temperature and light interception were monitored. The variables measured are listed in Table 3 together with details of the instruments used and their positioning within the experiment. Signals from all instruments except the prototype integrating quantum sensor were scanned every 6 minutes by a data logger which computed and stored hourly averages. The prototype integrating quantum sensor was used in conjunction with a polycorder (Matthews et al. 1987) and measurements were made at midday once a week.

Table 3. Instrumentation in intercropping and alley cropping experiments, ICRISAT Center, rainy seasons 1985 and 1986.

Variable[1]	Instrument	Position	
		Intercrop and sole crops	Alley crop and sole crops
Wind speed	'Met-one' anemometer	Two heights (30 and 90 cm) Ambient at 1.5 m	One height according to top of millet canopy Ambient at 3.0 m
Saturation deficit	Aspirated psychrometer	As for wind speed	As for wind speed
Air temperature	Aspirated psychrometer	As for wind speed	As for wind speed
Leaf temperature	T-type thermocouple	Two heights (30 and 90 cm)	Youngest fully expanded leaf
Soil temperature	T-type thermocouple	5 cm depth	5 and 20 cm depth
Intercepted radiation (60, and 90 cm)	Prototype integrating quantum sensor	Horizontal profiles at four heights (2, 30,	
	Tube solarimeter		Row-wise at ground level

[1] For frequency of measurement see text

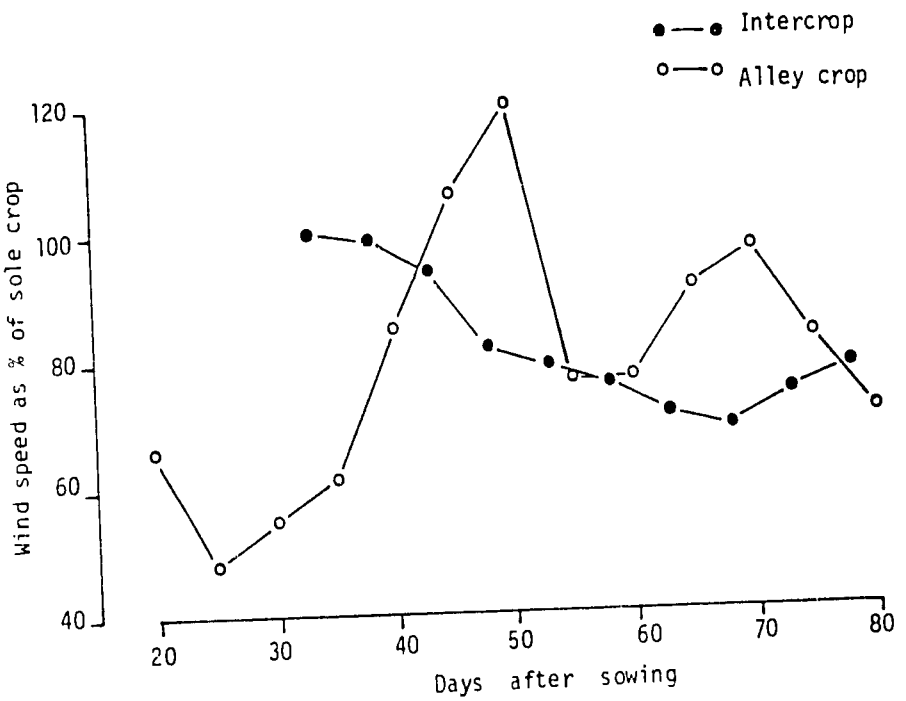
Results

Although results from both the 1985 and 1986 intercropping experiments will be presented we will concentrate on a comparison of the 1986 intercropping and alley-cropping experiments.

Wind speed

Figure 1 shows wind speed ab the intercropped groundnut and alley-cropped pearl millet, expressed as a percentage of the corresponding sole-crop value. Wind speed above the groundnut intercrop (anemometer at 30 cm) was apparently unaffected by the pearl millet until almost 35 days after sowing (DAS), by which time the pearl millet had grown sufficiently to alter the pattern of wind flow over the groundnut. This effect became larger as the pearl millet grew in height and increased in leaf area. The difference in wind speed between the sole crop and the intercrop decreased after about 68 DAS as the pearl millet began to senesce.

Figure 1 Wind speed above intercropped groundnut and alley-cropped pearl millet, expressed as a percentage of the corresponding sole-crop value.



In the intercrop, wind speed at 30 cm would be strongly dependent on the growth of the pearl millet but only weakly related to the growth of groundnut. In the alley-cropping experiment by contrast, wind speed at this height would depend on the relative rates of growth of leucaena and pearl millet. In 1986 the heights of the anemometers in the sole pearl millet (SM) and the alley crop (ML) were adjusted to keep them just above the pearl millet canopy. Figure 1 shows that between 40 and 55 DAS the mean wind speed over the pearl millet alley crop was apparently greater than that over the sole pearl millet, though the trees would have been expected to cause some reduction. However, in raising the anemometers in SM and ML by equal increments we overlooked the fact that the sole pearl millet was growing faster than that in the alley. At 44 DAS the average plant height was 94 cm in SM and 79 cm in the center row of ML, while in both treatments the anemometers were positioned at approximately 80 cm. Thus in effect, the wind speed was being measured at different relative heights on the vertical profile in the two treatments. There is also the complication that the leucaena was cut back to 70 cm after 30 DAS and at this time the pearl millet stems elongated rapidly, reducing the height difference between tree and crop.

Despite these problems, an important difference between the two systems was still evident. The intercropped groundnut experienced reductions in wind speed only during the last 40 days of millet growth and this to a maximum of 30%. In contrast, leucaena as

a perennial reduced wind speed by up to 55% during the early growth of the alley crop, a feature which could be maintained throughout the pearl millet growing season with appropriate hedge management.

Temperature

The values for accumulated thermal time over consecutive 10-day periods shown in Table 4 were calculated using equation [3] from hourly mean day and night-time temperatures and the constants shown in the table footnotes. T_m and τ_1 / τ_2 are not quoted for pearl millet since leaf temperature never rose above T_o. Columns 2 to 5 allow a comparison of leaf temperature for sole and intercropped groundnut, and sole and alley-cropped pearl millet. Each value is the arithmetic mean of 10 consecutive daily means, each representing the average of 12 daytime hourly means. This approach inevitably hides short-term variations in temperature but does illustrate the magnitude of differences between treatments.

Table 4. Ten-day means for daytime leaf temperature and accumulated thermal time, ICRISAT Center, rainy season 1986.

	Daytime canopy temperature (C)[1]				Thermal time (Cd)[2]			
DAS	Sole g.nut	Intercrop g.nut	Sole millet	Alley-crop g.nut	Sole g.nut	Intercrop millet	Sole millet	Alley crop
21-30	-	-	24.0	24.4	-	-	125	129
31-40	29.8	29.8	26.3	26.3	175	184	134	135
41-50	28.1	28.7	23.1	23.2	150	154	115	118
51-60	30.8	32.6	24.8	24.5	167	170	122	123
61-70	28.5	29.4	27.3	26.3	156	159	133	129
71-80	34.9	35.9	25.7	24.8	151	153	128	123

[1] For center row. Means calculated as described in text.
[2] Robut 33-1: T_b = 10°C, T_o = 36.5°C, T_m = 46°C, τ_1 / τ_2 = 2.79 (Mohamed 1984)
BK 560: T_b = 10°C, T_o = 33.5°C (Ong and Monteith, 1985)

Intercropping increased the 10-day mean daytime canopy temperature of groundnut by up to 1.8°C. This effect probably resulted from an increase in aerodynamic resistance, which would have reduced the ability of leaves to dissipate absorbed radiant energy by sensible or latent heat flux. Alternatively, competition for soil moisture in the intercrop might have reduced the amount of water available to the groundnut for evaporative cooling. Temperature differences between treatments were, however, small and amounted to only 21 degree-days from 31 to 80 DAS. A 1°C increase maintained over this entire period would have given a 50 degree-day difference in accumulated thermal time, sufficient to cause a difference in overall development of at most two days.

The pattern in the alley crop was more complicated, but the differences between treatments were again relatively small. Canopy temperature in the alley-cropped pearl millet was similar to or slightly higher than that of the sole pearl millet between 21 and 50 DAS, as is reflected by the accumulation of 8 more degree-days during this period.

Between 51 and 80 DAS, canopy temperatures were 0.3-1 °C higher in sole pearl millet than in the alley crop and the former accumulated 8 more degree-days. It thus appears that during this period shading by the leucaena may have reduced radiant energy fluxes to the pearl millet canopy to more than offset any decrease in the rate of heat loss caused by reductions in wind speed.

Saturation deficit

Table 5 shows mean daytime saturation deficits and calculated saturation deficit factors (Z) for consecutive 10-day periods in both intercropping and alley-cropping systems. The records suggest that groundnut experienced a lower saturation deficit when grown as an intercrop, with the difference rising to almost 1 kPa towards the end of the pearl millet season. This difference can be attributed to higher aerodynamic resistances within the intercrop canopy which would decrease vertical water vapour fluxes within and above the groundnut canopy.

The extent to which these differences might affect crop growth (other factors remaining constant) is indicated by Z as shown in Table 5. These values were calculated

Table 5. Ten-day means for daytime saturation deficit and the saturation deficit factor, ICRISAT Center, rainy season 1986.

	Daytime saturation deficit (kPa)				Satruation deficit factor (Z)[1]	
DAS	Sole g.nut[2]	Intercrop g.nut	Sole millet	Alley-crop millet	Sole g.nut	Intercrop g.nut
21-30	-	-	0.73	0.66	-	
31-40	1.07	0.82	1.08	0.96	0.98	0.98
1-50	1.24	1.27	0.76	0.55	0.93	0.93
51-60	1.82	1.54	0.94	0.60	0.83	0.86
61-70	1.18	1.09	1.34	1.27	0.93	0.95
71-80	1.99	1.04	1.09	1.05	0.78	0.92

[1] D_o = 1 kPa, D_m = 6 kPa (El Sharkawy et al 1984)
2 g.nut = groundnut

from equation [5] on an hourly basis using the values for D_o and D_m determined by El-Sharkawy et al. (1984) for cassava. More rigorous analysis would obviously require the determination of D_o and D_m for groundnut. Daily means (12 hours) and 10-day means were then calculated from the hourly values. It is interesting to note that between 31 and 50 DAS the differences between treatments in mean saturation deficit were not reflected by the factor values. This results from our assumption that net carbon assimilation is reduced only when D is greater than D_o and that there cannot be any increase in assimilation above the maximum rate if D falls below D_o. Thus, changes in D below D_o are of no importance in determining carbon assimilation, but may affect transpiration rate. Dry matter accumulation between 40 and 80 DAS would have been 89% and 93% of the maximum possible in the sole crop and the intercrop respectively if all other factors had been non-limiting.

Saturation deficits were generally lower in the alley-cropping trial, and the millet experienced lower deficits as an alley crop than as a sole crop. Since the alley-cropping trial was planted 14 days before the intercropping experiment the data for specific 10-day periods are not directly comparable. We have not calculated Z for the alley--cropping experiment. As the deficits were generally close to or below D_o, the small differences between the two treatments are unlikely to have significantly affected dry matter accumulation.

Light interception and yield

Table 6 shows total light interception, conversion efficiency, and yield on a row area basis for two seasons of intercropping and one of alley cropping. As dry matter accumulation is often considered to be proportional to accumulated light interception (Monteith 1972), changes in total light interception may be expected to affect yield. However, conversion efficiency, that is the quantity of dry matter produced per unit of intercepted radiation, is equally important. For instance Marshall and Willey (1983) and Willey et al. (1986) described the partitioning and utilization of light in a 1:3 pearl millet/groundnut intercrop and showed how the yield advantage of the intercrop could

Table 6 Total light interception, conversion efficiency and crop yield ICRISAT Center, rainy seasons 1985 and 1986.

Year	Crop	Total intercepted radiation (MJ m^{-2})	Light conversion efficiency[1] (g MJ^{-1})	Crop yield[2] (t ha^{-1})
1985	Millet	617	0.92	1.23
	Groundnut	550	0.46	0.93
	Millet/groundnut	580	0.29	3.40/1.09
	SE			0.05/0.06
1986	Millet	568	0.89	1.81
	Groundnut	752	0.25	0.16
	Millet/groundnut	780	0.18	4.16/0.07
	SE			0.07/0.02
1986	Millet	575	1.14	1.98
	Leucaena	450	0.89	3.90
	Millet/leucaena	725	0.90	1.60/3.87
	MLP			2.06/3.52
	SE			0.24/0.58

[1] Conversion of intercepted radiation to total above ground dry matter.
[2] Grain yield per row for annual crops, and total shoot dry matter increment for leucaena. Yields calculated on row area basis (see text).

be attributed to increased light interception (per row) by the pearl millet and an increased efficiency of conversion by the groundnut.

In the 1985 intercropping trial, yield of both species (on a row basis) was improved when they were grown as an intercrop, but in 1986 groundnut yield was very poor in the sole crop and even worse in the intercrop. These results cannot be explained by differences in light interception since groundnut intercepted more light in 1986 than in 1985. With respect to efficiency, pearl millet and groundnut performed substantially below their potential (Monteith 1972; Marshall and Willey 1983) in both 1985 and 1986. In both years, rainfall was well below the expected 600 mm during the groundnut growing season. The crops would therefore have been under drought stress for at least part of their lives, causing stomatal closure and reducing their ability to convert intercepted light energy into dry matter. The difference in crop performance between the two years originated largely from differences in rainfall distribution. Rainfall during the period of millet growth was more in 1986 than in 1985 but in 1986 no rain fell after the millet was harvested (Table 1), causing the groundnut to become highly drought stressed during the sensitive pod-filling stage. The yield difference between sole and intercropped groundnut in 1986 may be due to there being less water left in the intercrop profile after pearl millet harvest.

In the alley-cropping system, rainfall was adequate during pearl millet growth except for a 15-day period soon after emergence. Total light interception and conversion efficiency for sole pearl millet were similar to those obtained in the intercropping experiment.

Interception by leucaena was small even though the trees were already well established at the beginning of the season, largely because the wide alley spacing and severe hedge management led to under-utilization of available resources. Alley cropping increased total light interception by 26% and 61% compared with the sole millet and sole leucaena, respectively. Millet yield was significantly reduced in the rows immediately adjacent to the hedge though the yield of the treatment as a whole was not significantly different from the sole millet.

Similar yield reductions have been observed in other alley-cropping trials in the semi-arid tropics (Singh et al. in press) prompting the question of whether above or below-ground competition for resources was the principal limiting factor for pearl millet growth. Before planting the pearl millet, vertical polythene barriers were installed in a separate treatment at a distance of 24 cm from the leucaena hedges and to a depth of 50 cm (Table 1), a technique previously used to separate the root systems of intercrops (Willey and Reddy 1981). Results from this treatment show no significant differences in millet yield between rows within the alley, and no decrease in yield relative to the sole millet crop. This suggests that below ground interactions, probably in the form of competition for water, were responsible for limiting pearl millet growth adjacent to the hedges in the normal alley crop.

Implications for future research

The results presented here suggest that the microclimatic modifications produced by alley cropping in the semi-arid tropics, where the hedges are cut to 1.0 m or less during the rainy season, are not sufficiently large to play a major role in determining the growth and yield of the annual crop. Situations may be envisaged where microclimatic modification would be more pronounced, for example if the leucaena hedges were allowed to grow throughout the rainy season without pruning and/or if a shorter stature annual such as groundnut was substituted for pearl millet. Dense hedges would be most

beneficial to crops in areas prone to wind damage (Fryrear 1969). However, in most cases competition for water would increase, probably to a degree that could not be compensated for by concurrent improvements in either light or water use efficiency.

In the semi-arid tropics the prime consideration in the planning and management of agroforestry systems should be appropriate and efficient use of available water, with particular emphasis being placed on optimising its partitioning between tree and crop components. Whenever we seek to improve the aerial environment within specific systems we should always be aware of the possible implications and consequences of below-ground interactions.

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Water-balance and soil water relations studies in a mixed tree/grass/bare-soil system

J.E. Jackson and P.J.C. Hamer

Institute of Horticultural Research
East Malling, Maidstone, Kent ME19 6BJ, UK

B. Jackson

Sittingbourne College, Sittingbourne, Kent, UK

Abstract

Water balance studies in a mature apple orchard showed that where the grass between the tree rows had been killed by herbicide treatment the efficiency of rainfall in replenishing soil moisture was greatly reduced. The rate of infiltration of water into overall-herbicide treated soil was found to be much less than into soil of grassed alleys. Other experiments have shown soil from grass-free orchard plots to have higher bulk density and lower aggregate stability than that from grassed orchads. Bare soil in the alley-ways is accompanied by lower organic matter content and greatly reduced earthworm activity. It seems likely that the basic cause of the soil structural problems arises from the low rooting density of the trees and their relatively small contribution of organic matter to the soil. The importance of the contribution of the ground cover crop to the maintenance of soil structure in tree plantations and in agroforestry systems in general is dicussed.

Introduction

Light, water and nutrients can be considered as three "resource pools" exploited by the components of agroforestry systems. The amount of light available at any one site is fixed, so the trees and ground-cover crops share a fixed resource. This is not the case for nutrients where nitrogen-fixing symbionts associated with either the tree or the crop and mycorrhizal infection of the roots can lead to substantial increases in the amounts of available N and P.

With respect to water it has long been accepted that the components of a tree/crop mixture can influence total water availability. The emphasis has been on the effects of trees on the pattern of rainfall interception (through the effect of stemflow in, effectively, redistributing rainfall in the horizontal dimension), on evaporative losses (especially from wet leaves), and soil stability.

The present paper presents data on the effect of a ground cover crop in a mixed tree and crop system on water availability through its effects in reducing run-off, and discusses this in relation to the relative effects of trees and herbaceous ground cover on the factors controlling soil structure and infiltration of water.

Water balance studies

Experimental details

Soil water use was measured for the years 1977-83 in a trial to examine the effects of spacing and soil management on the growth and cropping of Golden Delicious apple trees on M.9 rootstocks which had been planted at East Malling in the winter of 1969/70. The soil is a sandy loam overlying ragstone at 90-120 cm depth and the land slopes from south to north at an angle of 2° to 3°. The trees were in N-S hedgerows (between-row spacings 4.25, 3.35 and 2.9 m, within-row spacings 2.7, 2.25, 1.35 and 0.9 m in all combinations). A belt of soil under the trees was kept clear of weeds by the use of herbicide. This 'herbicide strip' was originally 1 m wide but was gradually increased in width as the trees thickened and by 1983 was approximately 2 m wide. The alley-ways between the herbicide strips were grassed and were mown regularly. In 1977 the soil management regime on two of the four replicates was changed, with the grass in the alleys being eliminated with herbicide and a bare-soil regime, referred to subsequently as overall-herbicide (OH), maintained thereafter.

In the treatments reported here, soil water content was measured by neutron probe in the tree spacings of 1.8 m within the tree row and 4.25 m between the rows. Access tubes were arranged in a 50-cm grid from the tree centre, with access tubes parallel to the tree row and 50, 100 and 150 cm from it. All access tubes (16 swg aluminium) were installed to bedrock depth. Soil water content of the soil profile was determined using the method of Bell (1973) and the soil moisture deficit was taken as the difference from a reference value when the soil was close to field capacity. The moisture contents for each spacing and soil management type were estimated from measurements for each access tube multiplied by an area factor which represented the area associated with each access tube.

Meteorological data were acquired from the records of a standard meteorological site 200 to 250 m from the position of the access tubes. Potential evaporation (E_p) was calculated as for a well-watered grass surface (Penman 1962). The estimated evaporation rates for the orchard plots were calculated from the change in stored soil moisture and precipitation (cf. Hillel 1980). The assumption in this method is that capillary flow and runoff are small compared to evaporation/transpiration. The analyses were restricted to the summer months when, in general, soil moisture deficits were increasing and it could be assumed that drainage out of the root zone was minimal.

Results

Results of the experiment as a whole will be published elsewhere. Only those relevant to the effects of soil management (grass in the alleys versus overall herbicide) are reported here. Initial attempts to relate measured changes in soil moisture to rainfall, potential evaporation and characteristics of the tree and grass canopies showed that these factors did not explain the changes in soil water. The following results illustrate the nature of the discrepancies and the reason.

Changes in soil moisture deficit in relation to rainfall, evaporation and alley soil management

Table 1 shows changes in soil moisture deficit (SMD) over the period 17 September 1982 to 6 October 1982 during which there was 98 mm of rain (42% of which fell during

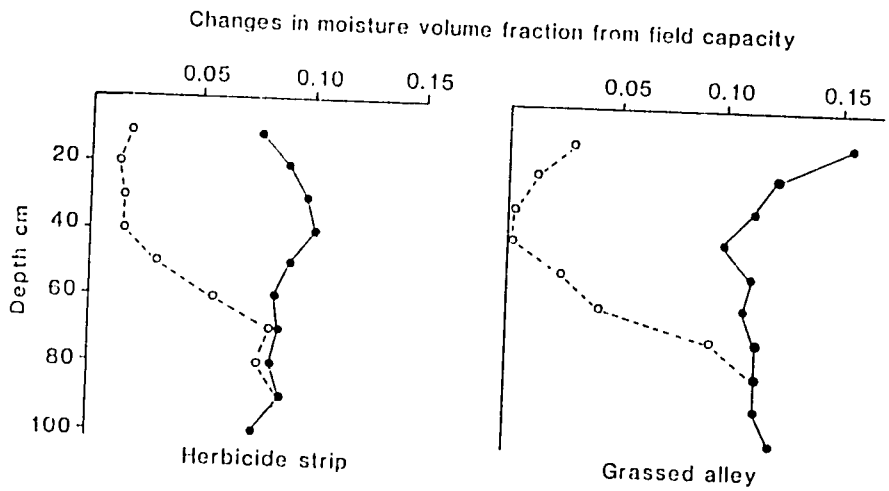
rainstorms with more than 6 mm per hour precipitation) and 18 mm of potential evaporation; i.e., there was an 'expected' change in SMD of about 80 mm.

Table 1 Soil moisture deficit (mm) in relation to rainfall, evaporation and alley soil management.

Rainfall 17 Sept to 6 Oct. (mm)	Evaporation 17 Sept to 6 Oct. (mm)	Ground cover in alley	Soil moisture deficit (mm) 17 Sept.	6 Oct.	Change	'Expected' change
98	18	Grass	136	66	70	80
		Herbicided soil	98	53	45	80
				98		

Figure 1 shows the changes in soil moisture deficit with depth between 17 September and 6 October at a distance of 150 cm from the tree trunk. The lack of change at 80 cm and below indicates that there was no drainage to this depth and, by implication, no drainage loss. The decrease of 45 mm in soil moisture deficit instead of the expected 80 mm decrease suggests loss of rain by runoff from the "bare-soil" plots. Similar discrepancies between rainfall and changes in soil moisture deficit under overall herbicide conditions were generally noted and surface runoff was regularly observed. The overall magnitude of the effect was established by looking at changes in soil moisture

Figure 1 Changes in soil moisture deficit with depth over the period 17 September (●————●) to 6 October (o--------o) in 1982 at a distance of 150 cm from the tree trunks.



deficit over 108 separate periods of a week or more over the seven years 1977-1983 (Table 2). These changes were considered as the dependent variable in multiple regression analysis in relation to potential evaporation (E_p) and rainfall (R) according to the equation

$$SMD = a_0 + a_1 E_p + a_2 R \quad (1)$$

Table 2 Regression analysis of change in soil moisture deficit on potential evaporation (E_p) and rainfall (R) in mm per day according to the equation $SMD = a_0 + a_1 E_p + a_2 R$ for grassed and herbicide treated alley-ways between tree rows 4.25 m apart with trees 1.8 m apart in the rows.

	grassed alley	Herbicide treated alley (Bare soil)
a_0	-0.53	-0.38
a_1	-0.49	-0.36
a_2	0.80	0.54
*R_2%	*81.10	*58.20

*108 sets of values 1977-1983 May-September inclusive

Infiltration rates of herbicide-treated and grassed alley-way soils

Samples were taken in March 1985 with an Eijkelkamp double ring infiltrometer at distances of 50, 100 and 150 cm from the centre of the tree row. The sample at 50 cm from the row centre was, in each case, taken from herbicide treated land (i.e. from the herbicide strip in the grassed-alley treatment), the other samples were from grassed and herbicide treated areas in the grassed-alley and overall herbicide treatments respectively. Results are shown in Table 3. Infiltration rates were very much lower in the overall-herbicide treated than in the grassed-alley plots.

Table 3 Infiltration rates (mm h^{-1}) into soil in orchard plots with either grassed alley-ways or bare-soil (overall herbicide)

	Infiltration rates mm h^{-1}	
Distance from tree row centre (cm)	Into grassed-alley plots	Into overall-herbicide treated plots
50	276	40
100	56	17
150	137	12

Effects of grass and bare soil between rows on soil structure

Atkinson and White (1976) compared soil bulk density in the grassed alley-ways of mature (9-year-old) apple orchards with that in corresponding alleys which had been kept free of grass and weeds for the last 3 years by use of herbicides. Soil bulk density was appreciably higher in the bare-soil alley-ways (1.54 g ml^{-1} as compared with 1.34 in the grassed alleys). Similar results were obtained in other experiments (Atkinson and Herbert 1979). Soil compaction, expressed as 'California bearing ratio' was also much more extensive and severe in orchard alley-ways treated with herbicide than in those which were grassed (Atkinson, Swain and Fricker 1979). O'Kennedy and Robinson (1984) showed that the percentage of water-stable aggregates was much higher in grassed orchard plots (45%) than overall-herbicide treated plots (24%) but that mulching the overall-herbicide treated plots with straw from the time of imposition of the herbicide treatment had some beneficial effect, raising the percentage of water-soluble aggregates to 34.

Density of rooting of fruit trees and grass

The most important factors controlling the creation of structural pores in undisturbed soils are plant roots and the larger members of the soil fauna such as earthworms, beetle larvae, ants and termites (Russell 1973). Structural pores, once created, are only stable against wetting if there is some agent holding the soil particles apart against the surface tension forces set up on wetting; among the agencies which maintain stability are the clay fraction, humus and decomposable organic matter.

Apple root systems tend to be sparse, reported values of root density expressed as cm root per cm^2 soil surface area (L_A) being within the range 0.8-23.8 (Atkinson 1980). In contrast the reported values for Graminae are in the range 100 to 4000 and for herbs 52 to 310 (Newman 1969). If rooting density is expressed as cm per cm^3 of soil (L_V) the highest value cited for apple by Atkinson (1980) was 0.20, in contrast with the L_V for grasses of 50 given by Bowen (1984). In an orchard with grassed alleys most of the tree roots are confined to the herbicided strip, in an orchard with overall- herbicide management the roots are much more evenly distributed (Atkinson and White 1976). Although there are no specific experimental comparisons of the density of rooting of grass in the alley-ways with that of apple in the combined herbicided strip/grassed alley system or in orchards treated with herbicide overall there is little doubt from the above figures that grass root density is many times that of apple trees.

Earthworm activity in relation to grass or bare-soil management between fruit trees

The effects of grass or bare (herbicided) soil in the alleys between apple tree rows on earthworm incidence and also the differences between the herbicided strip under the trees and the grassed or bare soil alleys in respect of earthworm population were determined in 1977 on a large replicated experiment at East Malling Research Station in which four contrasting management systems were being compared for their effects on tree growth and cropping, when nitrogen fertilizer was applied at either a high or low rate.

Experimental details and methodology

The experiment consisted of Cox's Orange Pippin and Spartan apple trees planted in rows 4.5 m apart in December 1972 with the following soil management treatments:

1. Overall herbicide; with herbicides applied to the entire orchard surface to remove any grass or weeds which might compete with the tree for water or nutrients. The main herbicides used were paraquat and simazine, but others were applied as needed.
2. Overall grass; with the alley-ways between the rows of trees sown with grass (S50 Timothy, *Phleum nodosum*) in March 1973, with only a very narrow strip (0.5 m) under the trees kept grass-free by the use of herbicides, the rest mown regularly to maintain a good working surface for the passage of farm machinery.
3. Wide herbicided strip treatment; as 2. but with the herbicided strip under the trees much wider so as to leave only a narrow grass strip for tractor use in the alley. The herbicided strips were 1.7 m wide, the grass alley 2.8 m wide.
4. Irrigated grass; basically as 2. but with regular irrigation by sprinklers to prevent soil moisture deficits in excess of -0.04 MPa arising. This was intended to eliminate the adverse effect of grass in competing for water.

Each of these four 'main plot treatments' was replicated three times and each was subdivided, half being given a high level of nitrogen fertilizer (potassium nitrate, 189 kg/ha) and half a low level of nitrogen fertilizer (63 kg/ha). This was intended to test whether addition of extra nitrogen fertilizer could overcome the adverse effect of competition by grass for mineral nutrients.

Each 'sub-plot' consisted of nine experimental trees of Cox on MM.106 rootstock, spaced 4.5 m apart and surrounded by guard trees, alternately Cox and Spartan at the same spacing. The individual plot size for soil management purposes was therefore 18 m x 18 m.

These treatments had all been applied from the time of planting. To test whether some effects of the herbicide treatments on earthworm numbers noted in this study were due to direct effects of the herbicide, or to effects on food supply, earthworm counts were also made on other plots in which the herbicide treatments had been carried out so recently that there was still plenty of dead grass on the soil surface.

Earthworms and other soil animals were brought to the surface by the application, using a watering can, of 5 litres of a solution of detergent containing 25 cm^3 of a proprietary liquid detergent to the area covered by a 0.5 m^2 quadrat. Worm counts were made on all plots in the strip (i.e., within tree rows) and alley (between tree rows) positions. In the irrigated grass and wide strip plots these 'strip' and 'alley' positions corresponded to herbicide-treated and grassed areas respectively. In the plots treated with herbicide overall, both the strip and alley positions were in bare, herbicide- treated soil.

Results

Results are given in Table 4 together with results of ancillary observations. In the overall-herbicide treated plots 'Alley' and 'Strip' all had the same treatment (herbicide) so reflect position, i.e., within-row or between-row, respectively.

Table 4 Effects of treatments on number of earthworms per 0.5 m^2 soil.

Main plot treatment	Sub plot treatment	Replicate 1	Replicate 2	Replicate 3	Extra sample A	Extra sample B
		11 Sept	22 May	21 May	23 Oct	23 Oct
Irrigated grass with narrow herbicide strips	LN Alley[1]	2	10	7	15	5
	LN Strip[2]	1	3	3		
	HN Alley	3	11	1	22	4
	HN Strip	2	5	0		
Grass with narrow herbicide strips	LN Alley	8	4	2	6	8
	LN Strip	0	0	0		
	HN Alley	5	1	2	18	8
	HN Strip	0	0	0		
Grass with wide herbicide strips	LN Alley	9	3	0	7	2
	LN Strip	0	0	0		
	HN Alley	0	3	0	12	12
	HN Strip	0	0	0		
Overall herbicide	LN Alley	0	0	0		
	LN Strip	0	0	0		
	HN Alley	0	0	0		
	HN Strip	0	0	0		
Newly overall-herbicided area in the same field						7

Key LN = Low Nitrogen
HN = High Nitrogen

1 Grass alley between tree rows
2 Herbicided area within tree rows.

Effects of overall herbicide and irrigation treatments

Worms were never observed in the overall-herbicide treated plots, although twelve separate assessments were made, and in this consistent absence of worms, these plots were unique. Worms were found in fifteen of the sixteen areas examined on irrigated plots, ten of the sixteen in the grassed plots and seven out of sixteen in the wide herbicided strip plots.

Chi-square analysis showed that a significantly higher proportion of the irrigated plots had worms than either the grassed ($P < 0.05$) or wide herbicide strip plots ($P < 0.01$). The total number of worms in the different treatments was 94 in the irrigated grassed plots, 62 in the non-irrigated grassed plots and 48 in the plots with wide herbicide-treated strips.

Effects of nitrogen

Although there appeared to be rather more worms in the high nitrogen plots the differences were not large or consistent enough to be statistically significant.

Effect of herbicided strip versus alley within a plot

This effect was very consistent. There were never more worms in the strip than the adjoining grassed alley whereas the reverse was true in 15 paired comparisons. This consistency of differences is highly significant (sign test). In terms of numbers of worms, when only the data recorded under the headings, Replicate 1, Replicate 2, and Replicate 3 of Table 4, are considered, 71 worms were counted in the 'alley' samples and only 14 in the 'strips'.

Worm counts on other sites

Because of the apparent trend for there to be more worms where there was more vegetation worm counts were also made in a recently herbicide treated area of grass near the main experiment where there was still dead grass. Seven worms were found here – a similar number to that found in non-herbicided grass plots on the same day.

In a separate East Malling experimental plot, previously grassed alley-ways had recently been herbicide treated and still had dead grass. Comparative worm counts were made on these areas and also on adjacent grass alleys which had not been herbicide treated. The numbers of earth worms in plots recently treated with herbicide was similar to that in unherbicided plots (1.3 per 0.5 m^2 vs 1.5 per 0.5 m^2).

Supplementary observations

- **Worm casts.** These were numerous on the surface of the grassed alleys, less frequent on the herbicided strips and seldom evident on the overall herbicide-treated plots of the main experiment. They were numerous on recently herbicided land with a dead grass cover.
- **Dead worms.** Following very heavy rain twenty small dead worms were counted on the surface of one of the plots treated with overall herbicide. This suggests some worm activity at depth in these plots, probably feeding on deeper organic residues.
- **Water absorption.** The grassed plots absorbed the detergent solution used to extract worms very readily. It soaked into the soil without runoff. On the herbicided plots it had to be applied slowly and carefully to ensure soaking in. If it was applied quickly it ran off the surface. After heavy rain erosion due to runoff was seen on the overall herbicide-treated plots.

- **Soil pH.** This was measured on the overall herbicide-treated plots and the irrigated grass plots (the two extremes for earthworm numbers). Both high nitrogen and low nitrogen plots were assessed. All samples came in the 5.5 to 6.0 range.

Organic matter in relation to grassed and bare soil in orchards

In the experiment used for the earthworm studies the grassed plots both with and without irrigation had 3.1% organic matter in the top 7 cm and 2.2% in the 7 to 15 cm and the 15 to 30 cm zones. The bare soil (overall herbicide-treated) plots had 2.1% organic matter in the top 7 cm and 1.8% in the 7 to 15 cm and the 15 to 30 cm zones (data supplied by Dr. D. Atkinson). Hipps and Fairall (1986) reported the results of another trial involving 14 years' application of herbicides overall in comparison with a grass/herbicided strip system. In this, the average organic carbon content in the top 7.5 cm was 1.47% in the overall-herbicide plots compared with 2.75% in the grassed alleys and 1.26% in the herbicided strips of those plots managed under the grassed-alley/herbicided-strip system.

Discussion

The very rapid deterioration of the structure of bare soil under and between apple trees when the grass sward was killed off in an already established row-and-alley apple orchard under the mild climatic conditions of southern England and on land with only a gentle slope is a cause for concern. It also raises questions of the contribution which widely spaced trees or trees in rows can make to the maintenance of soil structure and control of erosion and runoff in agroforestry systems. These questions are best considered in terms of the factors which appear to have led to the adverse changes in these experiments and to their likely occurrence under other circumstances.

Rooting density of trees and crops

Many other tree species are more densely rooted than is apple. The maximum L_V values quoted by Atkinson (1980) are around 0.1 cm root per cm^3 of soil for apple compared with 0.5-0.7 for a range of conifers. Bowen (1984) cites values of from 0.13 to 5.26 in the upper soil zones (0-10 cm and 0-15 cm respectively) for conifers and up to 8 in the 0-10 cm zone for Eucalyptus. It would seem from this that the root system of other trees might make a much greater contribution to the creation of structural pores than do apple root systems. However, even the highest L_V values which Bowen gives for trees are many times lower than the value of 50 in the 0-15 cm zone which he gives for grasses and at the lower end of the range of 5 to 25 which he gives for cereals. Newman (1969) gives the range of L_A values reported for Graminae as 100-4000, other herbs 53-310 and woody plants 5-110. The contribution of tree roots to creating good soil structure therefore seems likely to be small relative to that of grasses and crop plants. The inadequacies of trees in this respect will be accentuated in the early years of tree plantations unless there is a ground-cover crop.

Earthworms

The results in the experiments at East Malling are consistent with the incidence of earthworms being dependent on the availability of food supplies. Their numbers were approximately proportional to the vigour of grass growth, with most being found from under the irrigated grassed plots, next most from the unirrigated grass and none from the overall-herbicided plots.

It is unlikely that any direct effect of the herbicides in poisoning earthworms was involved. Worms and worm casts were frequent in newly herbicide-treated land with dead grass on the surface. Results from Rothamsted, England, showed that killing pasture with herbicide and slit-seeding a cereal crop without further cultivation gave a much higher population of earthworms in the first year out of pasture than did traditional ploughing (Russell 1973). The absence or greatly reduced numbers of earthworms in the orchard herbicided strips, which were 1.7 m or less in width, indicates the specificity of the link between above-ground vegetation and earthworm activity below ground, presumably as a result not only of leaf litter but also of the turnover of roots. It seems reasonable to suppose that a similar link will apply in all temperate and tropical areas where earthworms are an important component of the soil ecology. An obvious deduction is that any portion of the soil surface kept bare of vegetation in agroforestry systems or the early stages of forestry or tree crop plantations will be accompanied by absence of earthworms and potential development of poor soil structure and reduced water infiltration.

Organic matter

The trees in apple orchards, which usually have LAIs of less than 2.5 (Jackson 1980) and have the sparse root systems discussed previously can be expected to return less organic matter to the soil than many others. Broadleaf forest trees have LAIs of 6 to 7 (Kira and Kumura 1983), rubber an LAI at canopy closure of 6.3 (Moraes 1977); and cacao LAIs varying from 3.7 to 5.7 (Alvim 1977).

On the assumption that the root production and turnover in the soil is proportional to these LAIs (which may not be valid), the organic matter inputs into the soil from forest trees and crops such as cacao and rubber at maturity should be higher than those from apple. They will still, however, be low compared with those from grasses or grain crops (leaving root systems in the soil) with higher LAIs and net production efficiencies (Table 2; Kira and Kumura 1983). This will be particularly so in the early years of tree establishment when net dry matter productivity per hectare can be very low.

There are conflicting data on soil organic matter changes under different tree crops but in some cases at least, even under good management topsoil organic carbon has been reported to fall following the establishment of plantation tree crops, e.g., by 41% in 14 years in an oil palm plantation (Sanchez et al. 1985). A major factor controlling the organic matter inputs by trees and ground-cover plants into the soil is the actual destination of the organic matter produced. Apple orchards subjected to herbicide management suffer because the leaves shed on to the soil tend to blow off and accumulate against boundary fences. Litter removal from teak plantations may be the main reason for runoff and erosion where this occurs (Lundgren 1978). Apparently high efficiency in the use of the different products of trees for fodder, fuel and timber, may result in them making relatively little contribution to the maintenance of soil organic matter status.

Conclusions

At least under some conditions there is marked loss of soil structure leading to considerable reduction in the infiltration of rain water, and severe loss of this by runoff, in mature apple orchards in which the grass cover-crop in the alleys has been removed by herbicide use. This loss of structure is accompanied by, and probably caused by, reductions in the total root occupancy of the soil, in organic matter content and in earthworm activity as compared with grassed orchard soils.

These results are probably relevant to row-and-alley and other agroforestry systems in general. They may be relatively extreme because of the generally low Lv values of apple root systems and the low LAIs, hence potential biomass production, of apple orchards. The problems did, however, develop within a short space of years on land with only a gentle slope in the mild climate of southern England. This suggests that serious attention should be given to the ground- cover crops within all agroforestry systems, in which the trees, by definition, do not provide a dense closed canopy, if problems of soil structure, runoff and erosion are to be avoided. It is of interest that Cary and Evans (1972) in an experiment on the effect of soil management regimes under citrus trees found the highest infiltration rates to be into permanent sod, followed in turn by winter cloves, winter tick-bean and bare surface chemical weed control treatments.

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Protein and sugar production in Prosopis pods as affected by different climatic conditions

P. A. Oduol

International Council for Research in Agroforestry
P.O. Box 30677, Nairobi, Kenya

Abstract

Prosopis *pods used in this study were collected from trees grown under semi-arid conditions, at Riverside irrigated plots (California, U.S.A.) with July maximum temperature of 34.6 °C and mean annual rainfall of 340.8 mm and at Imperial Valley (California, U.S.A.) with July maximum temperature of 41.7 °C and mean annual rainfall of 106.6 mm. They were evaluated for pod protein and pod sugar contents. No significant differences were observed for pod protein due to the climatic differences of the two sites, but significant differences were observed for pod sugar across the irrigation treatments and at both sites. Areas with high moisture stress had high sugar means (*P. Alba, *0137 37.6%) in the pods. The presence of species by site interaction for sugar indicates that sugar is more environmentally sensitive and that individual species may perform differently on different sites with variable climatic conditions.*

This study shows that Prosopis *pods are of high nutritional quality and can be used for food, fodder and energy, thus warranting a multi-trait selection for multipurpose trees in Agroforestry.*

Introduction

The current strain on the world's resources posed by rapid population growth, dwindling supplies of non-renewable resources, and shortages of food, has aroused interest in investigating and promoting woody species that can be easily accepted by local people. The woody species in question are those that can serve a number of different purposes while providing a wide range of goods and services.

Poor distribution of arable land and the lack of technological interface with land resources has greatly lowered the world's potential, given the fact that 90% of human need for calories comes from plants (Revelle 1974). Under such circumstances the 'new crops' sought are those that can be grown on short rotation, mostly on marginal land with numerous stress problems; and have potential utilization of components such as pods and leaves, while at the same time providing wood and timber as by-products.

Selection of plant species for arid and semi-arid regions of the world poses a big challenge to plant scientists. These are areas of low and erratic rainfall, intense solar radiation, and high wind velocity. During most of the year, potential evapotranspiration far exceeds precipitation. All these factors affect plant responses. Under such agro-climatic conditions, crop production is a gamble if not impossible, and the productivity potential of the land is usually low.

Tree legumes of the genus Prosopis are well adapted to the arid areas of Asia, North Africa, North America, Central and South America (Felker 1979). Prosopis pods have been used in these areas both as human and animal food (Felker 1981; Becker 1982). Under these desert conditions, *Prosopis* has been evaluated for biomass as well as pod production (Felker et al. 1983a, 1984). The enormous potential Prosopis has for fuel-wood production, shade, shelter, nitrogen fixation and dry season fodder for animals makes it an ideal candidate tree species for agroforestry systems in semi-arid and arid areas.

Most of plant research in the arid and semi-arid areas has centred on survival and adaptability, a test for the effect of climatic factors on plant growth. Due to the complexity of the environment and the problems to be addressed in order to achieve success, climatic factors should be fully addressed while selecting tree species for agroforestry systems in different zones.

The objective of the research presented in this paper is to address the effect of climate on protein and sugar production in *Prosopis* pods, when grown at two different sites with varying moisture levels.

Materials and methods

The two study sites were described in detail by Felker et al. (1983b). The plots were located in California and designated as Riverside irrigation plots and Imperial Valley plots. The Riverside irrigation plots were established in July 1978 and were composed of 32 accessions (half-sibs), planted at a 1.2 x 1.2 m spacing in three randomized blocks. During summer months the blocks were irrigated when the moisture stress potentials at 30 cm depth reached -0.06 MPa, -0.2 MPa, and -0.5 MPa, respectively. The July maximum temperature for this site was 34.6 °C, with mean annual rainfall of 341 mm. The Imperial Valley plots, established in March 1979, were composed of 55 accessions (half-sibs) planted in 16 blocks at 55 trees per block as single tree replicates. They were planted at 1.5 x 3.6 m spacing. The July maximum temperature for this site was 41.7 °C, with mean annual rainfall of 107 mm.

Pod samples were collected in 1981. The pods were individually picked, oven dried at 50 °C for a minimum of six hours to 6% moisture content, catalogued and stored as single tree collections in freezer box at -8 °C (Felker, personal communication). For this study, pods were taken from freezer box and oven-dried at 50 °C for six hours. The pods were then ground in a Wiley mill to pass through a 1 mm sieve.

Total pod protein was determined using a factor of 6.25 x nitrogen per cent. Pod nitrogen was determined by microkjeldahl analysis (Williams 1980). Total soluble sugars were extracted from the ground pods by the Soxhlet method for about 1.5 hours using 70% alcohol. Total soluble sugar in the extracted solution was analyzed by improved anthrone method for determination of carbohydrates as described by Loewus (1951).

Results

Pod protein

Statistical analysis of the protein content of pods from the two sites showed no significant differences between sites; but significant differences existed between species at both sites ($P < 0.05$) (Table 1). Duncan's test shows that the protein means for those species are significantly different from each other at the two sites.

Table 1 Protein mean comparison across two sites (Riverside irrigation (RI) and Imperial Valley I).

Species	Accession number	RI %	I %	AVG %	Duncan's grouping
P. velutina	0032	18.0	15.7	16.8	A
P. velutina	0020	16.8	15.0	15.9	A
P. velutina	0025	17.0	13.0	15.0	B
P. glandulosa var. torreyana	0001	15.7	14.0	14.8	B
P. glandulosa var. glandulosa	0028	13.2	15.0	14.1	B
P. articulata	0016	14.7	13.3	14.0	B
P. alba	0039	9.2	12.0	10.6	C
P. alba	0137	9.0	12.0	10.5	C

RI = Riverside irrigation treatment plots; I = Imperial Valley plots
Means followed with same letter are not significantly different at $P < 0.05$

Significant protein differences existed at the Riverside irrigation treatments among species and species by treatment interaction at $P < 0.001$ and $P < 0.05$ respectively. However, the irrigation treatments (M1, M2 and M3) were not significant at $P < 0.05$ (Table 2). Duncan's test shows the protein means that are significantly different from each other for the three moisture levels at $P < 0.05$.

Table 2 Protein content for species at Riverside irrigation treatment plots.

Species	Accession number	Protein content				Duncan's grouping
		M1 %	M2 %	M3 %	Average %	
P. velutina	0032	18.0	19.9	17.0	18.6	A
P. articulata	0016	14.2	14.7	*	17.0	A B
P. spp	0080	17.8	17.2	15.2	16.5	A B C
P. velutina	0020	16.8	17.3	16.0	16.7	A B C
P. velutina	0025	17.0	13.3	15.4	15.0	B C D
P. glandulosa var. torreyana	0001	15.7	15.5	15.5	14.8	C D
P. glandulosa var. glandulosa	0028	13.2	13.1	14.2	13.4	D
P. spp	0074	13.0	13.2	12.7	13.0	D
P. alba	0137	9.0	*	11.4	10.4	E
P. nigra	0133	8.7	10.0	11.7	10.2	E
P. alba	0039	9.2	*	10.0	9.6	E

M1 = -0.6 bars (moist); M2 = -2.0 bars (medium); M3 = -5.0 bars (dry).
Means followed with the same letter are not significantly different at $P < 0.05$
* Missing values
Source: Oduol et al. 1986

Pod sugar

The two-site sugar analysis showed significant differences between sites, species and species x site interaction at $P < 0.1$, $P < 0.001$ and $P < 0.05$ respectively (Table 3). Duncan's test shows means that are significantly different from each other at $P < 0.05$

Table 3 Sugar mean comparison across two sites (Riverside irrigation and Imperial valley).

Species	Accession number	RI %	I %	AVG %	Duncan's grouping
P. alba	0137	45.0	33.2	39.1	A
P. alba	0039	37.2	36.0	36.6	A
P. velutina	0020	26.7	26.5	26.6	B
P. velutina	0032	25.0	25.5	25.3	B
P. glandulosa var. torreyana	0001	20.7	28.0	24.4	B
P. velutina	0025	19.0	28.0	23.5	B
P. glandulosa var. glandulosa	0028	11.7	22.0	16.8	C
P. articulata	0016	3.3	15.6	9.4	D

RI = Riverside irrigation treatment plots
I = Imperial Valley plots

Means followed by same letter are not significantly different at $P < 0.05$

Sugar analysis for Riverside irrigation treatments showed showed significant differences between species and species x treatment interaction at $P < 0.001$ and $P < 0.05$, respectively. However, treatment source of variation was not significant at $P < 0.05$, but was signficant at $P < 0.1$ (Table 4). Duncan's test shows sugar means that are significantly different from each other at $P < 0.05$.

Both protein and sugar values for the two sites (Riverside irrigation and Imperial valley) and the three moisture levels (Riverside irrigation treatments M1, M2, M3) showed an inverse relationship between protein and sugar. Species which tended to be high in protein had low sugar contents while those species high in sugar had low protein contents.

Table 4 Total sugar content for species at Riverside irrigation treatment plots.

Species	Accession Number	Sugar content M1 %	M2 %	M3 %	Average %	Duncan's grouping
P. nigra	0133	40.7	33.0	36.7	37.5	A
P. alba	0137	45.0	*	35.8	37.3	A
P. alba	0039	37.2	*	32.8	35.0	A
P. velutina	0032	25.0	22.9	31.5	25.7	B
P. velutina	0020	26.7	26.0	23.7	25.4	B
P. spp.	0080	22.4	26.7	25.9	25.4	B
P. velutina	0025	19.0	23.0	31.0	24.2	B
P. spp.	0074	19.5	16.4	33.7	22.2	B C
P. glandulosa var. torreyana	0001	15.7	18.5	24.2	20.1	B C
P. glandulosa var. glandulosa	0028	11.7	22.7	17.0	17.0	C
P. articulata	0016	*	3.3	6.7	5.3	D

M1 = -0.6 bars (moist); M2 = -2.0 bars (medium); M3 = -5.0 bars (dry).
Means followed with the same letter are not significantly different at $P < 0.05$
* Missing values
Source: Oduol et al. 1986

Discussion

The study shows variable results for both protein and sugar contents in *Prosopis* pods. There were no significant differences for pod protein for the Riverside irrigation treatments (M1, M2, M3). At both the sites, however, significant differences existed among species. The lack of protein differences due to treatment and site suggests that in these circumstances, the species were not overly sensitive to differences in environment.

Significant differences were noted in pod sugar content for the Riverside irrigation treatment (M1, M2, M3), between sites and among species. Irrigation treatment M3 (very dry) and Imperial valley site had the highest sugar-containing species, a factor attributed to the magnitude of moisture stress causing carbohydrate build up in fruit forming trees and hence high sugar concentration. This may also be due to carbohydrate conversion to sucrose in the fruits during ripening under moisture stress (Kramer and Kozlowski 1979). The high carbohydrate may also be attributed to the lack of nitrogen, thus hindering the use of carbohydrates for protein synthesis(Kramer 1983).

Protein and sugar differences at both sites among species is very important, if species are to be crossed in order to get hybrids that are high in both protein and sugar. The presence of species by site interaction for sugar indicated that sugar is more environmentally sensitive and that individual species may perform differently on different sites, with variable climatic conditions.

If the potential of *Prosopis* species as a food and energy feed stock is to be realized, then pod nutritional quality must be known. The pod can be fractioned into a high sugar fraction, a high fiber fraction, a high protein fraction and a high galactomannan gum fraction (Felker et al. 1980).

The survival of *Prosopis* in desert ecosystems renders a new hope to these often disregarded wastelands. The concept of establishing multipurpose trees in agroforestry systems on marginal lands, where there is no direct competition with conventional agriculture appears to be a promising solution to both the social and economic problems associated with the development of these areas in developing countries.

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SECTION 6

Agroforestry and animals

- Competition for water, light and nutrients in agroforestry association of *Pinus radiata* and pasture. — D.J. Connor, R. Sands, M. Strandgard
- Climate, animal and agroforestry. — M. Djimde, F. Torres, W. Migongo-Bake
- Impacts of sheep grazing on soil properties and growth of rubber. — Nik M. Majid, K. Awang, K. Jusoff

Competition for water, light and nutrients in agroforestry associations of Pinus radiata and pasture

D.J. Connor, R. Sands and M. Strandgard

School of Agriculture and Forestry, University of Melbourne
Parkville 3052, Australia

Abstract

An experiment to study the co-productivity of pine and sheep was established in 1983 when pine previously planted into improved pasture in 1981 was thinned to provide a range of pine-pasture combinations. The experimental site is 150 km northwest of Melbourne on an extensive basaltic plain at an elevation of 400 m. The annual rainfall is 650 mm and the annual evaporation 1100 mm. The soil is acidic, duplex with a clay loam surface soil 15 cm deep overlying a medium clay. The original vegetation of the area was a savanna woodland dominated by Eucalyptus camaldulensis *but previously converted to improved pasture of* Lolium perenne *and* Trifolium subterraneum *but now with considerable invasion of* Holcus lanatus.

There are five treatments of which the two boundary treatments are treeless pasture and a plantation of 1650/ha (3 m rows x 2 m tree spacing). The three agroforestry combinations are 100/ha (8 x 12 m), 277/ha (4 x 9 m) and a treatment in which 5 rows spaced 3 m apart (trees 4 m within rows) are separated by a 10-row gap. In this case the tree density in the planted area is 830/ha but on a total area basis it is also 277/ha. Plot size is 1.85 ha of which the inner 0.5 ha is separately fenced. Plots are grazed by individual flocks of sheep. Their performance is recorded as wool production and live weight gain.

The large treatment plots afford an excellent demonstration of agroforestry alternatives and the inclusion of grazing adds realism to the microclimate, productivity and nutrient flows in the systems. The comprehensive annual measurements that are being made of tree growth and animal production will, in the long term, allow a complete economic appraisal of the systems. However, it is the interfaces between trees and pasture that provide the most generally useful data. This is so because the co-productivity relationships to microclimatic modification across these margins can be generalized to assess the performance of otherwise unstudied combinations of pine and pasture.

Detailed measurements of the growth and hence of the interaction of trees and pasture are concentrated along transects across the margins between treed plots and the pasture controls. These include various attributes of tree size, pasture production and soil moisture content to 13 m. Measurements within the plots include light, wind run and the redistribution of rainfall by canopy interception and stem flow. Tree-pasture competition is also being studied in the 100/ha treatment using combinations of trenching and herbicide application.

Results so far are limited. Differences in tree growth are evident. The trees in the highest density are tallest but the stem volume of those evenly spaced at 277/ha is greatest. The low density trees (100/ha) have grown least, probably a response to exposure at this windy site but perhaps also to water stress because the lowest density treatment has the lowest

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subsoil water content of the treed treatments. This may reflect the aerodynamic roughness of the arrangement but it is evident that the presence of trees improves the infiltration of water into the clay subsoil. There has frequently been free water in surface irregularities of pasture and low density tree plots during the winter whereas in the plantation and the more-densely treed plots, free surface water has been conspicuously absent.

Analysis of pasture productivity shows that even in the open pasture the productivity is below potential with maximum spring growth rates over a 90-day period averaging only 60-70 kg/ha-day. So far there is little evidence of a decline in pasture productivity except in the plantation in which grazing was suspended during winter 1986 (5 years after planting). Except in the plantation, the tree cover in the agroforestry combinations, especially following their pruning in winter 1986, is insufficient to dominate pasture productivity.

Trenching of root systems and removal of pasture by the application of herbicide (glyphosate) in the vicinity of trees in the 100 ha treatment has demonstrated the significant effect of tree-pasture competition on the water relationships and growth of trees. To date it does not appear that the effects are any different in the other agroforestry combinations. However, measurements of soil water profiles during summer 1985 show that there was, for the first time, a marked drying under the treed treatments compared with pasture. Competition between the now larger trees and pasture appears to be intensifying after 5 years of relatively independent growth.

Introduction

Although much of the grazing during the past 150 years in southern Australia has been carried out on what was originally grassland or savannah woodland, the management of these grazing lands has been directed solely to the maximization of returns from animal products. Gradually many areas have been completely cleared of trees and replaced, often in a cropping rotation, with improved pastures. In other areas, trees have been thinned and the growth of improved pasture species encouraged by the application of phosphatic fertilizers and trace elements, generally with pasture seed broadcast or lightly scratched into the surface soil. Grazing and fire have prevented the regeneration of replacement trees so that, as the remaining trees die, most land is being converted to treeless pasture. There are a number of possible causes of the death of the remaining trees in what is commonly referred to as 'tree decline' and which is causing considerable community concern. The reasons include increased exposure, insect attack, rising water tables and salinity. However, given the lack of recruitment by tree seedlings to the tree layer under grazing, the result is inevitable as the remaining trees age, whether or not their death has been hastened.

The loss of tree cover is associated in many places with rising water tables and erosion of the surface soil. Over most of the area, the annual potential evaporation far exceeds rainfall but the rainfall/evaporation balance provides excess water which infiltrates into the subsoil during winter.

Whereas the native, evergreen trees and summer-active native grasses removed this water by active transpiration in summer, the winter-active species of improved pastures are summer-dormant annuals under which the subsoils become increasingly wet, leading ultimately to rising water tables in the lower parts of the topography. Where water tables become saline and encroach into the root zone, the productivity of what is often the best land in the topographic sequence is seriously impaired.

Agroforestry offers itself as one way to re-establish a hydrological balance that is compatible with continuing agricultural productivity. Alternatives are to concentrate on summer active agricultural species such as phalaris and lucerne, or to return some

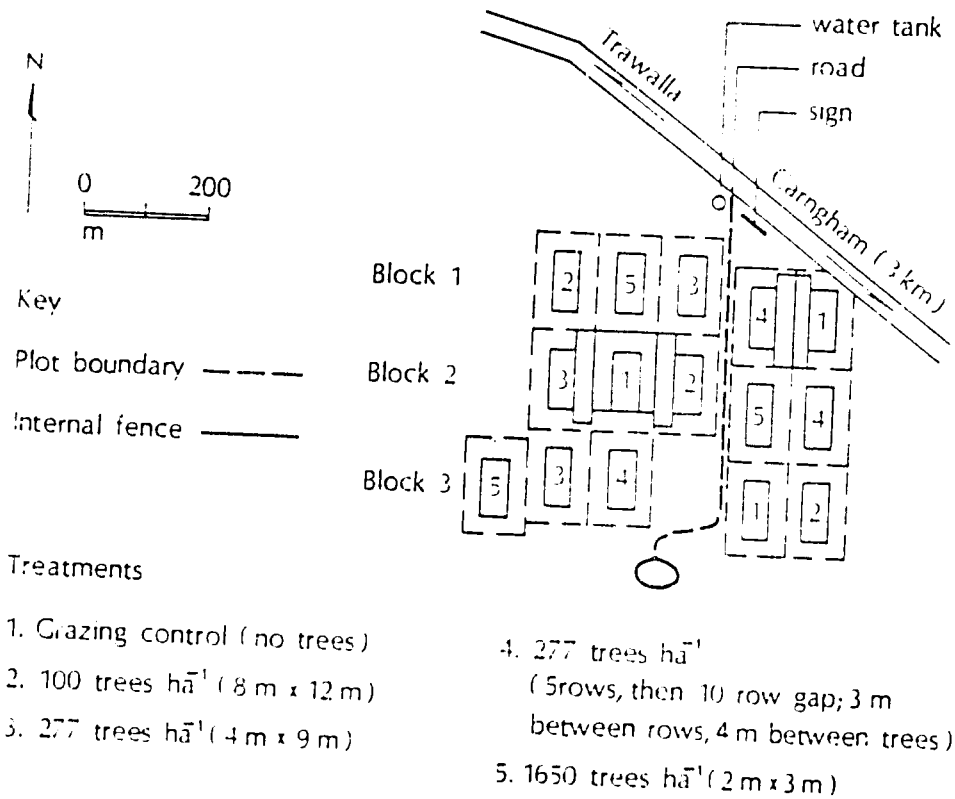
or all of the landscape to tree production. In agroforestry options there is an emphasis of *Pinus radiata* because there is a strong demand for softwood which cannot be met from the extensive, managed native hardwood forests. The combination of *P. radiata* and pasture has received much attention in Australia and elsewhere, e.g., New Zealand and Chile, but the refinement of the system for Victorian conditions, including its demonstration to farmers, requires further local experimentation. The experiment at Carngham was established for this purpose.

Methods

Experimental Site

The experiment is located at Carngham 150 km WNW Melbourne (Figure 1) on former farmland which was purchased by the government in 1981 for the establishment of

Figure 1 Design of the agroforestry trial at Crangham, Victoria.



P.radiata. The site is at the NW edge of a broad basaltic plain on which the original vegetation was a savannah woodland dominated by *Eucalyptus camaldulensis* (red gum) with a herbaceous storey of *Themeda australis* (kangaroo grass) and species of *Stipa* (spear grass) and *Danthonia* (wallaby grass). During 100+ years of grazing, mostly by sheep, and by sporadic application of superphosphate fertilizer, the vegetation has changed markedly. Tree seedlings have not regenerated so that trees are now virtually absent from the site. The herbaceous layer is dominated by introduced species of european and mediterranean origin. The preferred pasture contains *Lolium perenne*, (perennial ryegrass), *Dactylis glomerata* (cocksfoot) and *Trifolium subterraneum* (subterranean clover) but at this site there has been substantial invasion by *Holcus lanatus* (Yorkshire fog grass).

The soil is duplex with a clay loam A horizon sharply overlying a clay B horizon at 15 cm depth. The infiltration rate of the subsoil is low and the seasonal waterlogging that occurs at the junction is demonstrated by the layer of ironstone nodules that have formed there. The surface is slightly undulating but does not have the marked 'gilgai' micro-relief that is characteristic of many grassland and savannah woodland sites on heavy soils in southern Australia.

The seasonal waterlogging of the surface soil restricts cropping to areas of better drainage. The principal crop is oats grown for grazing and/or grain to support animal production but cropping is also a valuable part of the process of pasture renovation. The site of this experiment shows no evidence of previous cultivation.

Climate

Mean monthly climatic data for the nearby (20 km) city of Ballarat are summarized in Table 1. These data are generally applicable to the experimental site. Months of effective rainfall are defined as those in which rainfall exceeds one third of pan evaporation, a form of analysis that has wide applicability in southern Australia. In this case it shows that the five months from May to September inclusive have a supply of moisture adequate to sustain plant growth and that there is a high probability that conditions will remain effective in April and October also. On average the period of effective rainfall is nine months.

Table 1 Mean monthly climatic data for Ballarat.

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Rain (mm)	41	46	48	61	73	70	71	78	75	71	60	51	745
Evap(mm)	178	135	120	71	40	30	30	43	63	91	116	150	1070
Temp max	26	25	22	18	13	11	10	11	14	17	19	22	
Temp min	11	12	10	8	6	4	3	4	5	7	8	10	
Frost (days)	-	-	-	1	4	11	11	7	6	4	1	-	

Mean daily minimum temperatures fall below 10 °C in the period April to November and are below 5 °C in the three months June to August. During these three months the growth of temperate species (pine and pasture) are restricted by low temperature. Mean monthly maximum temperatures do not exceed 28 °C and although a few hot days

(35 °C) do occur, high temperature does not exercise an important direct controlling restriction on plant growth. During the summer months, water shortage caused by high temperatures and evaporative demand restricts growth of trees and pasture.

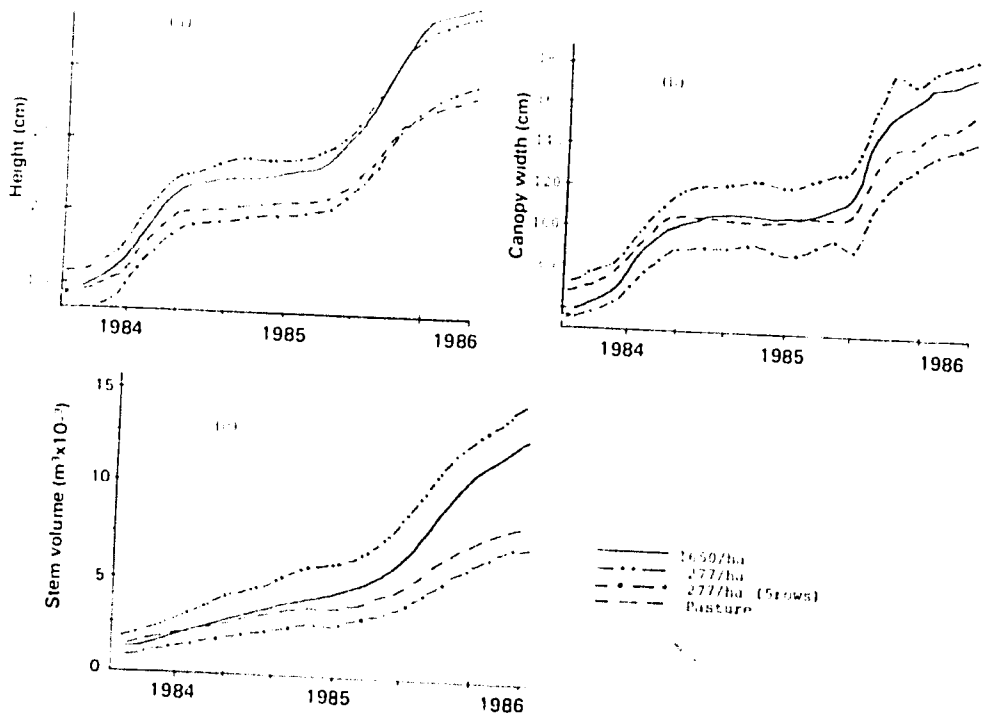
Strong winds are a feature of the climate of the basalt plains and one which can be successfully ameliorated by trees. The modification of wind, particularly of the 'chilling factor' during winter will receive attention in this experiment because of its significance to stock survival, particularly of ewes and lambs.

An automatically recording climate station was installed at the site. It records hourly integrals of global radiation, rainfall and wind run together with measurements on the hour (5-min average) of wet- and dry-bulb temperature and soil temperatures at two depths. Complete data are now available for 1985 and 1986. Two key parameters are wind run and global radiation; the former because modifications to the wind regime is an important feature of agroforestry systems and the latter because the potential productivity of pasture under trees depends ultimately upon the penetration of solar radiation to the grass layer.

Experimental design

The experiment was established in 1983 when pine previously planted in 1981 at plantation spacing (3 x 2 m = 1650/ha) was thinned to provide three replicates of the five treatments described in Figure 2. Plot size is 111 x 167 m (1.85 ha). Within each plot

Figure 2 Measurements of (a) tree height (cm), (b) canopy diameter (cm) and (c) stem conic volume ($m^3 \times 10^{-3}$) over a two-year period.



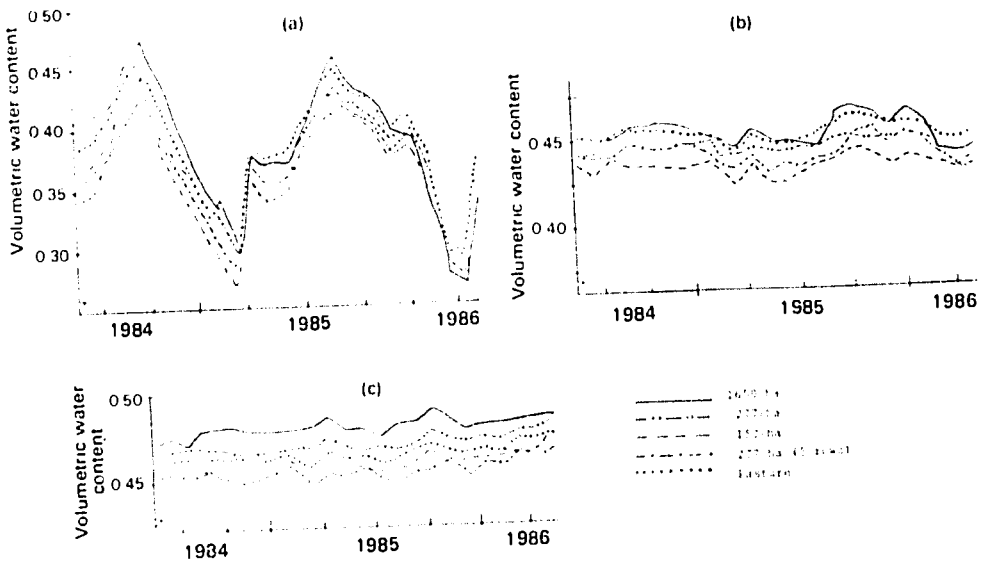
there is an internal plot of 48 x 104 m (0.50 ha) that is fenced, supplied with water and separately stocked with sheep for the measurement of grazing production. The external areas of all plots are, with a few exceptions where additional measurements are being made, bulk-grazed by a single flock of sheep. The pasture was slashed in the first year of the experiment but has been grazed since December 1984. The number of sheep grazing individual plots depends upon pasture availability. When feed is inadequate the sheep are removed.

Measurement

Regular measurements of soil water status, rainfall redistribution by the trees, and tree and pasture growth are made in each treatment. Additional measurements have been made of tree water potential and stomatal diffusive conductance in the 100/ha treatment in response to the removal of grass in the vicinity of the trees and to trenching designed to separate the root system of pasture from that of the trees.

Annual measurements of tree and animal production will provide the economic analysis of the agroforestry alternatives included in the experiment. Measurements of water redistribution, water balance and the competition studies will assist in the interpretation of the results. However, in order that the results obtained in this experiment can have the widest application, regular, detailed measurements of tree and pasture growth and water balance are concentrated along transects that traverse the boundaries between treed treatments and pasture controls. The establishment of tree and pasture growth response functions (Figure 3) across the interfaces and within the treed area will enable the competitive relationships included in this experiment to be extrapolated to tree-pasture combinations that are not included in this experiment.

Figure 3 Soil volumetric water content over a two year period for soil depths (a) 0-80 cm, (b) 80-140 cm and (c) 160-220 cm.



Soil water content is measured by neutron moisture meter (NMM) from the 20 cm depth at 20 cm-depth intervals in 3 m deep aluminium access tubes (90 in all) located along the transects. Pasture growth is measured at 3-monthly intervals (summer, autumn, winter and spring) in grazing exclusion cages of 1 m radius (200 in all) also located along the transects. Soil water is measured monthly whenever possible although the interval between readings can be extended to two months in winter with little loss of information when monthly changes are small. Canopy interception and stem flow are currently being measured in the 1650, 277 (even) and 100/ha treatments. Linear rain gauges (4 m) are deployed under tree canopies and between tree rows. Six trees per plot have been fitted with stem collars to collect stem flow. Additional NMM access tubes have been located in the vicinity of the interception equipment.

Results

Tree growth

Measurements of tree height, canopy width and stem conic volume are presented in Figure 2. Trees in the two most dense treatments (1650 and 277/ha) are the tallest, approaching 4 m by age 5 years. The trees in the low density (100/ha) treatment and the 5-row pattern are shorter by approximately 1 m.

Canopy width is greatest in the 277/ha treatment. The two open- spaced treatments have compensated for less height with greater lateral expansion of their canopies, but as with height growth, canopy width demonstrates their poorer growth. These estimates of mean canopy diameter lead to gross estimates of vertically projected cover of 0.42, 0.08 and 0.02 for 1650, 277 and 100/ha respectively. Within the treed area, the cover of the 5-row pattern is 0.13.

Tree productivity is most closely approximated by stem volume. The data in Figure 2 show that the trees at 277/ha, which have the widest canopies, also have the greatest stem volume. The open spaced planting (100/ha) and the 5-row pattern are 50% smaller after 5 years of growth.

Analyses of the growth of individual trees across the pasture- tree interface are presented for two occasions (August 1984 and April 1986) in Table 2. Trees grow best at the margins of the 1650/ha and 5-row treatments but performance across the interfaces of the other more open treatments is variable.

Soil water content

Changes in volumetric water content for three depth intervals 20-60, 80-140 and 160-220 cm are shown in Figure 3. Seasonal changes in soil water content have occurred only above 80 cm shown here in the data for the 20-60 cm. In this layer the pasture and the plantation had the highest soil water content for the first two years of measurement but during the last summer the plantation dried the most. The three agroforestry combinations (100/ha, 277/ha and 5-row pattern) were at all times drier than the pasture but during the last summer were wetter than the plantation.

Below 80 cm there is little evidence of seasonal change except in the last summer when water content in the 80-140 cm fell under the plantation. An interesting observation is that the soil water content at depth below the plantation has been wetter than that under all other treatments. There is no seasonal fluctuation and no differences have been established between treatments in the depth range 160-220 cm.

Table 2 Growth of individual trees.

Spacing	Tree No.	Distance edge(m)	Volume ($m^3 x10^{-3}$) August 1984	April 1986
100/ha	1	0	1.30	9.75
	2	12	1.03	7.73
	3	24	1.42	9.41
	4	36	1.10	7.34
	5	48	1.32	7.87
5-Row	1	0	1.05	8.47
	2	3	0.72	7.38
	3	6	0.60	6.73
	4	3	0.67	6.50
	5	0	0.79	8.68
277/ha	1	0	1.04	11.83
	2	9	2.03	16.94
	3	18	2.98	23.85
	4	27	1.89	14.72
	5	36	0.87	9.44
1650/ha	1	0	1.64	14.83
	3	4	1.44	14.84
	6	10	1.25	13.79
	10	18	1.07	11.98
	15	28	1.02	11.29

Analyses of the change in soil water content across the pasture- tree margins are incomplete but show that the gradients are steep across the interface between the pasture and the plantation and the 5- row pattern. In the case of the 100/ha and 277/ha treatments, the trees are so sparse that the gradients within the planting are as marked at this stage in the development of the systems as are those across the interface.

Pasture growth

The data presented in Figure 4 describe the 1986 spring pasture growth across the treatment-pasture interface for the plantation (1650/ha) and the 5-row pattern. These treatments now show an effect of treatment on pasture productivity. Within the 277/ha and 100/ha plantings there is still no difference in pasture production from that of open pasture.

In the 5-row pattern the effect is relatively small. The data show no sites of high production within the planted area so that the average production is less than in the pasture. Across the pasture- plantation interface the effect of trees on the productivity of pasture is sharp (Figure 4). Pasture productivity in the open averages 5.1 g $m^{-2}day^{-1}$ while that under the trees is 2.8. The variation in pasture production within the plantation reflects the distance of samples from individual trees rather than the distance from the edge of the treatment (Figure 5).

Figure 4 Spring pasture productivity (gm^{-2} day^{-1}) across (a) the platation-pasture interface, and (b) the 5-row treatment-pasture interface.

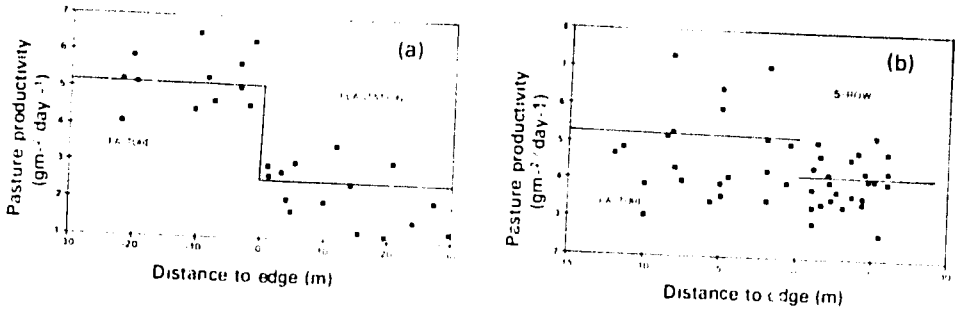
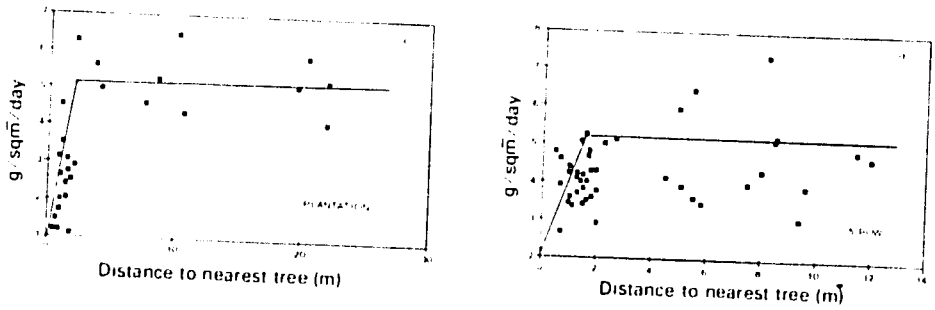


Figure 5 Pasture productivity (gm^{-2} day^{-1}) across (a) the platation-pasture interface, and (b) the 5-row treatment-pasture interface, expressed in terms of distance to the nearest tree.

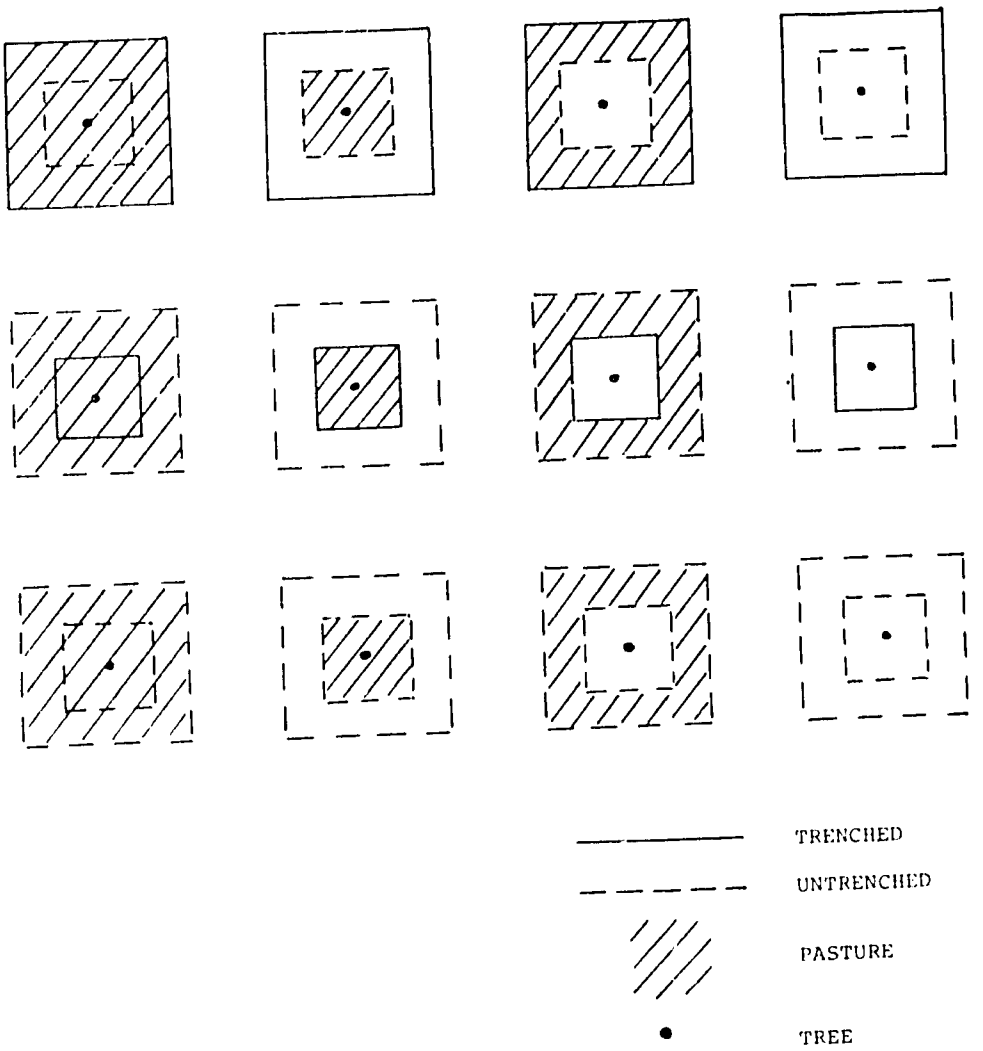


Tree-pasture competition

In the 100/ha treatment an experiment was undertaken to investigate the effect of pasture on the growth of trees. The 100/ha treatment was chosen because it was considered that there would be no significant competition between trees at this stage. Two square zones, inner (side 1.5 m) and outer (side 3 m), were established around a number of trees. Inner and outer trenches were dug to 1 m, lined with plastic film and refilled. Pasture growth was removed using the herbicide glyphosate. The combinations and further details are shown in Figure 6.

Removal of pasture from around the tree bole (no pasture and outer pasture treatments in Table 3) caused an improvement in tree water status as indicated by a significantly higher midday needle water potential measured in January 1986. Pasture removal treatments, made in June 1985, were associated with an increased wood production over the period to January 1986 (Table 3). The effect was more marked by January 1987.

Figure 6 Trenching and pasture removal combinations.



The increased wood production was probably due in part to the improved tree water status. However, even though the 'no pasture' and 'outer pasture' treatments were equally effective in raising needle water potential, they were quite different in their patterns of water use. The 'no pasture' treatment used least and the 'outer pasture' treatment used most soil water over the period June to January (Table 3).

Table 3 Growth and water relations of pine in response to the removal of pasture.

		All	Inner	Outer	None
Tree stem volume increment ($m^3 x10^{-3}$, 18/6/85 to 21/1/86)		3.89	4.00	4.00	4.09
Needle water potential (MPa, 31/1/86)		-1.50	-1.50	-1.24	-1.22
Soil gravimetric water content (0-40cm, 21/1/86)	inner	0.101	0.080	0.088	0.116
	outer	0.108	0.157	0.098	0.163

Discussion

The agroforestry trial at Carngham is a traditional randomized block design. Although statistically robust, such trials occupy large areas and are expensive to establish and maintain and consequently can compare a limited number of tree spacings. By contrast designs such as the Nelder Wheel and a variety of parallel row designs can examine tree spacing as a continuous variable over a wide range. These designs are, however, upset by silvicultural treatments such as thinning and are sensitive to tree mortality. In the experiments described here an attempt has been made to maintain the robustness of the traditional design while at the same time gaining some of the advantages of the systematic designs. This has been done by making additional measurements along transects across the interfaces between trees over a range of spacings and pasture.

It is envisaged that the examination of these interfaces will provide valuable information about the competition between trees and pasture and that the production functions of trees and pasture across the interfaces will be appropriate relationships to include in simulation models of the productivity of a wider range of agroforestry systems.

It will certainly give a more comprehensive understanding of an agroforestry system than could be gained from measurements taken only within the individual treatments. The approach should also assist the design of windbreaks and of a wide range of discontinuous agroforestry systems. At this early stage of the investigation only preliminary results have been obtained.

For the first five years the effect of pasture on tree growth has not been significantly different between treatments. Now, differences in tree growth are emerging and gradients are being established at the interfaces between treatments. The effect of tree growth on pasture production is evident in the plantation, becoming established in the 5-row treatment (effective density 825/ha) but at the lower tree densities, the growth of pasture is still unaffected.

The subsoil under the plantation (1650/ha) is wetter than under pasture. Considering the relative rooting depth of pasture and trees this is a surprising result. It is likely that the wetter subsoil reflects higher infiltration of water into the soil under the trees rather than a lower rate of water extraction. Certainly, while surface water has been relatively common during winter in the surface irregularities of the pasture treatment, it was infrequent and short- lived in the plantation and denser tree treatments. It is

expected that this trend will be reversed as the trees develop larger canopies and denser, deeper root systems. The beginnings of this are perhaps evident in the drying of the subsoil which was observed for the first time in summer 1986.

Agroforestry experiments typically test a range of tree spacings against pasture (or crops). Results from these experiments tell more about the effects of trees on pasture than of the effects of pasture on trees. The reciprocal experiment, in which a range of pasture densities (or treatments) is tested against a constant tree spacing is more informative about the effect of pastures on trees but few such experiments have been carried out except in studies of weed control in plantation forestry.

The pasture removal experiment reported in Table 3 is an example of such a reciprocal experiment. It is well known that clearing herbaceous competition from around the stem of pine can substantially improve growth, particularly in the early establishment phase when tree roots are shallow and actively competing with roots of herbaceous species for soil water and nutrients. The use of herbicides in the establishment of pine is now standard practice, and this may explain that while the effect of trees planted into pasture may appear to have minimal differential effect on total pasture productivity there is nonetheless significant competition which restricts the early growth of trees.

Measurements are being continued to measure the co-productivity and water balance of trees and pasture. Examination of their performance across the treatment interfaces will assist in the interpretation of the treatment responses and provide production functions that will be useful in the design of a wider range of agroforestry systems.

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Climate, animal and agroforestry

M. Djimde and F. Torres

International Council for Research in Agroforestry (ICRAF)
P. O. Box 30677, Nairobi, Kenya

W. Migongo-Bake

Semi-Arid Food Grain Research and Development (SAFGRAD)
Cameron Farming Systems Research Programme
BP 415, Garoua, Cameroon

Abstract

Climate affects domestic animals both directly and indirectly. Direct influences are on thermoregulation, feed and water intake and utilization, animal growth, milk production and reproductive performance. Major indirect effect of climate is on quantity and quality of feed supply. The second most important indirect effect of climate is its influence on the distribution of pests and diseases. There appears to be a great scope for agroforestry to alleviate adverse climatic effects on livestock through provision of shelter for animals and pasture. Tree shade, windbreaks, shelterbelts, trees in pasture have agroforestry potentials in alleviating climatic stress on animals and increasing pasture production.

Introduction

Environmental conditions under which livestock are produced vary greatly. They include the temperate zones; semi-arid areas; low wet tropics; and high-altitude areas. These environmental conditions i.e., climatic factors, influence animal husbandry and, in particular, animal reproduction and productivity. Livestock production is influenced by climate both directly and indirectly, affecting health, reproductive efficiency, productive conversion of feed and, indeed the very survival of the animal - particularly at critical stages of its life cycle. Direct influences affect in particular the heat balance of the animal whereas indirect influences affect land use and management, feed production and conservation, disease and parasites (Starr 1986). Therefore the provision of favourable microclimates represents an important management aspect in livestock production. In this framework we attempt in this paper to present climate-livestock relationships and the possible role of agroforestry in alleviating adverse effects of climate. Although the animal component in agroforestry includes a wider range of fauna (e.g., bees, worms, fish etc.), we concern ourselves with conventional domestic livestock (e.g., ruminants, pigs, poultry).

Direct effect of climate on livestock

Thermoregulation

All domestic livestock are homeotherms. That means, they attempt to maintain their body temperatures within a range most suitable for optimal biological activity. In order to maintain their body temperature animals must cope with the climate. Domestic livestock must preserve a thermal balance between their heat production or gain from the environment and their heat loss to the environment.

The thermal balance can be expressed by the equation

$$M - E \pm F \pm Cd \pm Cv \pm R = 0$$

where M is metabolic heat production; E, heat loss from skin and respiratory passages by evaporation; F, heat lost or gained bringing ingested food or water to body temperature; Cd, heat lost or gained by direct contacts between the body and surrounding surfaces; Cv, heat lost or gained by convection due to contact between the air and skin and/or linings of the respiratory passages; and R, heat lost or gained by radiation (Williamson and Payne 1984).

Of the various ways that domestic livestock lose heat, evaporative loss is potentially the most important under normal circumstances. It depends on the ambient air temperature, the amount of available moisture, the area of evaporating surface, the absolute humidity of the air surrounding the animal and the degree of air movement.

The ability of livestock to lose heat through conduction (Cd) is very limited. Convection (Cv) heat loss is of course increased when cool breezes blow on the animal, and increased air movement may also increase evaporative heat loss. Consequently livestock accommodations in the tropics should always be built in such a way as to encourage maximal air movement on and around the animals.

Solar radiation may not only increase the heat load on the animal but also directly affect the skin, causing skin cancers and other photosensitive disorders.

Climate and grazing behaviour

The effect of climate on livestock is manifested in their grazing behaviour. Cattle in the tropics if not yarded make use of any natural shade available rather than grazing in the middle of the day, to avoid the climatic stress due to high insolation and air temperatures. The reduction of night grazing practised in the tropics because of predators leads to significant decline in liveweight gain.

Climate and feed, water intake and utilization

Feed intake

High ambient temperatures depress the feed intake of all cattle. Increasing humidity combined with high ambient temperature also depresses the feed intake of all cattle.

Water intake

The direct effect of climate on the water intake of livestock is very complex, as water is required by the animal for at least two different purposes: first as an essential nutrient and component of the body, and secondly to assist the animal lose heat by evaporative cooling. In general, the water intake of livestock increases with increasing ambient temperature. Humidity also affects water intake. Increasing humidity combined with

high ambient temperatures decreases water consumption and increases the frequency of drinking.

Increased radiation load on livestock increases water consumption which is used for evaporative cooling (Williamson and Payne 1984).

Efficiency of utilization

Increasing ambient temperature may decrease the efficiency of feed utilization.

Climate and growth

Growth is a complex set of metabolic events which are environmentally and genetically controlled. Among the climatic conditions that may impose stress on the rate of prenatal, preweaning and postweaning growth are temperature, humidity, air movement and radiation (Hafez 1968). Reduced feed intake and grazing time is likely to affect animal growth (Webster and Wilson 1980; Williamson and Payne 1984).

Prenatal growth

The environmental temperature is perhaps the most important climatic component affecting prenatal growth. Miniature calves are often born to unadapted exotic breeds of livestock following summer pregnancy in the tropics. Pregnant ewes (breed dependent) exposed to high experimental temperatures bore miniature lambs, the reduction in weight being proportional to the length of exposure. This dwarfing is, according to Yeates (1958), a specific effect of temperature and not an effect of reduced feed intake.

Postnatal growth

Growth of the suckling offspring will depend upon both its own environmental surroundings and the environmental factors imposed upon its mother and her milk supply.

- Effect of heat. The growth of animals after weaning can be stunted by high environmental temperatures.
- Effect of air movement. Wind can be harmful to unsheltered animals at low temperatures, especially if they are wet.
- Nutritional and metabolic mechanism. Nutritional requirements of the animal are dependent on environmental temperature. Reduction or cessation of body growth at high temperatures is apparently due to reduction in voluntary feed intake; increase in energy expended for heat dissipation, particularly through respiration enhancement; reduction in the amount of nitrogen, fat or water stored; and changes in the differential growth of body organs.
- Hormonal and enzymatic mechanism. When homeothermic animals are subjected to environmental temperatures above or below their thermo- neutral zone, a vast array of physiological and biochemical changes take place. The enzymes that catalyse various metabolic reactions are to a great extent controlled by the levels of both substrates and hormones. Environmental temperature fluctuations ultimately alter the availability of these controlling factors by causing changes in the amount of food consumed.

Climate and milk production

Milk production is reduced during exposure to heat, or during the summer. This cannot be attributed solely to a fall in feed intake or forage quality. The effect of heat on physiological mechanisms related to lactation is also of importance, mainly the low level of thyroxine during the summer.

Similarly milk constituents undergo changes due to high environmental temperature. Most of the available experimental evidence indicates that, for example, butterfat and non-fat solids production is depressed by high ambient temperature.

Climate and reproduction

The major climatic factors affecting reproduction are ambient temperature, humidity and length of daylight (Williamson and Payne 1984).

Hypofunction of the anterior pituitary may be a major result of high temperature leading to an insufficient production of sexual hormones, which in turn results in reproductive failure (Hafez 1968). Sudden violent fluctuations in ambient temperature, such as occur in the sub-tropics, can directly affect the reproductive performance of cattle. High humidities reinforce these effects.

There is evidence from field observations that both embryonic death and foetal dwarfing of sheep occur in hot environments. High ambient temperatures also appear to affect embryo survival in sows and may have some effect on oestrus. Constant high ambient temperatures reduce the rate of laying of eggs and the total number laid as well as a diminution in egg weight and shell thickness.

In all male domestic livestock there is evidence that spermatogenesis is adversely affected by high ambient temperatures.

Indirect effect of climate on livestock

The major indirect effect of climate on livestock is on the quality and quantity of the feed available to them. Other indirect effects are on the incidence of disease and parasites and on the storage and handling of animal products.

Feed supply

The quantity and quality of feed available to tropical livestock are primarily dependent upon the climatic factors influencing plant growth (Webster and Wilson 1980). The most important climatic factors that limit plant growth, and hence the quantity of the feed available, are ambient temperature, effective rainfall, length of daylight and the intensity of solar radiation. The quality of feed depends mainly on effective rainfall and on the intensity of solar radiation (Williamson and Payne 1984).

Parasites and diseases

Another indirect effect of climate on farm animals is its influence on the distribution of the major pests and diseases and on the arthropod vectors that are responsible for their spread. High ambient temperatures and humidities provide a favourable breeding environment for internal and external parasites, fungi and disease vectors.

Storage and handling of animal products

Tropical climate, humid or arid, favours the rapid deterioration of stored animal products, thus increasing processing and handling costs. This indirectly affects animal production since increased processing, handling and storage charges may make increased production uneconomic in certain marginal areas that are otherwise suitable for the development of a livestock industry (Williamson and Payne 1984).

Role of agroforestry

Agroforestry can alleviate adverse climatic effects on livestock by providing shelter for animals and increasing pasture productivity. Shelter effect on livestock production can be direct or indirect; direct through shade trees and windbreaks; indirect through an increase of pasture productivity by utilizing trees, windbreaks and shelterbelts to improve microclimate.

Direct shelter effect on livestock

Literature on the specific effects of shade trees or tree windbreaks is very scarce. A thesis by Goldson (1973) on dairy production in a cashew-pasture combination in coastal Kenya indicates that the biggest contribution of the trees to the animal was the reduction of solar radiation as manifested in animal behaviour. However, there was no difference between the milk yields of animals in four treatments with and without shade during the wet and dry season.

According to Robinson (1982) the effects of heat stress reduction by shade trees on animal production are numerous and the extent of the effects depends on the climate and the animal breed. He postulated some of the effects as follows:

- Animals eat and graze longer.
- Animals need less water.
- Conversion efficiency of fodder is improved.
- Growth rate, milk yields and wool production are improved (independently of the quality and quantity of fodder available).
- Reproductive rates should be improved (independently of quality and quantity of fodder available) due to the following likely influences: earlier puberty (related to higher growth rates), higher conception rates, more regular fertile periods, lengthened reproductive life, reduced embryo loss and need for a lower ratio of males to females.
- The survival rate of the offspring is also higher due to the following likely influences: mothers in better condition, easier parturition, larger and stronger offspring, higher milk yields.

Norman and Ernest (1986) reported shade to be beneficial to livestock in a high temperature environment and suggested that tree plantings can be designed with the primary function of providing shade for livestock and helping to distribute grazing uniformly in a pasture.

Whereas provision of shade to animals is crucial in hot environments, windbreaks become important management tools at low temperatures. With the cold windy weather of New South Wales, sheltering lambing ewes from the wind by using a tall unpalatable

phalaris reduced mortality of single lambs from 18 to 9%, and that of multiple births from 51 to 36% (Alexander et al. 1980).

McLaughlin (1970) compared the survival of new born lambs in south-western Victoria, Australia, in 3 lambing systems: a) exposed paddocks; b) paddocks surrounded by Cyprus (*Cupressus macrocarpa*) hedges 5.8 m high; and c) individual pen lambing in a shed. In the first year, the two last systems increased the survival of single and twin lambs in the period between birth and 48 hours of age. In the second year, the third system increased the survival of single lambs, but no other differences were significant. They concluded that the second system offers an alternative to individual pen lambing as method of improving lamb survival.

The value of tree windbreaks for reducing lamb mortality on sheep properties in south-eastern Australia has been discussed by Ive (1986). He used 22 years of daily meteorological data from Ginninderra Experiment Station (New South Wales) to calculate the relationship between lamb mortality and wind velocity, and found that major reduction in lamb mortality does not occur until wind velocity is reduced to near zero. Ive concluded that tree windbreaks (which cannot be expected to reduce wind velocity to near zero, at least for any substantial distance from the windbreak) should be seen as only one farming practice in a management program to reduce lamb mortality.

Indirect effect of shelter on livestock

In environments where water stress prevails some evidence suggests that pasture can grow earlier in the understorey of trees due to better moisture conditions. Furthermore pasture growth can continue considerably longer into the dry season, owing mainly to a suitable moisture regime being maintained for longer (Robinson 1982). The effect of shelter on the productivity of grasslands, was reviewed by Marshall (1967).

The effect of artificial windbreaks (sheet iron fences) on behaviour and production of sheep in adjoining paddocks was studied by Lynch and Marshall (1969). They compared body weight after a 21- month drought period with a 23-month non-drought period at three stocking rates (15, 30 and 38 ewes per hectare in a *Phalaris tuberosa*/*Trifolium repens* pasture) at Armidale, Australia. During the drought period, sheep body weight increased more in the sheltered than unsheltered paddocks, ranging from 7% to 22% at the low and medium stocking rates. Pasture productivity in the sheltered paddocks was about double that of the unsheltered ones at all stocking rates. Increases in body weight during the rainy period was approximately 20%, but only for the medium and high stocking rates. Sheep at the lowest stocking rate had abundant feed in the wet period in both the sheltered and unsheltered paddocks, and little difference in sheep live weight between these treatments was found.

They concluded that variation in animal productivity was largely due to differences in pasture availability rather than to the direct effect of shelter because: a) the sheep were in full wool through mid-winter and were consequently well insulated against cold; b) the threshold wind speeds above which most sheep move to shelter are encountered infrequently at Armidale and consequently the opportunity to benefit from shelter in windy weather was slight; and c) the shading effect of the fences from direct sun is minimal in mid-summer at the latitude of Armidale. According to the authors, moisture conserved by the shelter was probably the main factor to which the pasture responded in the experiment, a conclusion which is supported by the fact that the sheltered pasture invariably remained green for longer than the unsheltered pasture with the onset of dry spells.

Wind may also affect pasture growth directly. In experiments where *Festuca arundinacea* and *Lolium perenne* grasses were exposed to constant windspeeds of 1.1, 4.0, 7.4

and 10.0 m s^{-1} in a wind tunnel for 14 days, Russel and Grac (1978a; 1978b) found that increasing windspeed reduced rate of leaf extension, relative growth rate and leaf area ratio. They concluded that mechanical stimulus itself may have caused the reduction in leaf growth rates since no water stress and no change in rate of photosynthesis were observed.

It has been shown that shading may have an adverse effect upon both growth and chemical composition of pasture species, at least under temperate conditions. However the known negative effect of temperature upon quality of forage grasses (Deinum 1966) may lead to a beneficial effect of shading under tropical conditions (Norman and Ernest 1986).

Conclusion

Weather and climate are environmental factors affecting domestic animals both directly and indirectly. Any improvement in animal health and production necessitates managerial measures to alleviate adverse climatic effects. There appears to be a great scope for agroforestry to counter these climatic disturbances on livestock production by providing shelter to the animals and creating favourable microclimates for an increase in pasture production (shade, windbreaks, trees in pasture, shelterbelts).

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Impacts of sheep grazing on soil properties and growth of rubber (Hevea brasiliensis)

N.M. Majid, K. Awang and K. Jusoff

Faculty of Forestry, Universiti Pertanian Malaysia
43400 Serdang, Selangor, Malaysia

Abstract

*The agrometeorologic importance of sheep grazing is receiving increased attention in rubber plantations in Malaysia. Measurements of soil physical and chemical properties, foliar and tree girth of rubber (*Hevea brasiliensis*) in a Rubber Industry Smallholders Development Authority (RISDA) mini-estate at Bukit Mahang, Ketereh in Kelantan showed 15 months of grazing did not cause soil compaction enough to restrict water movement through the soil profile especially during intense rainstorms. All measurements of soil physical properties, namely soil moisture content, particle density, bulk density, total pore space, macropores, micropores, saturated hydraulic conductivity, soil temperature, particle-size distribution, loss on ignition and resistance to root penetration indicated an aggradation at the soil surface (0-10 cm depth) due to grazing. Except for K, soil nutrients — namely total N, P, Ca and Mg levels — and soil pH under analysis showed that N, P, Ca, Mg and Na increased with grazing. Potassium, however, decreased with grazing. Trees under grazing have higher girth increment than ungrazed area. The quantification and understanding of these parameters will allow proper agroforestry management practices to be adopted.*

Introduction

Integration of livestock under plantations is not a new form of husbandry. It is an old farming practice and has been carried out by many farmers in Asia and other parts of the world. What is perhaps new is the realization that the integration of livestock and crop can improve productivity per unit area of land. With the present rapid population growth, the allocation of land for agriculture and forestry does not appear to be able to meet the increasing demand for arable land. Thus, increasing productivity per unit area of land is very vital.

In Malaysia, the integration of livestock under plantation crops such as rubber (Wan Mohamed and Abraham 1976; Wan Mohamed 1977; Lee, Ng and Goh 1978; and Rubber Research Institute Malaysia 1980), coconut (Selvadurai 1967), and oil palm (Chen et al. 1978) has been shown to be technically feasible and financially profitable. It has been found that such practice provides extra income to the farmers as well as providing effective biological control of weeds. With the introduction of sheep under rubber, the overall cost of weeding can be reduced by 15 to 25% compared to chemical control

(Tajuddin 1984; and Rubber Research Institute Malaysia 1985). Apart from the biological and economic advantages, it is believed that the droppings of sheep can improve soil fertility. According to Tajuddin (1984), an adult sheep can produce every day about 186 g (dry matter basis) of manure containing 2.4% N, 0.5% P, 2.9% K, 1.8% Ca, 0.5% Mg, and 507 ppm Na. This amount of manure added to the soil will significantly increase the supply of nutrients for tree growth.

A number of workers have also reported that grazing animals can cause changes in the chemical and physical properties of soil. According to Vitosh, Davis and Kaczek (1973), and Wallingford et al. (1975), soil chemical properties, particularly organic matter, soil nitrogen and exchangeable cations increase when manure is applied. Besides providing plant nutrients, manure also improves the physical properties of soil. These include increased aggregate stability of soils, water infiltration and water-holding capacity (Mathers and Stewart 1980; Hall, Hedrick and Keniston 1959; Hedrick and Keniston 1966).

There is some evidence that the introduction of livestock in tree-crop areas may improve the yield of the crop. A study made by Fernandez (1970) showed that grazing cattle on pasture under coconuts improved yield from 5,780 to 110,180 nuts per ha over a four-year period. A similar finding was also reported by Nitis and Rika (1978) and Thomas (1978). Other studies also showed that poultry (Wan Mohamed and Kuan 1976; Wan Mohamed and Abraham 1976) and sheep grazing (Tajuddin 1984) under rubber plantation improves growth of rubber trees. Likely reasons for the increase in yield of tree crops were the reduction in weed competition and increased soil nutrient content originating from animal droppings.

Although the benefits of animal manure and grazing on crop yields have been well-documented, animal-crop integration may also cause problems. Steinbrenner (1951) and Adams (1975) reported that livestock trampling drastically reduced soil infiltration rate, pore space, aeration, seepage, microfaunal activity as well as causing damage to the tree roots from poaching and decreased organic matter content. Gerald and Hawkins (1978) reviewed the hydrologic impact of grazing on infiltration. They reported that grazing effects on runoff, erosion, on-site water use, and consequent downstream impacts are especially obvious and of great concern. As these processes are affected by grazing, so are nutrient cycles, soil moisture patterns, erosion and sediment yields, downstream water quality, and productivity. Investigations by Leaf (1958) in southern Wisconsin showed that the weight and nutrient content of the litter were much lower in grazed stands and that soils in grazed stands were more acid and lower in organic matter, exchangeable K, Ca, and Mg. On the other hand, Lund, Doss and Lowry (1975) and Elliot and Stevenson (1977) reported that surface application of manure can pollute streams by contaminating runoff water. Heavy application of manure may produce forage with excessive nitrate levels or equivalent ratios of K/(Ca + Mg) that are detrimental to animal health. Excessive loading will often cause nitrate contamination of the ground water or excessive salt accumulation in the soil.

There is little evidence in Malaysia that sheep grazing under rubber plantations is a problem. Moreover, little information has been reported concerning the impacts of grazing on soil characteristics and growth of rubber trees. Such information is important for better management of the agricultural land resource..

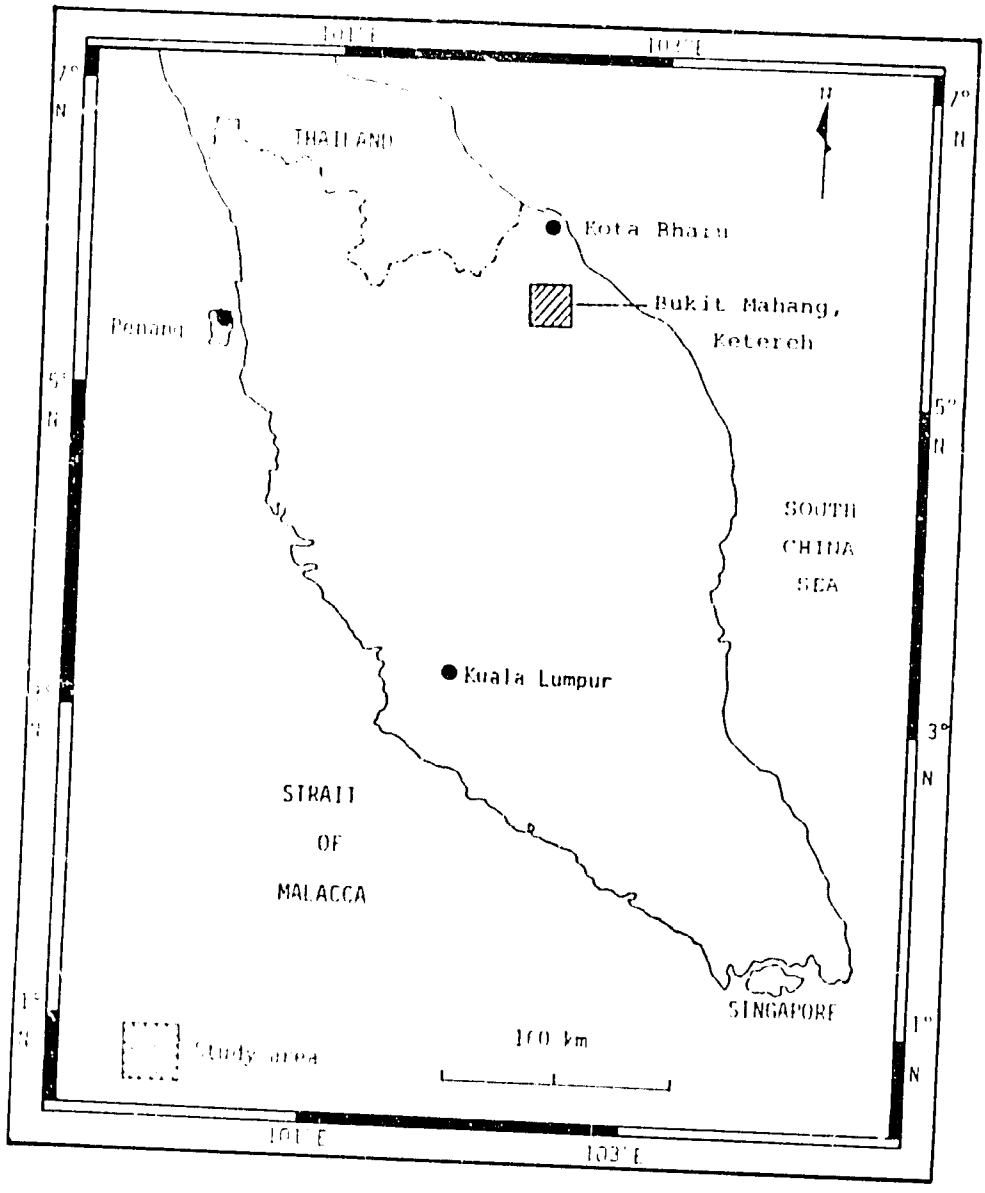
The objective of this paper is to examine the impacts of sheep grazing in a rubber plantation on the physical and chemical properties of the soil and the growth of the rubber trees.

Materials and methods

Description of the study area

The study was conducted in a RISDA estate at Bukit Mahang, Ketereh (latitude 5° 58′N, longitude 102° 16′ E) in the state of Kelantan, Malaysia (Figure 1).

Figure 1 A map of Peninsular Malaysia showing the study site.



Meteorology and Agroforestry

The area is characterized as having a tropical humid climate. Mean annual rainfall ranges from 3,048 to 3,302 mm. The wet season starts around November to January with the arrival of the north-east monsoon. The dry season lasts from February to August. Temperature is high and uniform. Mean annual temperature is 24 °C. The area has a mean annual relative humidity of about 96%. Soils of the study area have a loamy-sand texture.

Detailed characteristics and historical background of the study area are given in Table 1.

Table 1. General characteristics and historical background of the study area.

Characteristics	Data
Total area under plantation	80.5 ha
Total area under grazing	40.5 ha
Year of planting	1983
Planting distance	4m x 6m
Clone types	GT1, PR255, PR281
Month, Year sheep introduced	August, 1985
Number of sheep	556
Females	471
Males	85
Sheep	Dorset Horn
Stocking rate	13.7 sheep/ha
Daily grazing time	9:00 am - 5:00 pm
Pasture/grass species	*Ottochloa-nodusa, Paspallum-conjugatum, Mikania-cordata, Axonopus-compressus, Digtaria spp*
Month/year of basal fertilizer application	May, 1986
Rate of application	0.14 kg/tree
Type of fertilizer	RISDA 2

Source: Kamarul Aizan, Assistant RISDA Officer, Ketereh Station, Kelantan.

Experimental design

Two treatment plots (grazed and ungrazed) 50 m x 100 m in size were randomly established at the study site. Repeated observations were taken at several sites within the each plot.

Soil sampling

Soil sampling was done in November 1986. Soil from 0 to 10 cm depth was randomly sampled from the areas between the rows of the rubber trees, using ELE soil augurs. These disturbed samples were used to determine chemical properties.

For the determination of physical properties, 20 undisturbed soil cores were also randomly collected from each site at 0 to 10 cm depth with metal core rings 7.6 cm in diameter and 4 cm high. A depth of 10 cm was chosen because variability in soil properties was greater in the surface layer than in the lower zones (Gent, Ballard and Hassan 1983). Both ends of the cores were fitted with plastic covers to prevent loss of water by evaporation.

Field measurements and sampling

Soil temperature

Soil temperature was measured at a depth of 5 cm with soil probe thermometers. Readings were taken three times a day for one week at each site and the average for the day was recorded.

Resistance to penetration

A CL-700 Soil Test Inc. pocket penetrometer was used to measure resistance to root penetration on the grazed and ungrazed plot. The resistance to penetration test is commonly used to measure soil strength or root penetration resistance since soil engineering tests for shear strength, such as the triaxial and direct shear tests, have limited use due to the larger number of samples and tests required to obtain an adequate degree of precision in structured soils (Bradford 1980). Twenty replicated samples of each probe were taken in each of the treatment plots.

Tree growth

Tree girth at 0.5 cm height was used to measure growth on one hundred randomly-selected trees in each plot.

Foliar sampling

Leaf samples were collected as composite samples from three to five trees. For every selected tree, 20 leaves were randomly sampled. Twenty composite leaf samples were collected from each treatment plot.

Laboratory analysis

Soil chemical properties

The soil chemical properties determined were total N, P, K, Ca, Mg, Na and soil pH. Total N in the soils was determined by the micro-Kjeldahl method (Mackenzie and Wallace 1954); and available P by Deniege's method using a Spectronic 20 spectrophotometer. Exchangeable cations K, Ca, Mg, and Na were extracted with 50 ml ammonium acetate from a 10 g soil sample. Their concentrations were then determined with an atomic absorption spectrophotometer.

Soil physical properties

Soil physical properties determined were soil moisture content, particle density, bulk density, total pore space, macropores, micropores, loss on ignition and particle-size distribution. Moisture content was determined by the gravimetric method after oven-drying at 105 °C for 24 hours. Soil particle density was determined using a picnometer. Bulk density was calculated from oven-dry weight and measured volume of each core. Total pore space was calculated as: 100 x (1 - bulk density/particle density).

Large-pore space (macropores) equalled the volume of water drawn from the saturated cores at tensions up to 60 cm of water. Small-pore space (micropores) was cal-

culated as the difference between total porosity and large-pore space. Loss on ignition was determined using a high temperature kiln at 750 °C for two hours. Particle-size distribution of samples was determined by the pipette method.

Foliar analysis

The composite leaf samples were washed with distilled water and kept in paper envelopes before drying in a forced-draft oven at 65 °C for two days. The dry samples were then ground using a stainless Fritch pulverisette mill and then passed through a 1 mm sieve.

Ground leaf samples of 0.25 g were subjected to rapid wet digestion (Thomas, Sheard and Moyer 1967) using concentrated sulphuric acid and hydrogen peroxide in the ratio 5:3 for the analysis of N, P, K, Ca, Mg and Na. These elements were determined by procedures similar to those used for the soil samples.

Statistical analysis

There is no replication in this experiment. The repeated observations within each plot do not constitute true replications. However they do indicate the level of repeatability of observations within the two plots. As much standard deviations are indicated in each table. However they should not be used to test for statistically sigificant differences due to the applied treatments.

Table 2. Plot differences in physical properties of soil. [1]

Physical properties	Grazed			Ungrazed		
Soil moisture content	16.9	±	4.8	17.2	±	4.7
Particle density (g/cm-3)	2.48	±	0.17	2.68	±	0.29
Bulk density (g/cm-3)	1.59	±	0.12	1.57	±	0.22
Total pore space (%)	35.9	+	2.3	43.5	±	2.4
Macropores (%)	8.0	±	1.2	10.2	±	1.3
Micropores (%)	27.9	±	1.1	33.3	±	0.9
Mechanical analysis						
% sand	75.2			80.2		
% silt	11.9			10.1		
% clay	12.9			9.7		
Soil texture	Loamy sand			Loamy sand		
Soil temperature (oC)	25.8	±	0.7	25.4	±	0.6
Saturated hydraulic conductivity (cm/hr)	26.9	±	1.1	54.2	±	0.2
Resistance to penetration (kPa)	215.2	±	3.6	160.6	±	5.2
Loss on ignition (%)	2.27	±	0.16	3.12	±	0.21

[1]Data are mean of 20 observations within the plot
± 1 standard deviation from the mean

Results and discussion

Soil physical properties

Results are presented in Table 2. Total pore space, saturated hydraulic conductivity, resistance to penetration, and loss on ignition show large differences between the two plots, and these observations could be expected to be altered by grazing.

The weather at Bukit Mahang, Ketereh, in November 1986 was wetter than normal. It was raining heavily when soil sampling was carried out. Thus, high soil moisture contents were recorded in both grazed and ungrazed plots.

No difference in soil temperature was recorded between grazed and ungarzed plots. This may have been due to shading from the rubber trees.

Particle-size distribution was relatively uniform among samples collected from the same depth. The percentage of clay was slightly higher in the grazed plot. This may indicate that gully erosion had taken place in the bare areas under rubber. Both grazed and ungrazed plots have a loamy-sand texture which may be associated with poor structure, loose consistency, excessive drainage and thus with low water-retention (Donahue 1977).

Although particle-size distribution and particle density (or specific gravity) are usually unaffected by grazing per se as found in this study, they may be altered indirectly. Smith (1940) reported, for instance, that the proportion of clay in the surface soil increased as erosion progressed under intense grazing. Thus, similarity in texture and particle density between soils with and without sheep suggests that gully erosion was not accelerated sufficiently to affect particle size and density at the early stage of grazing.

Due to the beating action of intense rains with large drop-size during soil sampling, both plots were subjected to compaction. In comparison with no grazing, grazing increased bulk density by 1% in the surface layer (Table 2). This increase was very small compared to those reported in other studies, especially those in Nort America. For example in South Dakota, surface soils averaged 1.22 g/cm in shelterbelts frequented by livestock, but only 1.01 g/cm where livestock was excluded (Read 1957). Bulk density of A horizon soils in the Allegheny River watershed, averaged 0.92 g/cm for the ungrazed woodlands, as compared to 0.52 g/cm (Trimble, Hale and Potter 1951). Animal concentration was unspecified in both instances. On Oklahoma range, the 10-to-15 cm layer averaged 1.72 g/cm in ungrazed exclosures (Rhoades et al. 1964); differences were even greater at the 30-to-60 cm depth. Heavy grazing consisted of stocking throughout the year at one animal per 5 ha. They found that 20 years of light grazing increased bulk density of a loamy fine sand to the 7 cm depth.

Reduction in large pores of the surface soil layer on grazed land is readily understandable (due to animal treading) but reasons for responses of small-pore (micropore) space to grazing are less apparent. The increase in micropores under grazing, coupled with the sharp reduction in macropores, suggests a transformation of large pores into small pores. Van der Weert (1974); Dickerson (1976); Kamaruzaman and Muhamad (1986b); and Kamaruzaman, Muhamad and Desa (1986) reported that when forest soil is compacted following logging activities, total porosity is reduced at the expense of the large voids. Hence, the proportion of micropores increased because micropores were relatively less affected by compaction (Kamaruzaman Desa 1988; Kamaruzaman and Muhamad 1986a, 1986b).

Saturated hydraulic conductivity (a measure of infiltration) was reduced by grazing (Table 2). During a one- hour period, 26.9 cm of water entered the soils on the grazed plot as compared to 54.2 cm on the ungrazed. In their review, Gifford and Hawkins (1978) showed considerable evidence of reduction in infiltration caused by animal tram-

pling. A reduction in infiltration rate of grazed area may be due to the removal of vegetative cover crops from the soil and compaction upon grazing. Wilkinson and Ania (1976) reported a high rate of infiltration (25.4 cm/hr) into sandy soil (10% clay) under tropical forestfallow; and reduction of the rate of inflitration to 9.1 cm/hr after two consecutive years of maize cropping. Infiltration rate was reduced in this case because of the compaction effect by the maize roots.

Grazed soil showed an increase in resistance to penetration (a measure of soil strength or bearing capacity) compared to ungrazed soil. The increase in soil strength that occurs as a result of grazing indicates that the soil is compacted by sheep trampling due to the large hoof pressure of sheep when walking with two to three hooves on the ground which could raise the hoof pressure to about 220 kPa. Another factor is that the hoof (estimated to have a pressure of 83 kPa) is not necessarily placed flat on the soil surface, again tending to increase the applied pressure. For comparison, the value obtained with a forestry tractor is 30 to 150 kPa (Sohne 1958).

Table 3. Plot differences in soil chemical properties.[1]

Chemical properties	Grazed			Ungrazed		
Soil pH	4.3	±	0.7	4.1	±	0.4
N (%)	0.19	±	0.01	0.14	±	0.02
P (ppm)	46.4	±	1.2	15.0	±	1.9
K (ppm)	21.9	±	0.1	28.7	±	0.7
Ca (ppm)	10.0	±	0.4	6.9	±	0.3
Mg (ppm)	6.9	±	2.1	4.3	±	0.5
Na (ppm)	37.6	±	2.5	15.0	±	3.5

[1] Data are mean of 20 observations within the plot
± 1 standard deviation from the mean.

Root growth may be inhibited as soil strength increases. There are many laboratory studies showing this effect; see for example, Gradwell (1968). Significant reduction in root growth could take place as penetration resistance increases by between 20% and 30% for the grazed plot as compared with the ungrazed plot. However, in this study, resistance to penetration increased by 26% but showed no pronounced effect on growth of rubber trees in the grazed plot, the reason being the abundance of sheep manure which provided fertilizer.

Soil chemical properties

The mean values of the chemical analyses are shown in Table 3.

On the average, total N and available P were higher in the grazed plot. The increase in total N was probably due to the increased output of organic matter from the sheep manure. In the case of available P, the increase could be attributed to the organic part of the manure retarding P fixation by mechanically separating soluble P from the mineral part of the soil.

The higher level of the exchangeable cations (Ca, Mg and Na) in the grazed plot compared to the non-graze plot was most likeley due to the added manure and its sub-

Table 4. Plot differences in some foliar nutrients and girth difference.

Nutrient element [1]	Grazed			Ungrazed		
N (%)	1.64	±	0.06	1.18	±	0.14
P (ppm)	375.46	±	6.26	313.45	±	0.74
K (ppm)	0.14	±	0.01	0.16	±	0.01
Ca (ppm)	0.32	±	0.02	0.24	±	0.01
Mg (ppm)	0.25	±	0.02	0.21	±	0.01
Na (ppm)	168.58	±	5.49	143.33	±	0.88
Tree girth increment (cm)[2]	6.20	±	1.71	5.56	±	1.25

[1] Data are mean of 20 observations within the plot ± 1 standard deviation from the mean.

[2] Data are mean of 100 observations within the plot ± 1 standard deviation from the mean.

sequent decomposition. The decrease in K of the grazed soil may be due to the rduction in the water-soluble K which caused excessive salinity as a result of the addition of sheep manure. It is also likely that the highly mobile K is lost by leaching, especially in the loamy sand, since heavy rain showers were experienced during the taking of soil samples.

Foliar nutrient content and tree girth

Except for K, the other foliar minerals analysed showed an increase in the grazed compared to ungrazed plot (Table 4).

The increase in P, Ca and Mg uptake is, however, small compared to N and Na under grazing. The variability of nutrient availability for uptake by the rubber trees under grazing may be due to the variation in the amount of sheep manure in the soil and leaching losses. Potassium is less available for tree uptake in the grazed area because of the lower amount of K as explained above.

The tendency for higher nutrient uptake by the rubber trees in the grazed plot is evident from their larger girth increment (Table 4). Apart from the addition of organic matter deposited by the sheep, suppression of weeds by grazing led to lesser competition for nutrients and water.

Conclusions

The data suggest that 15 months of grazing slightly compacted soils under rubber as a result of trampling or treading. Nevertheless, sheep grazing improved soil fertility through the addition of nutrients to the soil. Grazing also reduced weed competition for soil and nutrients. This resulted in increased nutrient uptake by the rubber trees, thereby enhancing their growth.

Future research should be directed towards the study of the relationships between latex production, stocking rate and intensity, change in pasture composition, and time of grazing with the presence of sheep under rubber plantations.

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SECTION 7

Windbreaks

- Les effects aerodynamiques et microclimatiques des brise vent et des amenagements regionaux, — G. Guyot
- Crop prodection from very strong winds: recommendations in a Costa Rican agroforestry case study, — C.J. Stigter, T. Darnhofer, S.H. Herrera
- Wind profil and soil water availability near a Caatinga shelterbelt, — P.C.E. Frota, A.D. Ramos, E. Carrari

Les effets aérodynamiques et microclimatiques des brise-vent et des aménagements régionaux *

G. Guyot

INRA - Station de Bioclimatologie
B.P. 91 Domaine St Paul - 84140 Montfavet

Abstract

By reducing wind speeds, windbreaks modify energy exchanges near the ground surface and thus the different microclimatic factors.

The influence of windbreaks has to be considered at two different scales: the local shelter zone of each hedge and the regional effects in the case of a network of hedges.

This paper summarises aerodynamic and microclimatic effects of windbreaks. The action of windbreaks is analysed in the light of current theoretical and experimental knowledge.

Résumé

Les brise-vent en réduisant la vitesse du vent modifient également l'ensemble des échanges énergétiques au voisinage de la surface du sol et ainsi les différents facteurs du microclimat.

L'action des brise-vent doit être considérée à deux échelles différentes: celle de la parcelle et également celle de la région où un réseau de protection peut avoir un effet spécifique.

Cet exposé résume les différents effets aérodynamiques et microclimatiques des brise-vent. Les différents mécanismes d'action des brise-vent sont analysés et expliqués à l'aide d'une synthèse des connaissances théoriques et expérimentales actuelles.

Les effets aérodynamiques des brise-vent isolés

Le rôle des caractéristiques géométriques des brise-vent

Les effets aérodynamiques d'un brise-vent dépendent tout d'abord de ses caractéristiques géométriques (hauteur, longueur, porosité, forme de sa section transversale).

La hauteur est un facteur important et pour des brise-vent de même forme et même posorité, la longueur de la zone qu'ils protègent est proportionnelle à leur hauteur. Aussi prend on généralement comme unité de mesure des distances et des hauteurs la hauteur H du brise-vent, ce qui facilite les comparaisons.

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* The essential parts of this paper have been presented at an international seminar on shelterbelts, held in Tunis, Tunisia from 31 October to 3 November 1983 and are included in the IDRC Report MR 117 published 1985.

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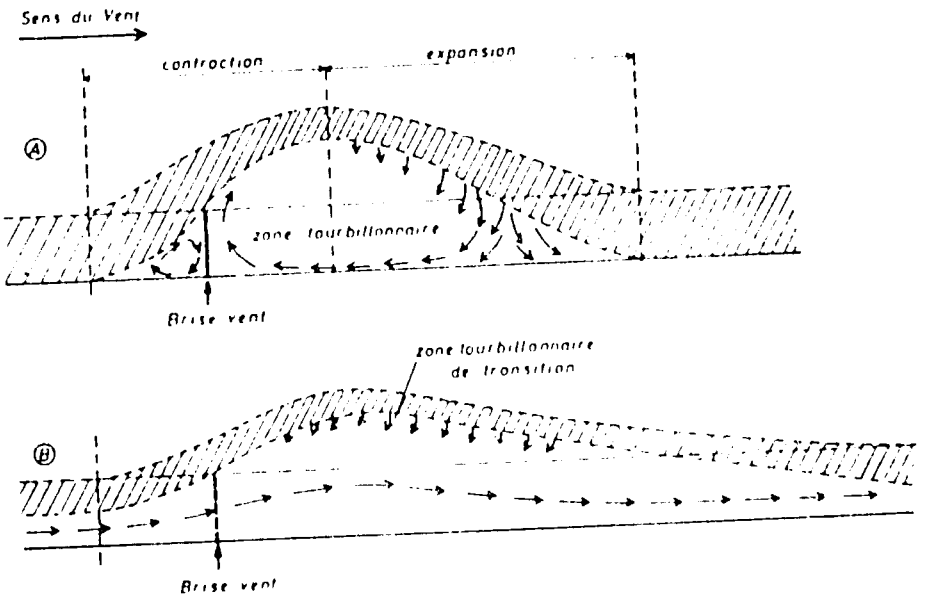
Le rôle de la porosité des brise-vent

Un autre facteur important est la porosité du brise-vent, et schématiquement on peut distinguer deux types de brise-vent: les brise-vent perméables et les brise-vent imperméables.

La figure 1 représente les effets de ces deux types de brise-vent sur l'écoulement de l'air. La partie supérieure (fig. 1A) correspond au cas d'un brise-vent imperméable (mur ou rideaux d'arbres très denses). L'air est totalement dévié vers le haut et il se crée un vaste tourbillon à l'aval du brise-vent. Aussi, on observe au voisinage du sol un vent de sens opposé à celui du vent incident. L'air qui est passé par dessus le brise-vent se rabat vers le sol à une distance voisine de 5 à 6 fois la hauteur (5 à 6 H). Dans cette zone, au voisinage du sol, le vent va tantôt dans un sens, tantôt dans l'autre et il peut alors occasionner des dégâts sur la végétation (chutes de fruits en particulier).

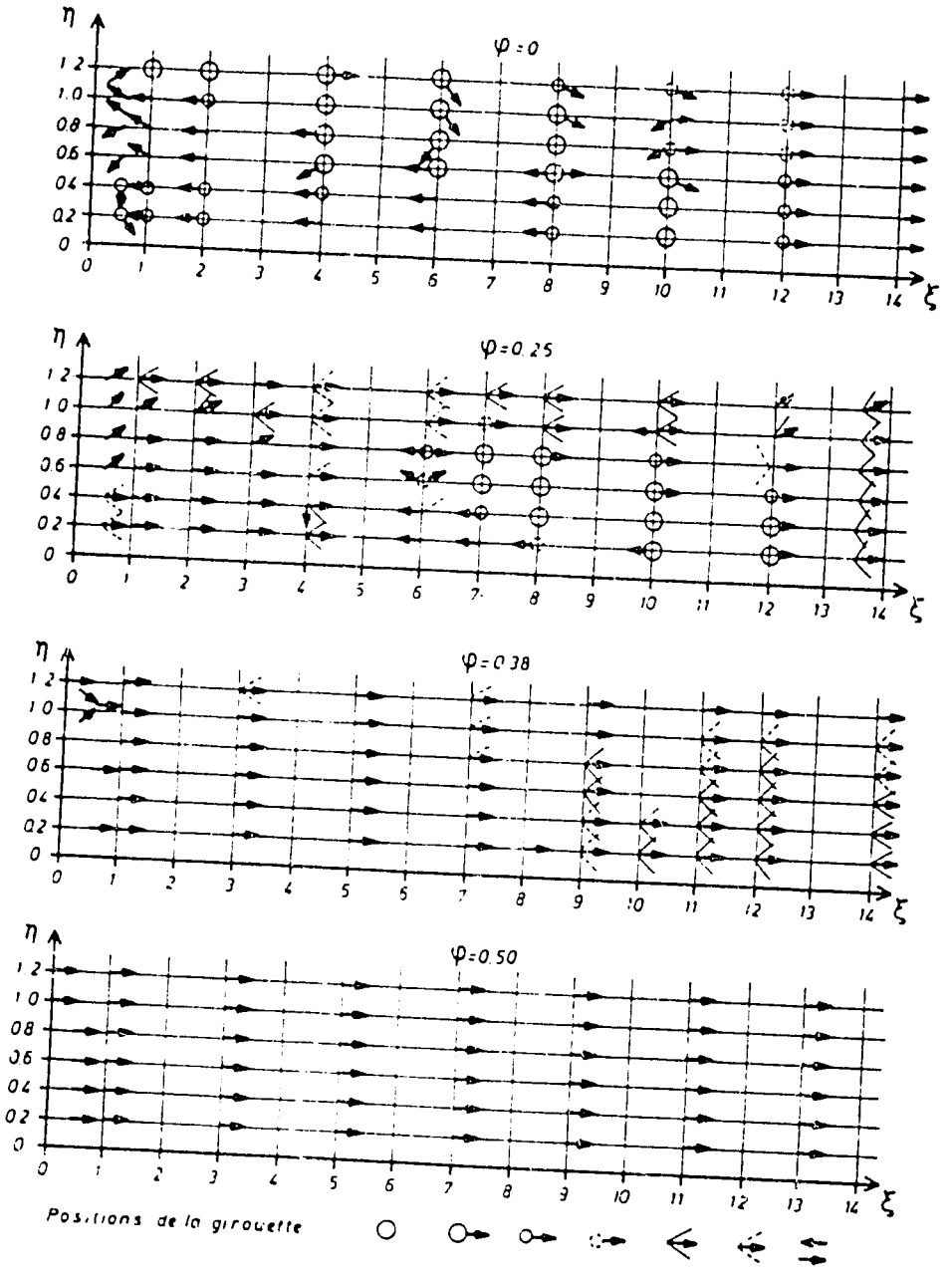
Lorsque le brise-vent est perméable (fig. 1B), une partie de l'air incident passe à travers et empêche la formation de tourbillons. La vitesse du vent est moins réduite que dans le cas d'un brise-vent imperméable mais la réduction du vent se fait sentir sur une distance plus grande.

Figure 1 Représentation schématique de l'effet d'un brise-vent sur l'écoulement de l'air - (A) Brise-vent imperméable (B) Brise-vent perméable.



La figure 2 due à Baltaxe (1967) est une illustration des phénomènes qui viennent d'être décrits. Elle représente les résultats de mesures effectuées en soufflerie. L'écoulement de l'air à l'aval de brise-vent de différentes porosités est exploré à l'aide d'une petite girouette à axe horizontal. La figure 2 montre bien l'existence à l'aval d'un brise-vent imperméable d'un vaste mouvement tourbillonnaire qui s'éloigne et disparaît

Figure 2 Représentation schématique des différentes positions prises par une girouette dont l'axe est horizontal et qui est utilisée pour explorer la zone 'sous le vent' de brise-vent de porosités Φ différentes en soufflerie.



lorsque la posorité augmente. Elle met également en évidence l'existence d'une intense turbulence dans le sillage des brise-vent imperméables ou peu perméables qui disparaît lorsque la porosité augmente.

Ces résultats expérimentaux montrent ainsi l'existence de 2 types d'écoulements à l'aval d'un brise-vent: un écoulement de type 'obstacle imperméable' qui se manifeste lorsque la porosité est inférieure à 25% et un écoulement de type 'obstacle perméable' lorsque la porosité est supérieure à 25%.

Les symboles utilisés pour représenter les positions de la girouette sont regroupés au bas de la figure et correspondent de gauche à droite au passage d'un tourbillon sans orientation privilégiée à un courant stable en direction (d'après Baltaxe 1967).

Les figures 3 et 4 représentent l'évolution de la vitesse réduite du vent: $\hat{u}(\xi,\eta)$ en fonction de la distance au brise-vent,

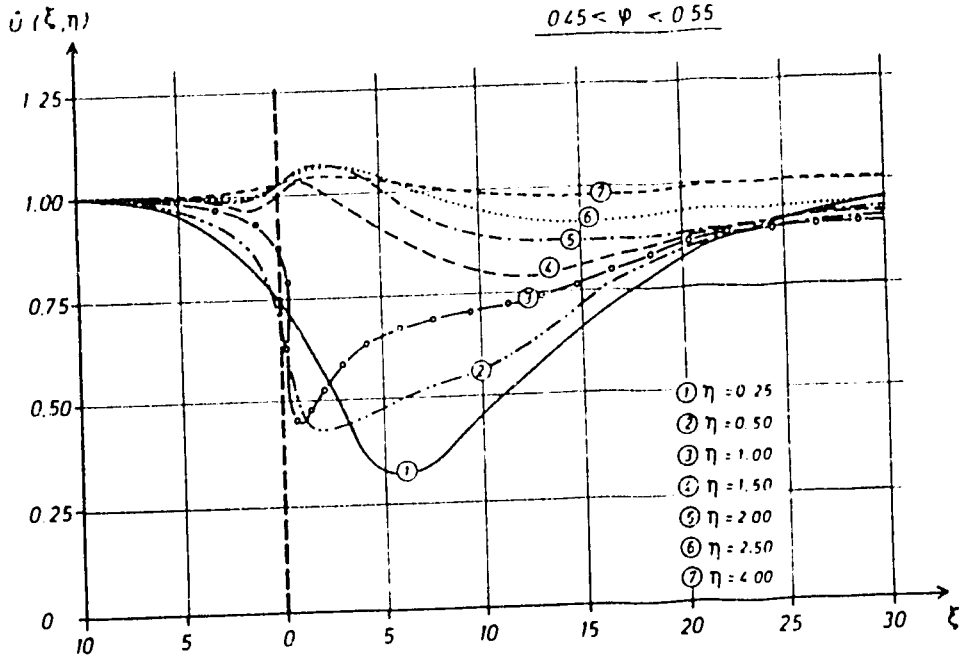
$$u(\xi,\eta) = \frac{u(\xi,\eta)}{u_0(\eta)}$$

avec $u(\xi,\eta)$ vitesse moyenne du vent au niveau $\eta = Z/H$ et à la distance $\xi = x/H$ et $u_0(\eta)$ vitesse moyenne du vent au niveau $\eta = Z/H$ (H : hauteur du brise-vent).

Les différentes courbes tracées correspondent à des mesures effectuées à différents niveaux $\eta = Z/H$ au-dessus du sol.

Les figures 3 et 4 qui sont tracées pour un brise-vent perméable ($0,45 < \Phi < 0,55$) et un brise-vent peu perméable ($0,15 < \Phi < 0,20$) mettent bien en évidence l'existence

Figure 3 Influence d'un brise-vent perméable de 2,2 m de haut, constitué par une claie de roseaux, sur la vitesse réduite du vent à différents niveaux (d'après Naegeli, 1953)



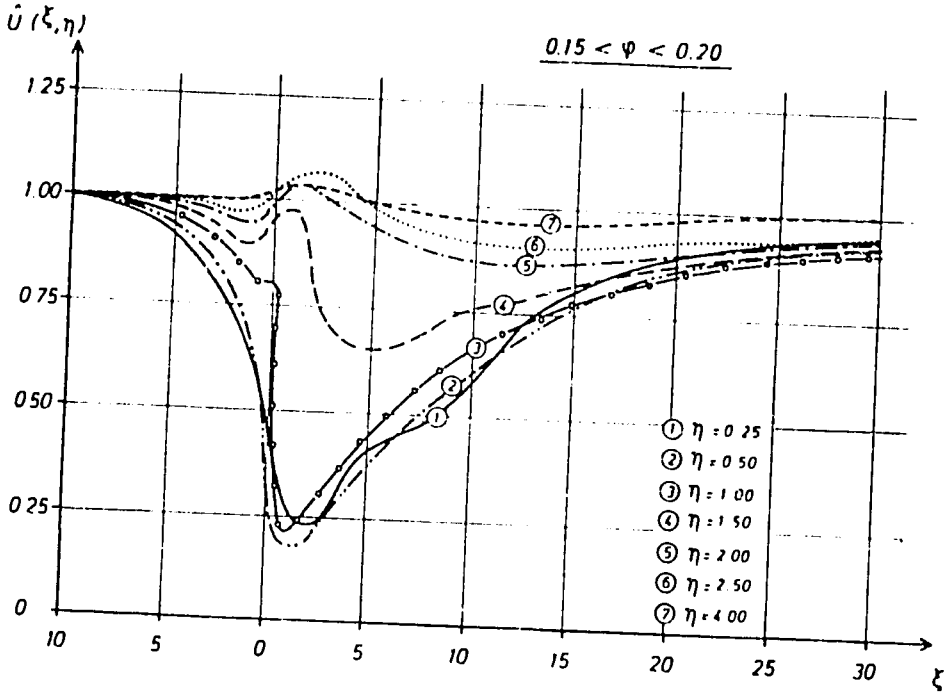
d'une survitesse au voisinage du sommet du brise-vent ($\xi = 0, \eta > 1$). Elle est beaucoup plus marquée pour le brise-vent peu perméable que pour le brise-vent perméable.

A l'aval du brise-vent et pour des hauteurs inférieures à la propre hauteur du brise-vent ($\eta < 1$) les courbes représentatives de $\hat{u}(\xi, \eta)$ ont toutes la même allure. Elles passent toutes par un minimum dont la position semble varier en fonction de la porosité et de l'altitude. Après ce minimum, la vitesse du vent croît progressivement et $\hat{u}(\xi, \eta)$ tend vers 1 (c'est-à-dire vers la vitesse mesurée en témoin). La pente de la courbe de reprise de la vitesse est d'autant plus grande que la porosité est plus faible.

Ces quelques résultats expérimentaux laissent penser à l'existence d'une valeur optimale de la porosité pour laquelle la combinaison de la réduction du vent et de l'extension de la zone protégée a une valeur maximale. De nombreux travaux expérimentaux ont monté que cette porosité optimale était de l'ordre de 40% pour un brise-vent sans épaisseur. Pour un brise-vent constitué par un rideau d'arbres, le problème est plus complexe car il faut tenir compte à la fois de la porosité de la surface du brise-vent et de la tortuosité du parcours du vent.

L'extension de la zone protégée par les brise-vent est très variable. Elle dépend, comme nous le verrons, de nombreux facteurs. Mais pour fixer les idées, nous pouvons dire que dans une zone dégagée la longueur moyenne de la zone protégée par un brise-vent perméable est de l'ordre de 20 fois sa hauteur et pour un brise-vent imperméable elle est de 12 fois sa hauteur.

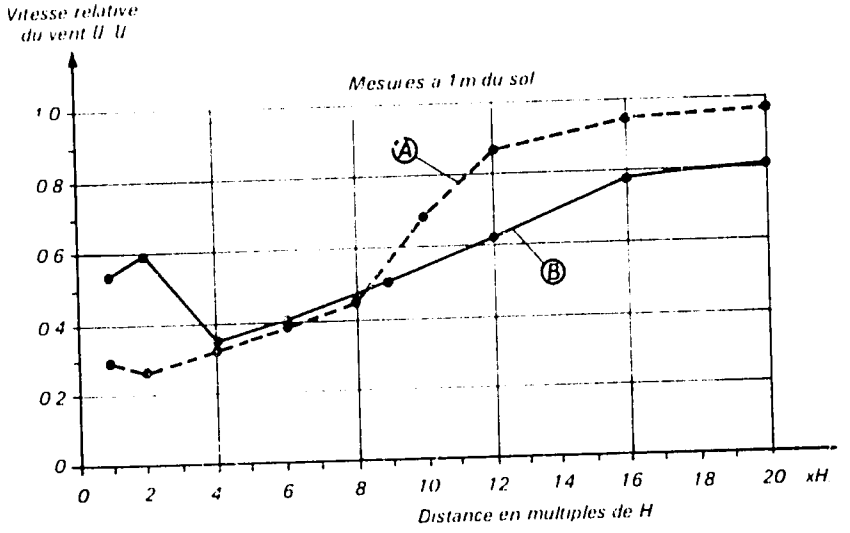
Figure 4 Influence d'un brise-vent peu perméable de 2,2 m de haut, constitué par une claie de roseaux, sur la vitesse réduite du vent à différents niveaux (d'après Naegeli, 1953)



Le rôle de la structure des brise-vent

Dans les prise-vent constitués par des rideaux d'arbres, la porosité peut varier en fonction de l'altidude. Ils peuvent avoir soit une base imperméable par des buissons ou des arbustres, soit, au contraire, une base très perméable et une partie supérieure peu perméable. La figure 5 donne des résultats d'une expérience destinée à montrer l'influence de la variation de la prorosité en fonction de l'altitude. L'essai a été effectué avec un brise-vent artificiel de 2 m de haut constitué par 3 bandes parallèles de 67 cm de haut. Dans un premier cas, on a placé une bande imperméable à la base du brise-vent, une bande peu perméable au milieu et une bande très perméable en haut. Dans un deuxième cas, les positions des bandes placées à la base et au sommet du brise-vent ont été inversées. La figure 5 montre que la position de la bande imperméable a des répercussions importantes sur la réduction du vent. Le brise-vent dont la base est imperméable se comporte pratiquement comme un brise-vent totalement imperméable alors que le brise-vent dont la base est perméable se comporte comme un brise-vent perméable sur toute sa hauteur.

Figure 5 Evolution de la vitesse du vent exprimée en fonction de la vitesse mesurée en témoin à l'aval de 2 brise-vent constitués par 3 bandes superposées: (A) Bande imperméable en bas - (B) Bande imperméable en haut.



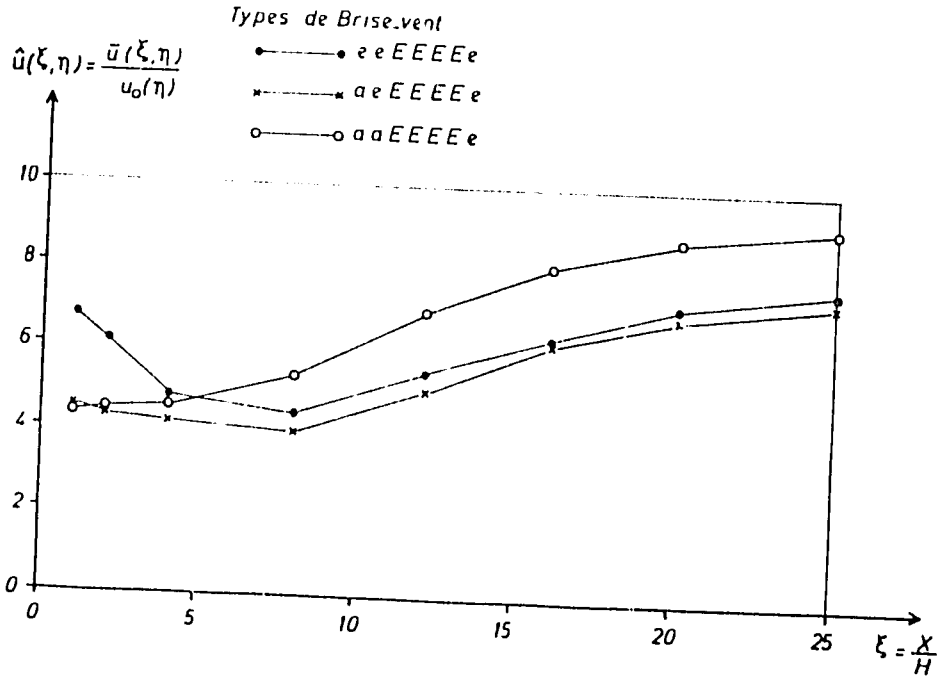
Cette expérience montre donc que la porosité de la base d'un brise-vent joue un rôle très important. Il est nécessaire pour qu'un brise-vent soit efficace que sa base soit perméable. On peut également améliorer l'efficacité d'un brise-vent trop imperméable en élagant sa base.

Une expérience effectuée en Tunisie centrale dans la région d'Hadjeb el Aioun (Charfi 1980) vient également à l'appui de cette thèse. En effet, parmi les différents brise-vent testés, existaient 3 brise-vent composés de 7 rangées d'arbres. Le premier comportait 4 rangées d'eucalyptus de grande taille (E) encadrés par des eucalyptus de petite taille (e) : 2 rangées du côté au vent et une du côté sous le vent (e e E E E E

e). Pour le second, la première rangée d'acacias buissonnants (a) (a e E E E E e) et pour le troisième, les deux rangées d'eucalyptus du côté au vent étaient remplacées par deux rangées d'acacias buissonnants. Comme ces brise-vent sont installés dans une région très sèche (300 mm de pluie par an) le développement des arbres est limité et bien que les brise-vent aient une épaisseur de 22 m, ils sont relativement perméables.

Le brise-vent constitué uniquement par des eucalyptus a la base très ouverte. Le remplacement des eucalyptus de petite taille par une ou deux rangées d'acacias réduit la porosité de la base. La figure 6 représente les résultats expérimentaux qui ont été obtenus. Elle montre que le remplacement d'une rangée d'eucalyptus par une rangée d'acacias a amélioré l'efficacité du brise-vent constitué uniquement d'eucalyptus et dont la base était trop perméable. Par contre la deuxième rangée d'acacias ferme trop la base du brise-vent et il devient nettement moins efficace.

Figure 6 Evolution de la vitesse réduite du vent à l'aval de brise-vent de 22 m de large comportant au centre 4 rangées d'eucalyptus de grande taille E, espacement 4 x 4, bordées par des eucalyptus de petite taille (e) ou des acacias buissonnants (a) (espacement 2 x 2 m), à Hadjeb el Aioun en Tunisie centrale (d'après Charfi 1980).



Influence des caractéristiques du vent

Influence de la vitesse du vent

De nombreuses expériences ont montré que les courbes représentant l'évolution de la vitesse réduite du vent $\hat{u}(\xi, \eta)$ étaient indépendantes de la vitesse du vent en témoin. Il est ainsi possible de comparer les effets d'un même brise-vent obtenus avec des

vitesses de vent différentes à condition d'utiliser pour cette comparaison les vitesses réduites.

$$\hat{u}(\xi,\eta) = \frac{u(\xi,\eta)}{u_0(\eta)}$$

Cependant, lorsque les mesures sont effectuées non pas sur des brise-vent inertes, à géométrie bien définie, mais avec des brise-vent vivants, on constate alors que la réduction du vent dépend de sa vitesse. Ainsi, pour les brise-vent de feuillus, les feuilles ont tendance à se placer parallèlement à l'écoulement. La porosité augmente alors avec la vitesse du vent et la réduction du vent diminue. Par contre, pour les brise-vent constitués par des conifères, les branches ont tendance à se plaquer les unes contre les autres lorsque la vitesse du vent augmente, la porosité diminue alors et la réduction du vent est plus forte.

Influence de la stabilité de l'atmosphère

Au cours de la journée, la surface du sol absorbe le rayonnement solaire et échauffe l'air à son voisinage. Ainsi, l'air chaud et léger, donc instable, se trouve au voisinage du sol. Comme le montre la figure 1, les brise-vent ont pour effet de soulever une partie de l'écoulement; ainsi an cours de journées très chaudes, un brise-vent va faciliter l'ascension de l'air. Une partie plus importante de l'écoulement contournera donc le brise-vent et tout se passera comme si sa porosité avait diminué (réduction du vent plus intense mais sur une distance plus courte). Au cours de la nuit, la surface du sol se refroidit par rayonnement et elle refroidit l'air qui se trouve à son contact. Ainsi, l'air froid et stable se trouve au voisinage du sol. Une partie plus importante de l'écoulement passera alors à travers le brise-vent et on observera un freinage plus intense du vent et sur des distances plus grandes que durant la journée.

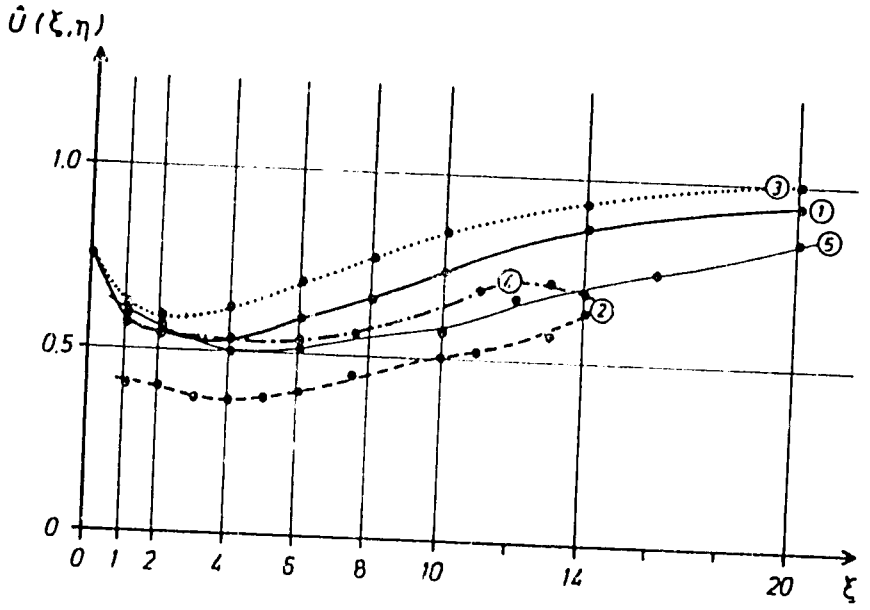
Influence de la turbulence du vent (Guyot 1972)

La figure 7 représente les résultats de mesures effectuées avec des brise-vent artificiels constitués par des grilles en matière plastique, implantés dans des lieux différents. Les mêmes grilles ont été installées sur un plateau bien dégagé dans la région parisienne (La Minière) et dans la basse vallée du Rhône près d'Avignon (Montfavet). La figure 7 montre que des brise-vent identiques peuvent avoir des effets nettement différents. Les mesures ont pourtant été effectuées avec des vitesses moyennes de vent voisines, sur un sol nu assez lisse et en période hivernale pour éviter d'avoir des effets dûs à l'instabilité de l'air. La seule différence entre ces deux expériences est la turbulence du vent. Dans la région parisienne, les mesures ont été effectuées avec un vent régulier peu turbulent alors que dans la basse vallée du Rhône, le vent soufflait en rafales et était très turbulent. Très schématiquement, le taux de turbulence du vent représente la proportion de tourbillons dans l'écoulement. L'extension de la zone protégée par un brise-vent, dans laquelle la vitesse du vent est réduite, est fonction du mélange qui s'effectue entre l'air à vitesse ralentie au voisinage du sol et l'air qui passe au-dessus.

Ce mélange s'effectue par l'intermédiaire des tourbillons qui se trouvent dans l'écoulement du vent. Plus les tourbillons seront nombreux, plus le mélange sera facilité et plus la zone protégée par le brise-vent sera réduite. Le nombre de tourbillons dépend de la densité des obstacles que le vent a rencontrés sur son parcours. Dans les zones de plaines dégagées, la longueur protégée par un brise-vent sera maximale alors que

Figure 7 Variation de $\hat{u}$ (ξ , η) au niveau η = 0,50 en fonction du type de grille et de son lieu d'implantation:

1 - Grille n° 2 Montfavet
2 - Grille n° 2 La MinièrE
3 - Grille n° 1 Montfavet
4 - Grille n° 1 La Minière
5 - Grille n° 5 La Minière



dans une région où existent déjà des brise-vent ou des accidents topographiques, l'extension de la zone protégée par un brise-vent sera réduite.

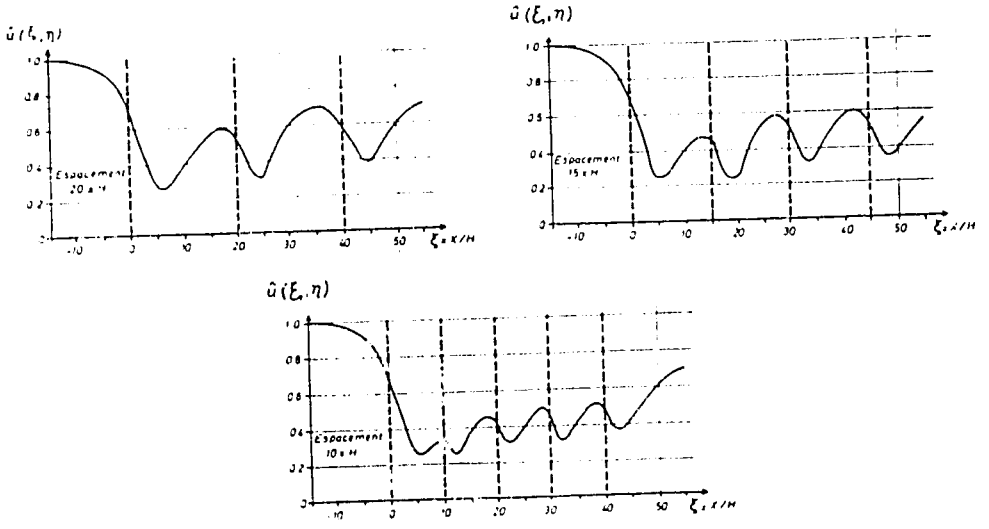
Espacement des brise-vent successifs

La figure 8 (Naegeli, 1965) montre la réduction de la vitesse du vent par des brise-vent successifs dont l'espacement est progressivement réduit. Elle met également bien en évidence le phénomène cité plus haut: la diminution de l'efficacité d'un brise-vent lorsqu'il est précédé par d'autres brise-vent.

Sur la figure 8, nous voyons également que le passage d'un espacement entre les brise-vent de 20 à 15 H (réduction de l'espacement de 25%) se traduit par une réduction supplémentaire de la vitesse du vent de 14% (passage de la vitesse moyenne de 51 à 44% de celle mesurée en témoin).

La réduction de l'espacement de 15 à 10 H (réduction de l'espacement de 33%) se traduit seulement par une réduction supplémentaire de la vitesse du vent de 7% (passage de la vitesse moyenne de 44 à 41% de celle mesurée en témoin). D'après ces données, on peut donc concevoir que dans un réseau de brise-vent, il arrive un moment où l'augmentation de la surface occupée par les brise-vent n'est plus compensée par un accroissement sensible de la réduction du vent.

Figure 8 Effet d'une série de brise-vent identiques constitués par des claies de roseaux de 2,20 m de haut et de porosité voisine de 50% sur la vitesse du vent, exprimée en fonction de celle qui est mesurée en témoin en fonction de leur espacement (d'après Naegeli 1965).



Les effets aérodynamiques des aménagements régionaux

La rugosité régionale

Nous venons de voir que si l'on considère une série de quelques brise-vent, leurs effets aérodynamiques ne sont pas cumulatifs. Maintenant, si l'on considère un ensemble de brise-vent constituant un réseau recouvrant toute une région, il se développe alors ce que l'on peut appeler une "rugosité régionale". (Guyot et al., 1976; Guyot, Seguin, 1978). (figure 9

Les effets aérodynamiques d'un brise-vent placé à l'intérieur d'un réseau de protection

La figure 10 présente de manière schématique les effets qui peuvent être constatés à l'aval d'un brise-vent situé à l'intérieur d'un réseau de protection.

Deux effets se superposent: l'effet local de la haie qui se manifeste sur une distance relativement courte (à cause de la turbulence induite par les haies qui la précédent) et l'effet de l'aménagement régional qui se traduit par une réduction générale du vent sur toute la parcelle.

La figure 11 représente un résultat expérimental obtenu en Bretagne, dans l'ouest de la France, comparé à des données acquises dans différentes conditions. La courbe 1 est determinée en aval de brise-vent isolés. Les courbes 2 et 3 sont relatives à un même brise-vent placé dans un écoulement peu turbulent (Versailles) et très turbulent (-

Figure 9 Représentation schématique de l'influence d'un aménagement régional sur l'écoulement de l'air. En A, développement de la couche limite régionale et en B, détail de l'écoulement à l'échelle parcellaire.

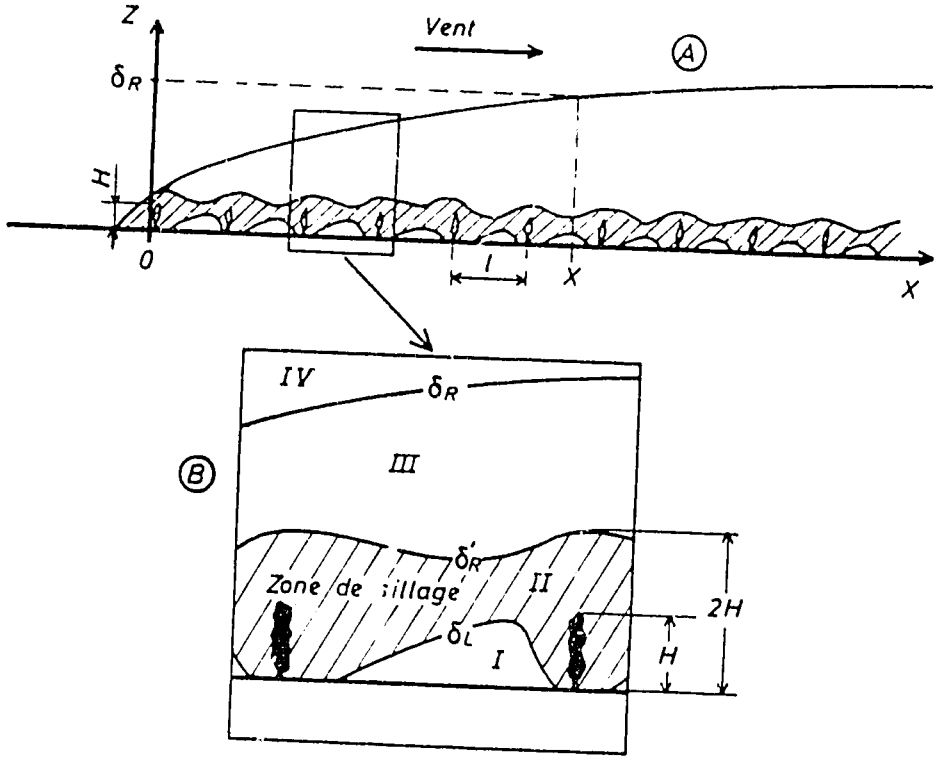


Figure 10 Représentation schématique des effets aérodynamiques d'un brise-vent situé à l'intérieur d'un réseau de brise-vent. (B.V. emplacement d'un brise-vent).

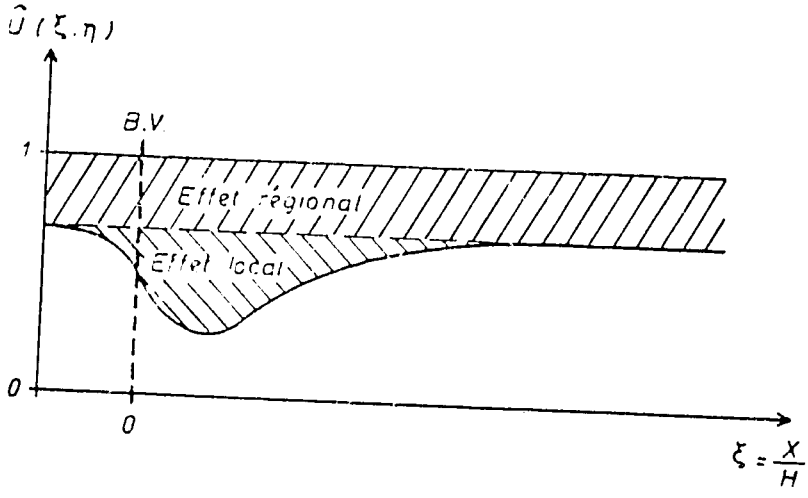
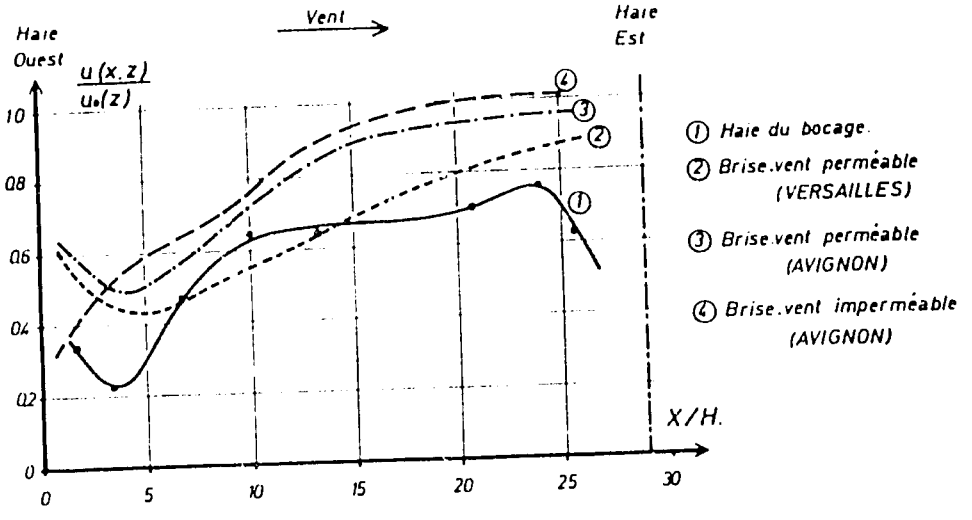


Figure 11 Evolution de la vitesse réduite à l'aval de différents types de brise-vent.
(1) Mesures effectuées en Bretagne dans une parcelle de bocage.
(2) Brise-vent perméable avec un faible taux de turbulence de l'air.
(3) Brise-vent perméable avec un taux de turbulence de l'air élevé.
(4) Brise-vent impermeable avec un taux de turbulence de l'air élevé.



Avignon). La courbe 4 correspond à un brise-vent imperméable placé dans un ecoulement très turbulent.

Si on ajoute la valeur 0,30 à tous les points de la courbe 1, on constate alors qu'elle se place entre les courbes 3 et 4. Ainsi, tout se passe comme si la vitesse du vent qui atteint la haie était déjà réduite de 30% environ par rapport à celle qui est mesurée en témoin. Cette réduction de la vitesse du vent incident est due à l'effet global de l'amenagement en amont de la parcelle.

On peut également remarquer sur la figure 11 que la vitesse du vent reste constante et inférieure à la vitesse témoin, bien que l'on soit très éloigné du brise-vent. Cela montre bien que lorsque la couche limite régionale est développée, la présence de quelques grandes parcelles au milieu d'un réseau de brise-vent ne modifie pas de façon sensible l'écoulement au voisinage du sol.

Les effets des brise-vent sur le microclimat

Le facteurs du microclimat résultent à chaque instant de l'équilibre qui s'établit entre les différentes formes d'échange d'énergie au niveau de la surface du sol ou d'un couvert végétal. Les brise-vent, en modifiant la vitesse du vent au voisinage du sol et les échanges radiatifs, modifient l'ensemble des facteurs du microclimat. Aussi, dans ce paragraphe et le suivant, nous examinerons les différents mécanismes d'action des brise-vent et des aménagements régionaux sur les facteurs du microclimat.

Le bilan d'énergie à la surface du sol

Equation du bilan d'énergie

Les différents échanges d'énergie entre le sol (pris dans son sens large) et l'atmosphère se traduisent par des flux que l'on exprime généralement en watts par m^2 : $W\ m^{-2}$. A tout instant, la somme algébrique de ces différents flux est nulle, par suite du principe physique de conservation de l'énergie. Le bilan d'énergie de la surface s'écrit alors:

$$R_n + \Phi S + \Phi H + \Phi L = 0$$

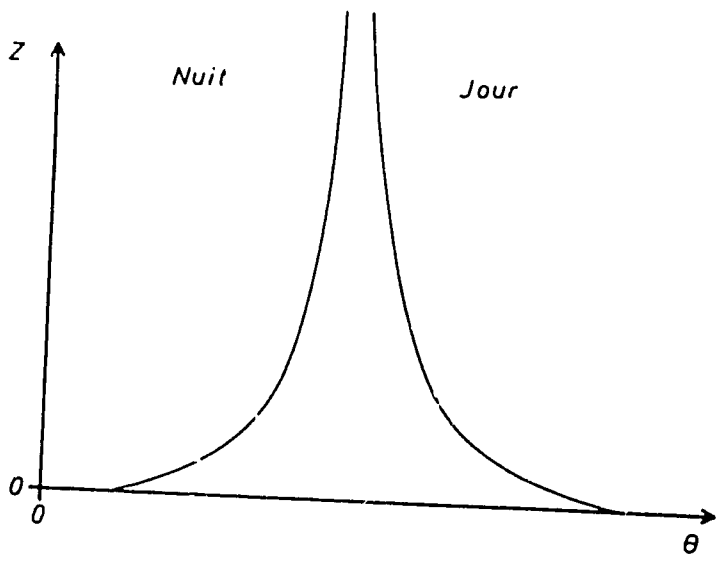
avec
- R_n : rayonnement net : bilan des échanges radiatifs
- ΦS : flux de chaleur dans le sol
- ΦH : flux de chaleur sensible
- ΦL : flux de chaleur latent: flux énergétique équivalant au flux d'évaporation de l'eau.

Cette équation est valable pour les valeurs instantanées des flux. Elle peut être étendue à des échelles de temps quelconques, à condition d'établir correctement les valeurs moyennes de chacune des composantes.

Bilans de jour et de nuit

De façon générale,les caractéristiques des bilans énergétiques de jour et de nuit sont les suivantes:

Figure 12 Profils verticaux de températures diurne et nocturne dans l'air.



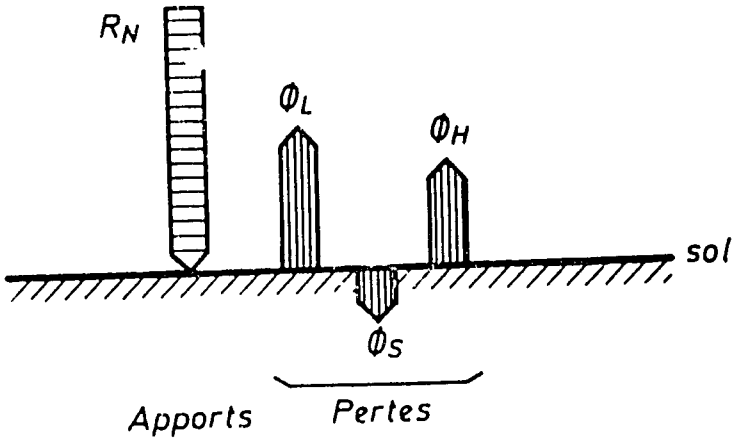
De jour
Le bilan radiatif est généralement positif. Compte tenu de cet apport d'énergie, la surface du sol s'échauffe. Le couches d'air voisines s'échauffent à leur tour par conduction et convection et échauffent de proche en proche les couches d'air supérieures par le même processus. Le profil de température de l'air qui en résulte a l'allure indiquée sur la figure 12. Ce profil est dit suradiabatique ou instable. Le flux de chaleur H est dirigé vers le haut, Φ H est négatif.

La température de surface du sol étant supérieure à celle qu'il a en profondeur, les échanges se font de la surface vers la profondeur: Φ S est négatif.

Par ailleurs, l'humidité de l'air est inférieure à l'humidité en surface: il y a évaporation, Φ L est donc négatif.

Ainsi, l'énergie apportée à la surface par le rayonnement net est en grande partie dissipée par les processus d'échanges convectifs et d'évaporation, le reste est absorbé par le sol.

Figure 13 Bilan d'énergie diurne



On a donc $R_n > 0$
$\Phi S < 0$
$\Phi L < 0$
$\Phi H < 0$

Le bilan d'énergie se traduit alors par la relation (fig.13).

$$|R_n| = |\Phi S| + |\Phi L| + |\Phi H|$$

De nuit
Le rayonnement global est nul et seuls subsistent les échanges radiatifs dans l'infrarouge thermique. Le rayonnement net est alors négatif et la perte d'énergie est d'autant plus forte que le ciel est plus clair (nuit de gelée). La température de la surface du sol est alors inférieure à celle de l'air. Le profil de température est dit d'inversion ou stable; sa forme est donnée sur la figure 12.

Le flux Φ H est dirigé vers le bas. Il est positif. De même, le sol réchauffe la surface par conduction; Φ S est positif. Il peut y avoir évaporation ou condensation durant cette période nocturne, aussi le flux Φ L peut-il être soit positif, soit négatif.

Figure 14 Bilan d'énergie nocturne avec évaporation

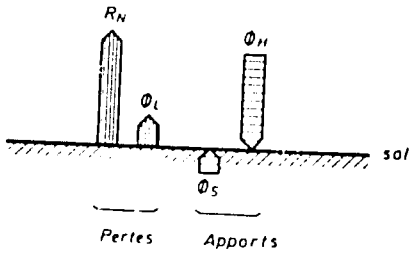
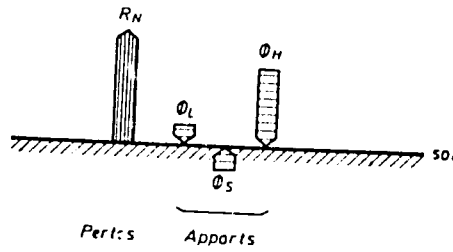


Figure 15 Bilan d'énergie nocturne avec condensation



Le bilan énergétique peut donc s'écrire selon les cas:

- Evaporation nocturne (fig. 14)

$$R_n = |\Phi S| + |\Phi H| - |\Phi L|$$

- Condensation nocturne (fig.15)

$$R_n = |\Phi S| + |\Phi H| + |\Phi L|$$

La formation des microclimats dans le cas d'une zone plane et homogène

Dans les zones planes et homogènes les variations climatiques sont uniquement fonction de l'altitude Z (stratification plane). La distribution des facteurs climatiques et fonction de l'altitude est fonction de la vitesse du vent, des apports radiatifs et de l'eau disponible. La figure 16 résume de façon schématique l'influence de ces facteurs sur les profils diurnes et nocturnes de température et d'humidité.

Les brise-vent en modifiant la vitesse du vent et le bilan radiatif vont bouleverser l'ensemble des conditions microclimatiques comme le laisse prévoir l'examen de la figure 16.

Le rayonnement net Rn

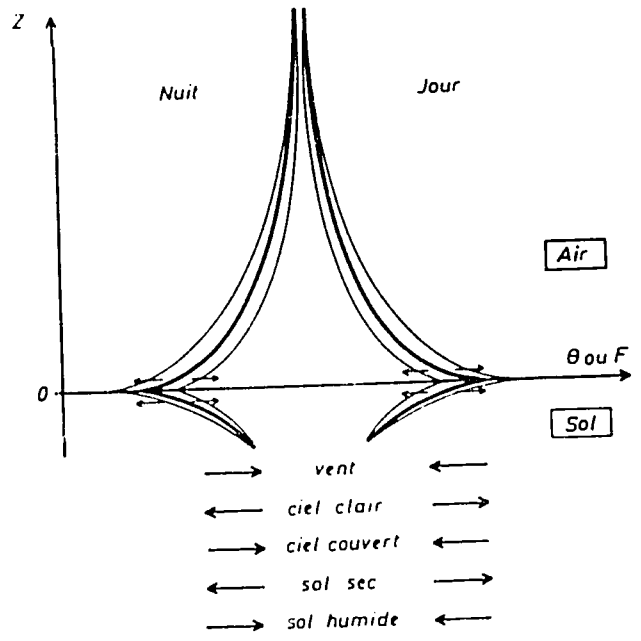
Le rayonnement net est le bilan des différents échanges d'énergie radiative de la surface du sol. Il comprend:

Le bilan des échanges radiatifs de courte longueur d'onde

Le rayonnement d'origine solaire dont 99% de l'énergie est comprise entre 0,15 et 4 m parvient au sol sous forme de rayonnement direct I et de rayonnement diffus D. La somme du rayonnement diffus D et de la composante verticale du rayonnement direct S constituent le rayonnement global G (si h est la hauteur angulaire du soleil $S = I \sin h$).

Une partie du rayonnement global est réfléchie par la surface du sol. Le taux de réflexion du sol pour l'ensemble du spectre solaire est appelé albédo: a. Ainsi, si le rayonnement d'origine solaire qui parvient au sol est G, la fraction réfléchie est aG et

Figure 16 Influence de la vitesse du vent, du bilan radiatif et du bilan hydrique sur les profils de température ou d'humidité diurnes et nocturnes.



la fraction absorbée: (1 - a) G.
La valeur de l'albédo est propre à chaque type de surface. Elle varie cependant légérement en fonction de la hauteur du soleil, de l'état de la surface, etc...

Citons comme ordre de grandeur pour a:

Neige	:	0,70	-	0,90
Gazon	:	0,18	-	0,25
Sable	:	0,30	-	0,40
Eau	:	0,05		

Le bilan des échanges radiatifs de grande longueur d'onde
La surface terrestre rayonne dans l'infrarouge thermique (99% de l'energie émise correspond à des longueurs d'onde comprises entre 4 et 120 m et le maximum d'émission est centré sur 10,5 m).

Le flux de rayonnement émis par le sol est donné par :

$$RS = \varepsilon \sigma TS$$

ε	émissivité de la surface $\varepsilon = 0{,}98$
σ	constante de Stefan-Boltzman $\sigma = 5{,}67 \quad 10^{-8}\ W\ m^{-2}\ °K^{-4}$
TS	température de surface du sol en °K

Ce rayonnement est absorbé, dans les basses couches de l'atmosphère, par la vapeur d'eau et le gaz carbonique, ou éventuellement par les nuages. Une partie est réémise vers le sol en fonction de la température de la couche d'atmosphère considérée.

Ce processus complexe se traduit globalement par l'existence d'un rayonnement descendant : le rayonnement atmosphérique, que l'on peut écrire :

$$R_a = \sigma T_a^4$$

Ta : température fictive de l'atmosphère intégrant l'ensemble des processus d'absorption et d'émission. Elle est d'autant plus faible que le ciel est plus clair et l'humidité plus basse.

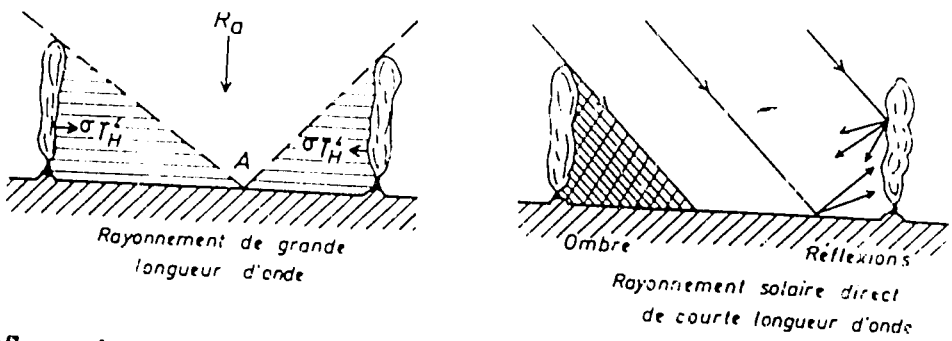
Si les flux constituant les apports d'énergie pour la surface sont comptés positivement et ceux qui constituent les pertes négativement, le rayonnement net peut s'écrire:

$$Rn = (1 - a) G + Ra - Rs$$

Influence des brise-vent sur le bilan radiatif à l'échelle de la parcelle

A l'intérieur d'une parcelle, l'ensemble des composantes du bilan radiatif de grande et de courte longueur d'onde est modifié.

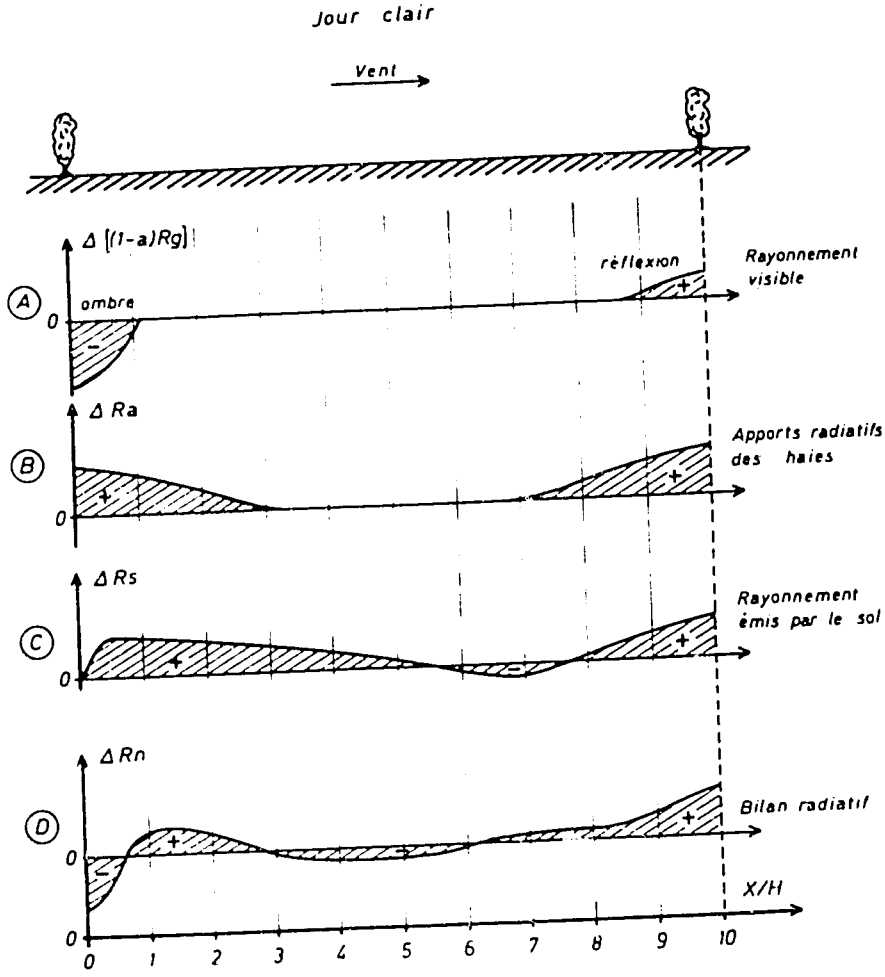
Figure 17 Schéma illustrant les effets des brise-vent à l'échelle parcellaire sur les échanges radiatifs de courte et de grande longueur d'onde.



Influence des brise-vent sur le bilan radiatif diurne

L'effet des brise-vent sur le rayonnement global est assez facile à comprendre comme l'indique la figure 17. Mais un effet moins évident des brise-vent est leur action sur les échanges de rayonnement de grande longueur l'onde. La figure 17 montre qu'au rayonnement atmosphérique reçu au niveau du sol se substitue, dans une partie de l'angle solide, le rayonnement thermique des brise-vent dont la température de surface TH est supérieure à la température radiative apparente de l'atmosphère, et cela d'autant plus que le ciel est plus dégagé (un ciel clair parfaitement dégagé, avec une atmosphère sèche, peut avoir une température radiative apparente de - 40 °C). Ce gain d'énergie dû à la présence des haies est sensible sur une distance comprise entre 3 et 4 fois leur hauteur (Chiapale, 1975).

Figure 18 Représentation schématique des effets des brise-vent sur le bilan radiatif au cours d'une belle journée. La différence de rayonnement net entre la parcelle entourée de brise-vent et une zone ouverte est donnée par $Rn = (1 - a)G + Ra = Rs$.



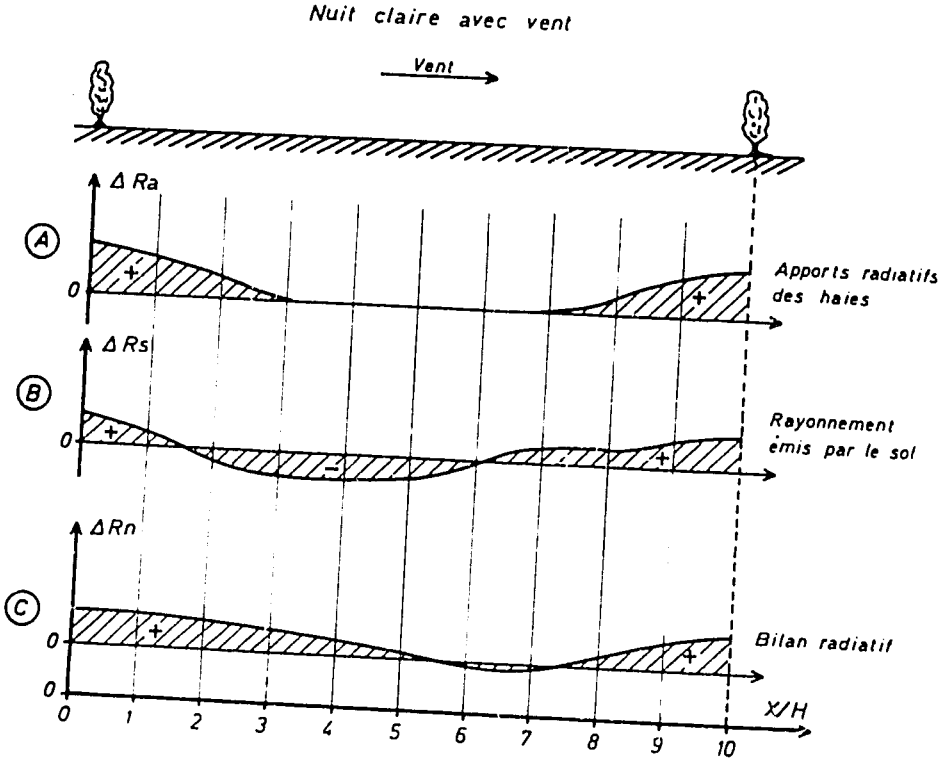
Le flux de rayonnement émis par le sol est également affecté par les brise-vent. En effet, il dépend de la température de sa surface. Cette dernière est fonction de l'énergie radiative qu'elle reçoit et également de la vitesse du vent. Pour une même quantité d'énergie radiative reçue, la température de surface du sol sera d'autant plus élevée que la vitesse du vent sera plus faible. Ainsi, la valeur la plus élevée de rayonnement du sol sera observée près du brise-vent et elle diminuera lorsqu'on s'en éloignera.

La figure 18 représente de façon schématique les effets de deux brise-vent parallèles sur les differentes composantes du bilan radiatif.

Influence des brise-vent sur le bilan radiatif nocturne

Au cours de la nuit, les facteurs essentiels de la variation du bilan radiatif sont l'apport radiatif des haies, qui est sensible sur une distance de l'ordre de trois fois leur hauteur, et la répartition des températures de surface du sol. La figure 19 regroupe sous une

Figure 19 Représentation schématique des effets des brise-vent sur le bilan radiatif au cours d'une nuit avec vent. La différence de rayonnement net entre la parcelle entourée de brise-vent et une zone ouverte est donnée dans ce cas par : $\Delta Rn = \Delta (I - a) G + \Delta Ra - \Delta Rs$



forme très schématique les différents effets des brise-vent sur le bilan radiatif à l'intérieur d'une parcelle.

Cette analyse montre ainsi que les brise-vent introduisent une très grande hétérogénéité horizontale du bilan radiatif à l'intérieur d'une parcelle.

Les effets des brise-vent sur les températures à l'échelle de la parcelle

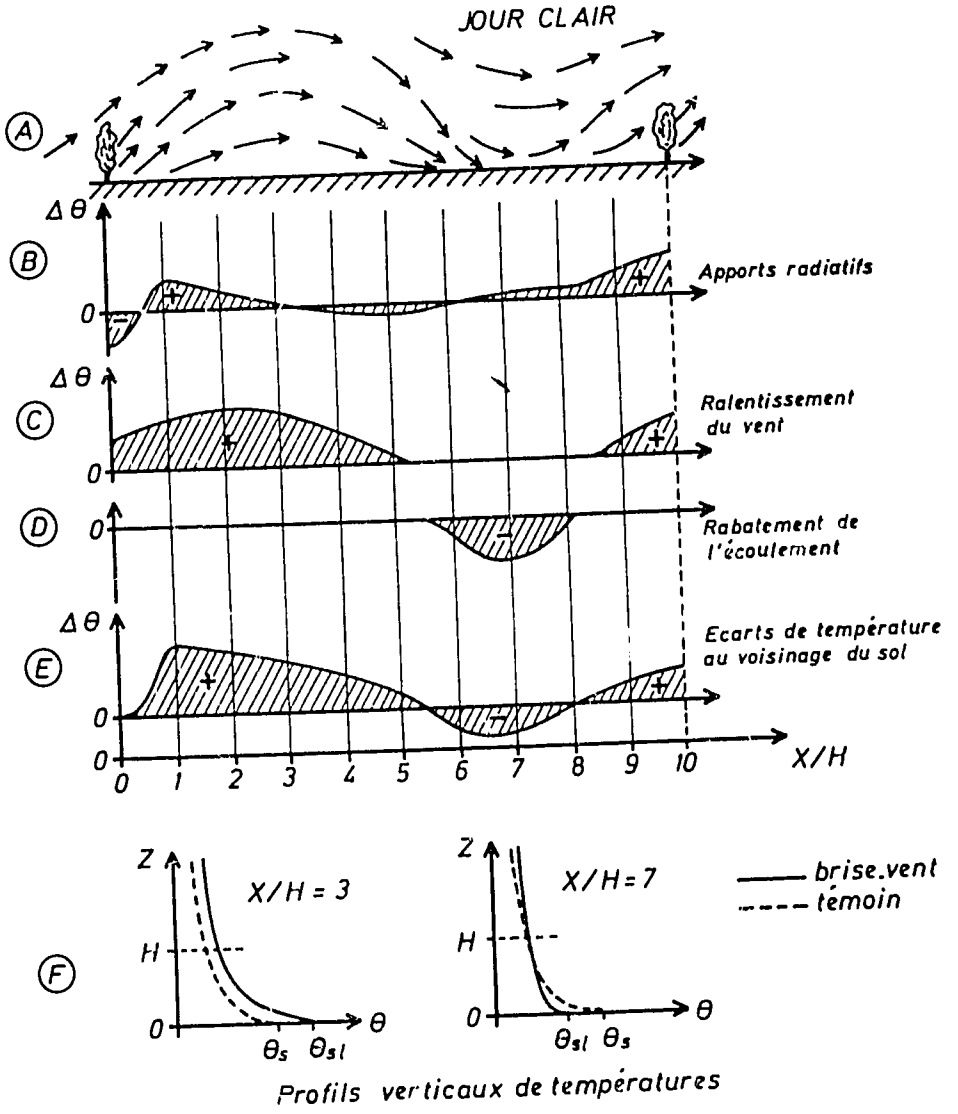
Des analyses détaillées ont montré que les effets des brise-vent sur la température de l'air et du sol sont très complexes. Ils dépendent, entre autres, de la distance aux brise-vent, du bilan radiatif, du bilan hydrique et de la vitesse du vent (van Eimern et al., 1964; Guyot et al., 1976; Guyot et Seguin, 1978).

Les effets des brise-vent sur les températures diurnes

Cas des régions bien alimentées en eau

La figure 20 représente sous une forme schématique la manière dont les brise-vent modifient la répartition des températures diurnes dans une région bien alimentée en eau. La parcelle choisie a une dimension égale à 10 fois la hauteur H des brise-vent. La partie A de la figure représente l'effet des brise-vent sur l'écoulement de l'air. Les

Figure 20 Représentation schématique de l'effet des différents facteurs agissant sur la température diurne à l'intérieur d'une maille de brise-vent dans une zone bien alimentée en eau.



études effectuées aussi bien en France (Guyot - Verbrugghe, 1976) qu'en Tunisie (Charfi, 1980) sur des réseaux de brise-vent ont permis de constater que dans une parcelle située à l'intérieur d'un réseau de brise-vent, on observe un rabattement de l'écoulement comme cela est indiqué sur la figure 20 A.

Près des brise-vent, l'ascendance de l'air est accentuée par l'échauffement qu'il subit, en particulier au niveau de la couronne des arbres. Ce mouvement ascendant est d'autant plus important que la vitesse du vent est plus faible. Ensuite, l'écoulement se rabat vers le sol à une distance comprise entre 6 et 8 fois la hauteur du brise-vent amont.

En B, C et D sont représentés les différents termes dont dépend essentiellement la répartition des températures de l'air au voisinage du sol. La partie B correspond aux effets des brise-vent sur le bilan radiatif (elle est reprise à la figure 18 D). Le ralentissement du vent s'accompagne, comme nous l'avons vu, d'un réchauffement de l'air. Par contre, le rabattement de l'écoulement entraîne au sol de l'air plus froid provenant des couches supérieures de l'atmosphère. (Décroissance de la température avec l'altitude de jour). (Cf. fig. 12). Les écarts de température résultant entre la zone cloisonnée et une zone témoin sont représentés en E. Enfin, en F sont tracés les profils verticaux de températures à des distances des brise-vent égales à 3 et 7 fois leur hauteur. A X/H =3 les températures sont plus élevées dans la zone cloisonnée que dans la zone dégagée à tous les niveaux et le gradient thermique vertical peut être plus élevé si les mouvements convectifs ne sont pas trop importants. Par contre à X/H = 7, le brassage de l'air se traduit par une réduction des gradients thermiques verticaux et la température de surface du sol dans la zone cloisonnée peut être plus basse que la température de surface du sol dans la zone dégagée.

Ce phénomène de rabbattement de l'air à l'aval d'un brise-vent avait déjà été mis en évidence par Woodruff, Read et Chepil (1959) et ils avaient constaté que la distribution horizontale des températures était pratiquement telle qu'elle est décrite sur la figure 20.

L'élévation de la température de l'air dans la zone protégée par un brise-vent à une distance comprise entre 2 et 3 fois sa hauteur est en moyenne de l'ordre de 2 °C. Elle varie en fonction de la porosité des brise-vent et de la vitesse du vent.

Cas des régions seches

Dans ces régions, le flux d'évaporation est très faible et le flux de chaleur latente qui lui correspond l'est également. L'effet des brise-vent est surtout marqué sur le flux de chaleur sensible. La réduction de celui-ci se traduit par une élévation de la température dans la zone protégée. L'effet des brise-vent est donc du même type que celui que l'on observe dans une zone bien alimentée en eau. La figure 21 donne à titre d'exemple le résultats de mesures effectuées en Tunisie dans une zone aride au cours du mois de juillet alors que soufflait le Sirocco. Le brise-vent était constitué par 4 rangées d'eucalyptus de 7 à 8 m de haut bordés du côté au vent par deux rangées d'acacias épineux (*Acacia ferox*) de petite taille et du côté sous le vent par une rangée d'eucalyptus de petite taille. La température maximale de l'air était de 40 °C et la température moyenne de la journée de 35 °C.

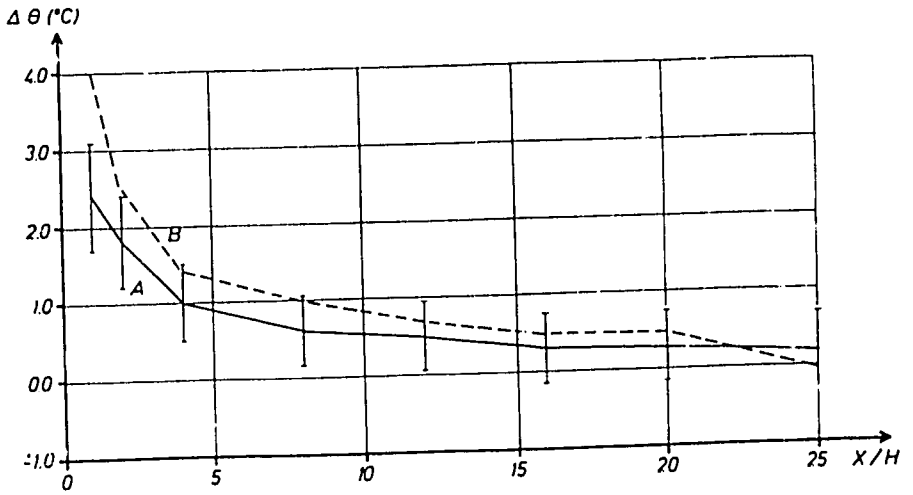
Le courbes présentées montrent que l'élévation de la température de l'air est très marquée, notamment dans la zone comprise entre 1 et 5 fois la hauteur du brise-vent (Charfi, 1980).

Ainsi, en conditions seches, les brise-vent auront pour effet d'accroître encore l'aridité du climat.

Interaction de l'activité du courvert végétal avec la température de l'air

Dans les régions où le facteur eau est un facteur limitant, l'effet brise-vent sur la température de l'air va dépendre en partie de l'évapotranspiration du couvert végétal de la zone protégée (flux de chaleur latente). Ainsi, dans des conditions semi-arides ou arides avec des cultures irriguées, on pourra observer dans la zone protégée par un brise-vent des températures identiques ou même plus basses que dans une zone ouverte. Nous verrons l'explication de ce phénomène après avoir étudié les effets des brise-vent sur l'évapotranspiration réelle.

Figure 21 Evolution de l'écart de température entre une zone protégée et une zone ouverte en fonction de la distance à un brise-vent en climat aride au cours d'une période de forte chaleur, (Tunisie, Hadjeb el Aioun). A: écarts thermiques au moment du maximum de température - B: écarts thermiques sur la moyenne des températures diurnes (d'après Charfi, 1980).



Les effets des brise-vent sur les températures nocturnes

La figure 22 correspond à la figure 20 mais pour une nuit claire et ventée. L'ascendance de l'air au voisinage des brise-vent est moins importante que durant la journée. Les apports radiatifs des brise-vent produisent une élévation de la température de l'air au voisinage du sol; par contre, le ralentissement du vent a pour effet de faciliter le refroidissement nocturne. Le rabattement de l'écoulement entraîne une réduction des gradients verticaux de température et apporte de l'air plus chaud au voisinage du sol. La répartition des écarts de température résultants entre la zone cloisonnée et une zone dégagée, au voisinage du sol, est représentée en E. En F, les profils verticaux de température à X / H = 3 et X / H = 7 montrent que dans la zone où le vent est ralenti, les gradients thermiques verticaux sont accrus, alors qu'ils sont réduits dans la zone de rabbattement de l'écoulement.

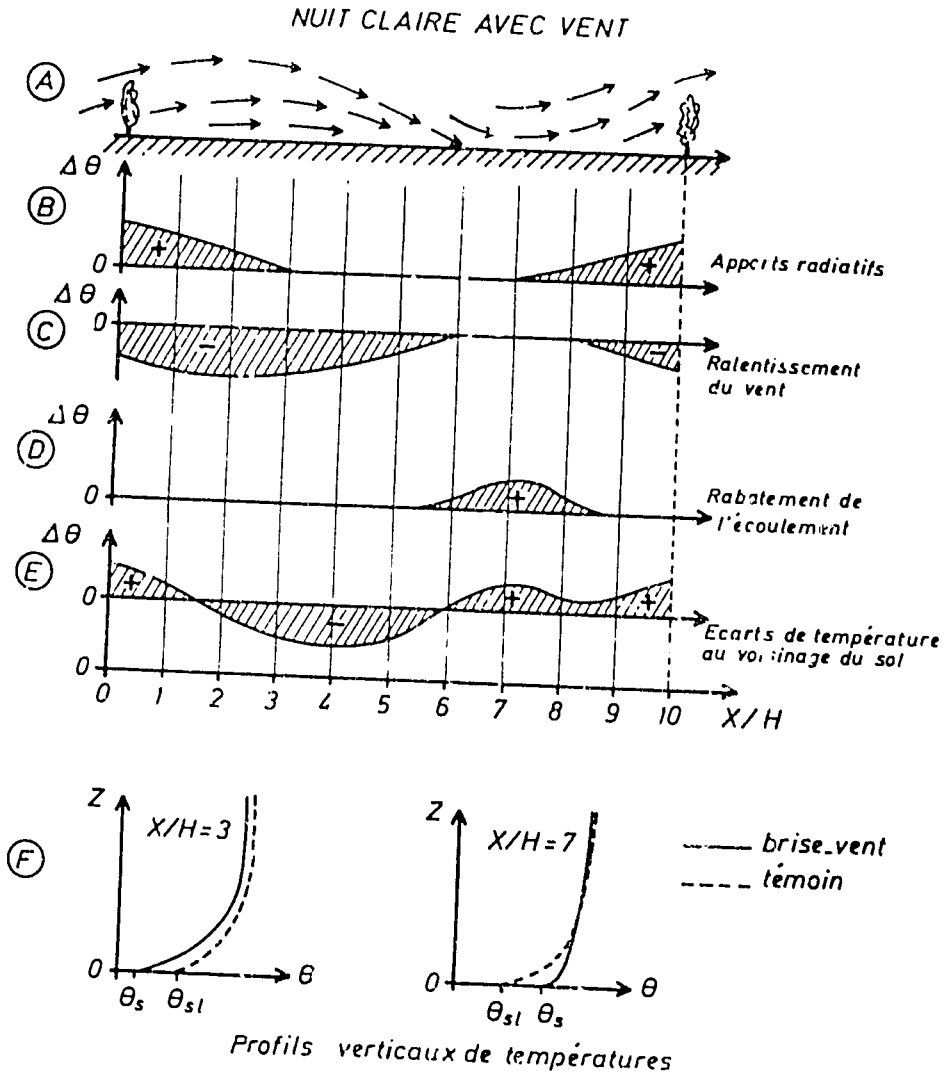
Alors que l'effet d'un brise-vent sur les températures diurnes dépend des conditions d'alimentation en eau des végétaux, son effet sur les températures nocturnes est pratiquement le même quelles que soient les conditions climatiques locales.

Ainsi, les brise-vent ont pour effet, dans la zone comprise entre 1 et 8 fois leur hauteur, d'accroître les amplitudes thermiques en augmentant les températures diurnes et en abaissant les températures nocturnes. L'abaissement des températures nocturnes pourra augmenter sensiblement les risques de gelées nocturnes durant les périodes froides.

Les effets des brise-vent sur la température du sol

La modification des échanges thermiques de la surface du sol par un brise-vent entraîne la modification de la température de l'air et de celle du sol. L'amplitude maximale des

Figure 22 Représentation schématique de l'effet des différents facteurs agissant sur la température nocturne à l'intérieur d'une maille de brise-vent.



phénomènes thermiques est ainsi observée à la surface du sol, elle diminue ensuite lorsqu'on s'élève dans l'air ou lorsqu'on s'enfonce dans le sol.

Cas du sol nu

Lorsque le sol est nu, la répartition des températures dans les premiers centimètres, au-dessous de la surface du sol, est semblable à celle qui est observée dans l'air à l'aval

d'un brise-vent; la température du sol est plus élevée le jour et plus basse la nuit que dans une zone ouverte.

Par contre, au-delà de quelques centimètres de profondeur, la température du sol dépend non seulement de l'amplitude thermique de la surface mais également de la durée des périodes de réchauffement et de refroidissement au cours de la journée. En effet, au printemps, lorsque la durée du jour est supérieure à la durée de la nuit, le sol se réchauffe plus vite à l'abri d'un brise-vent que dans une zone dégagée, car la période d'accumulation de la chaleur en profondeur est plus longue que celle où la chaleur est restituée à l'atmosphère.

Cet effet est très intéressant pour l'agriculture car il permet un départ plus rapide de la végétation. Les élévations de température, constatées par un certain nombre d'auteurs cités par Van Eimern et al., (1964), sont comprises, à 10 cm de profondeur, entre 0,5 et 3 °C. Ce réchauffement du sol s'atténue avec la profondeur et, généralement, se limite aux 50 premiers centimètres.

Par ailleurs, il faut noter que l'échauffement du sol le jour et son refroidissement la nuit sont d'autant plus importants qu'il est plus sec. En effet, lorsque le sol est humide, il conduit mieux la chaleur et son amplitude thermique est alors tamponnée.

Cas du sol couvert de végétation

La végétation en se développant couvre le sol et limite ses échanges de chaleur de jour et de nuit. La surface au niveau de laquelle l'amplitude thermique est maximale est alors la surface supérieure de la végétation.

Les effets des brise-vent sur l'évapotranspiration potentielle

L'évapotranspiration potentielle (ETP), quantité maximale susceptible d'être évaporée par un couvert végétal en phase active de croissance et parfaitement alimenté en eau, peut être déterminée à l'aide de formules telles que la formule de Penman (1956), dérivée de l'équation du bilan d'énergie. Cette formule peut s'écrire:

$$ETP = \frac{\Delta Rn + \gamma Ea}{\Delta + \gamma}$$

(Cf. Doorenbos et Pruitt, 1976).

avec
- Δ : pente de la courbe de tension de vapeur d'eau
- Rn : rayonnement net
- γ : constante psychrométrique
- Ea : pouvoir évaporant de l'air

Le terme Ea est défini par l'expression:

$$Ea = f(U) \mid E(\Phi a) - e_a \mid$$

f (U) est une fonction de la vitesse du vent et de la rugosité du sol. Le second terme représente le déficit de saturation de l'air, avec E (Φ a) tension de vapeur saturante à la température de l'air Φ a et e tension de vapeur d'eau dans l'air. Les brise-vent en réduisant les mouvements de l'air réduisent les transferts de vapeur d'eau et l'humidité de l'air est généralement plus élevée dans la zone protégée mais cet accroissement reste cependant généralement faible.

Ainsi, la formule de Penman peut s'écrire:

$$ETP = a\,Rn + b\,Ea$$

avec $a = \dfrac{\Delta}{\Delta + \gamma}$ et $b = \dfrac{\gamma}{\Delta + \gamma}$

aRn est le terme radiatif de l'ETP et bEa le terme advectif. Un brise-vent modifie Rn et Ea mais l'effet essentiel des brise-vent porte sur la réduction de Ea. Les modifications du bilan radiatif n'apportent que des corrections de relativement faible amplitude.

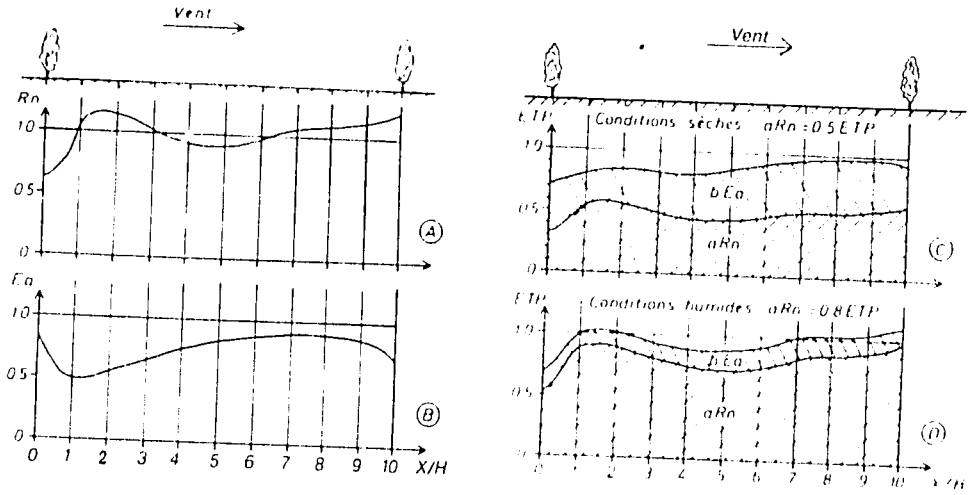
Le données expérimentales, relatives à l'influence des brise-vent sur l'évaporation, sont très nombreuses (Van Eimern et al., 1964) et tous les observateurs constatent une réduction de celle-ci de 20 à 40%. Mais les résultats ne peuvent pas être directement transposés à l'ETP. C'est pourquoi Van Elmern (1966) met en garde les expérimentateurs contre cette difficulté.

Les brise-vent sont situés dans une zone où il existe une forte advection

Le poids relatif du terme bEa dans la formule de Penman est important (40 à 60%) et toute réduction de Ea sera sensible sur l'ETP. De tels résultats peuvent être obtenus dans les zones relativement sèches.

La figure 23 représente les effets des brise-vent sur l'ETP à l'intérieur d'une parcelle. En A est représenté l'effet sur le bilan radiatif. La courbe est déduite de la figure 18. En B est représenté le terme advectif, la forme de la courbe tracée est semblable à celle

Figure 23 Représentation schématique des effets les brise-vent sur l'ETP et ses composantes. En conditions sèches, la figure est établie dans le cas où les termes a Rn et b Ea représentent chacun 50% de l'ETP. En conditions humides, on suppose que a Rn représentent 50% de l'ETP et b Ea 20%.



des courbes d'évolution de la vitesse du vent en fonction de la distance du brise-vent. La partie C est la résultante de l'addition des deux termes a Rn + b Ea. Nous voyons qu'ainsi les brise-vent réduisent l'ETP mais de façon bien moins importante que ne l'est le pouvoir évaporant de l'air.

Les brise-vent sont situés dans une region où l'advection est faible

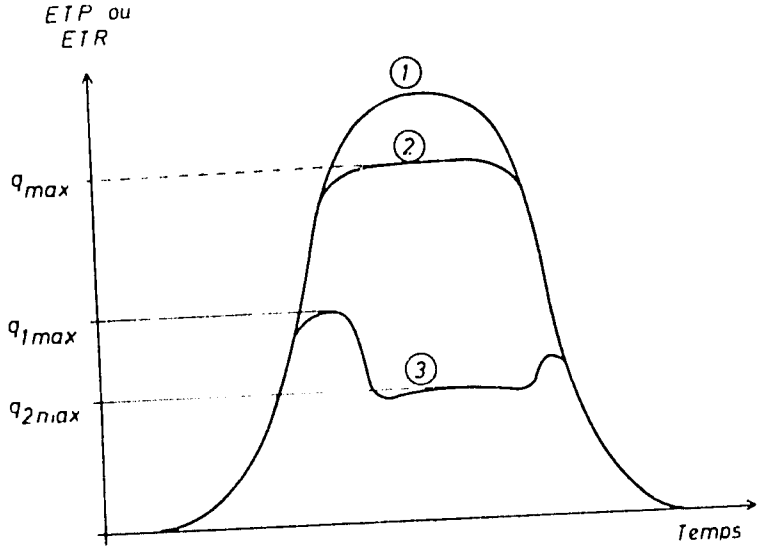
Ce cas se rencontre dans les zones humides où l'évapotranspiration réelle (ETR) est voisine de l'ETP. Dans ces conditions, la contribution relative du terme b Ea à l'ETP est faible (de l'ordre de 20%) et sa réduction par un brise-vent n'entraîne alors que peu de modifications de l'ETP, comme le montre la figure 23 D.

Les effets des brise-vent sur l'évapotranspiration réelle

Les effets des brise-vent sur l'ETR sont complexes car ils dépendent non seulement de leur action sur l'ETP mais également des réactions physiologiques des végétaux protégés.

L'évapotranspiration potentielle évolue au cours de la journée: nulle au lever du jour, elle passe par un maximum lorsque le soleil est au zénith. Bien souvent, la valeur maximale de l'ETP est supérieure au débit Q max que les plantes sont susceptibles de fournir. Elles réagissent contre le dessèchement en fermant partiellement ou totalement leurs stomates par où s'effectuent les échanges de vapeur d'eau mais aussi du gaz carbonique de la photosynthèse. Deux cas peuvent alors se présenter selon l'intensité de la contrainte hydrique que subissent les plantes (Stocker, 1956; Guyot, 1963).

Figure 24 Représentation schématique de la variation journalière de l'ETP (1) et l'ETR (1, 2, 3) dans différentes conditions climatiques (d'après Guyot, 1963).



La contrainte hydrique est modérée
Le débit Q max est légèrement inférieur à l'ETP max, la régulation stomatique intervient alors pour réduire l'ETR dont l'évolution est représentée par la courbe (2) de la figure 24. La fermeture des stomates n'est que partielle.

La contrainte hydrique est forte
Le débit Q max est nettement inférieur à l'ETP max. Ce cas se rencontre en conditions très sèches. L'évolution de l'ETR peut alors être telle qu'elle est indiquée par la courbe (3) de la figure 24. Lorsque l'ETP atteint une valeur Q1 max, les stomates se ferment complètement et, avec un retard variable selon les conditions locales, les plantes se flétrissent. Lorsque les stomates sont fermés, les pertes d'eau sont alors uniquement dues à la transpiration cuticulaire. La plante ne fournit alors que le débit Q2 max inférieur à Q1 max. En fin de journée, lorque l'ETP devient inferieur a Q1 max, les tissus végétaux reprennent leur turgescence et les stomates s'ouvrent à nouveau.

A partir de ces données, il est alors possible de prévoir sur un plan théorique, les effets des brise-vent sur l'ETR, en fonction des conditions climatiques (Guyot, 1963).

Dans les conditions humides

Les valeurs instantanées de l'ETP sont faibles et sont généralement inférieures ou au plus égales à Q max.

Dans ces conditions, la régulation stomatique n'intervient que très peu ou pas du tout. L'ETR est voisine de l'ETP et, comme un brise-vent a peu d'action sur l'ETP, il en a peu également sur l'ETR. L'élévation de température au voisinage du brise-vent peut cependant produire un léger accroissement de l'ETP et l'ETR. La température est alors plus élevée dans la zone protégée que dans la zone ouverte.

La contrainte hydrique est modérée

L'ETP max est supérieure à Q max, la régulation intervient durant une partie de la journée. Comme les brise-vent diminuent l'ETP dans de telles conditions, ils diminuent également l'ETR comme le montre la figure 25 A. La température diurne est alors peu modifiée par le brise-vent ou légèrement abaissée.

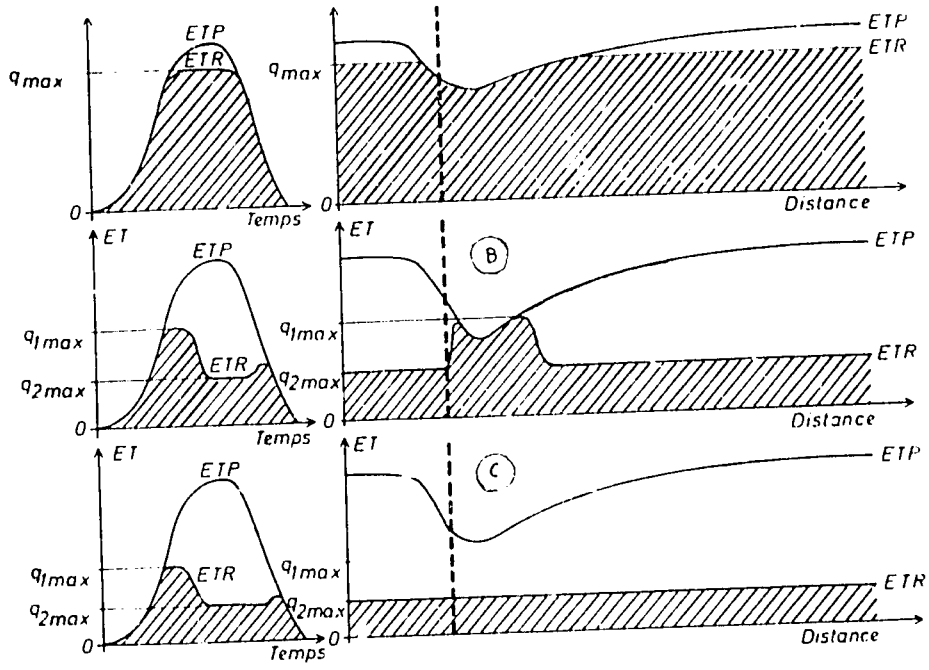
La contrainte hydrique est forte

L'ETP max est nettement supérieure à Q max, les plantes peuvent fermer complètement leurs stomates dans la zone ouverte alors que la réduction de l'ETP par les brise-vent plaçant les plantes dans des conditions moins sévères, elles peuvent continuer à transpirer (figure 25 B). Dans ces conditions, le brise-vent a pour effet d'augmenter l'ETR et d'abaisser la température de l'air.

La contrainte hydrique est très forte

Les plantes ferment leurs stomates aussi bien dans la zone ouverte que dans la zone protégée (figure 25 °C). Le brise-vent n'a alors pratiquement plus d'effet sur l'ETR. Mais la vitesse du vent étant réduite dans la zone protégée, la température des végétaux s'élève pour pouvoir évacuer la chaleur reçue. Le brise-vent a alors un effet néfaste sur les cultures.

Figure 25 Représentation schématique de l'effet d'un brise-vent sur l'ETP et l'ETR au moment ou l'ETP est maximale. La partie gauche de la figure indique l'évolution journalière de l'ETR et l'ETP en zone ouverte (d'aprés Guyot 1963).



Ces prévisions théoriques sont confirmées par de nombreux résultats expérimentaux (Guyot, 1983).

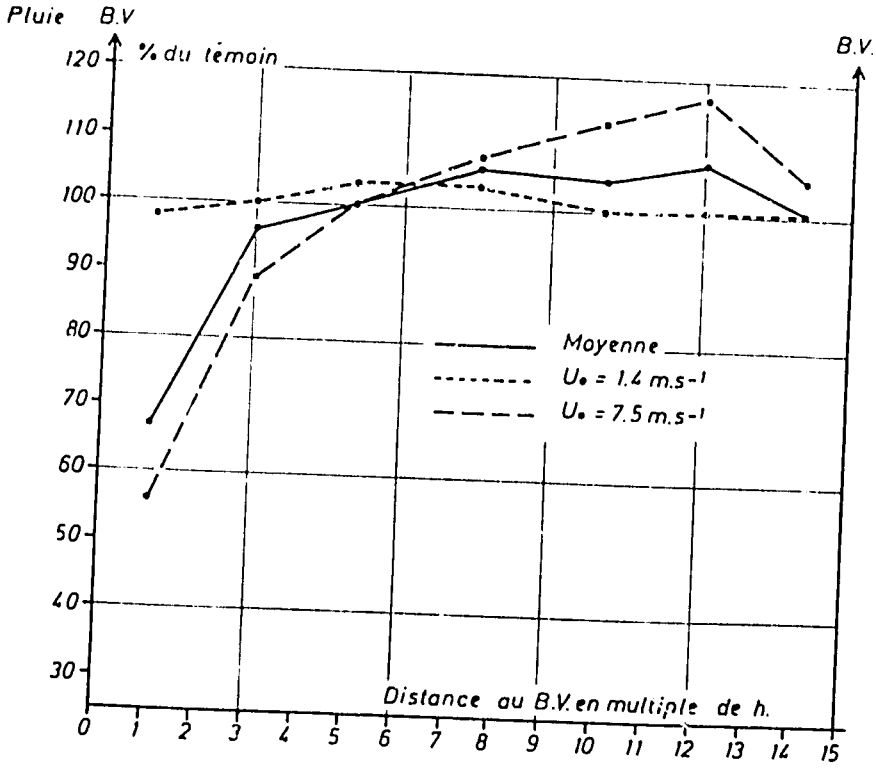
L'évapotranspiration propre des brise-vent

Les brise-vent captent plus d'énergie qu'une culture basse. En effet, à cause de leur forme dressée, ils interceptent plus d'énergie solaire et ils reçoivent plus d'énergie advective qu'une culture basse qui occuperait la même surface.

Ainsi, l'évapotranspiration potentielle des brise-vent est supérieure à celle des cultures basses qu'ils protégent ou des cultures situées dans une zone ouverte et qui occuperaient la même surface. On peut estimer à partir des travaux de seguin (1975) que l'ETP des brise-vent est de l'ordre de 2 à 3 fois celle de la même surface occupée par une culture basse.

Considérons des brise-vent de 10 m de haut et 5 m de large espacés de 200 m. S'ils réduisent en moyenne l'ETP sur la zone protégée de 10% et s'ils consomment 2 fois plus d'eau que la culture, la réduction de l'ETP par l'ensemble du système est alors de

Figure 26 Evolution de la quantité d'eau reçue au sol entre 2 brise-vent perméables de 2 m de haut espacés de 30 m et installés sur un plateau dégagé près de Versailles (La Minière) pour différentes vitesses de vent. Les pluviomètres sont enterrés de telle sorte que leur anneau soit au niveau de la surface du sol (Guyot, 1983).



7% (l'ETP serait réduite de 5% si l'on supposait que les brise-vent avaient une ETP triple de celle de la zone dégagée).

Les effets des brise-vent sur les précipitations

Comme les précipitations (pluie ou neige) sont accompagnées de vent, les brise-vent modifient leur distribution.

Les effets de brise-vent sur la pluie

Avec le vent, la trajectoire des gouttes est inclinée. Aussi, la face au vent du brise-vent intercepte une partie de la pluie destinée à la zone protégée et la quantité d'eau reçue immédiatement du côté sous le vent est plus faible que dans une zone ouverte. Par contre, le ralentissement du vent dans la zone protégée augment le volume des précipitation reçues. C'est ce que montre la figure 26 qui représente le résultat des mesures effectuées dans la zone protégée par un brise-vent implanté sur un plateau dégagé dans la région parisienne. Selon la vitesse du vent, la distribution des précipitations reçues

au sol peut varier de façon sensible. Les écarts sont d'autant plus grands que la vitesse du vent est plus forte.

Les effets des brise-vent sur la neige

Les effets des brise-vent sur la neige sont du même type que leurs effets sur la pluie, mais ils sont beaucoup plus spectaculaires et ils jouent un rôle extrêmement important dans les régions sèches à hiver froid (plaines du sud de l'URSS, grandes plaines des Etats-Unis et du Canada).

En effet, après les chutes de neige, les brise-vent vont également s'opposer aux transports horizontaux par le vent, ils vont même favoriser la formation de congères qui, en fondant au printemps, vont réalimenter le sol en eau.

Les mécanismes de transport de la neige par le vent et de formation de congères sont identiques à ceux de l'érosion éolienne. Comme ce problème est très important, il fait l'objet de nombreuses études notamment en URSS, aux Etats-Unis, en Europe centrale, en Europe du Nord, au Canada...

Les effets des brise-vent sur les précipitations occultes (rosée et brouillard)

La rosée se dépose surtout au cours de nuits claires et calmes au cours desquelles les brise-vent ont un effet limité sur les facteurs climatiques. Pour que les brise-vent aient une action sensible sur le dépôt de rosée, il faut qu'il y ait un léger vent dans la zone ouverte.

Son ralentissement dans la zone protégée, combiné avec l'humidité de l'air plus élevée et l'abaissement supplémentaire de la température, se traduit par un accroissement du dépôt de rosée. Cependant, ce phénomène est difficilement mesurable et présente un intérêt limité. Par contre, l'effet des brise-vent sur la durée d'humectation des feuilles joue un rôle biologique important. En effet, même si les brise-vent n'accroissent pas le dépôt de rosée, ils ralentissent son évaporation le matin et les plantes restent mouillées pendant une période plus grande, ce qui peut favoriser le développement des maladies cryptogamiques (oïdium en particulier).

Les brise-vent peuvent également avoir une action sur les brumes et brouillards. Ils peuvent en particulier capter les gouttelettes en suspension. Cet effet peut être intéressant notamment dans les zones désertiques côtières qui sont souvent recouvertes de brouillards denses. Ceux-ci peuvent apporter une partie de l'eau nécessaire à la croissance des végétaux utilisés comme brise-vent.

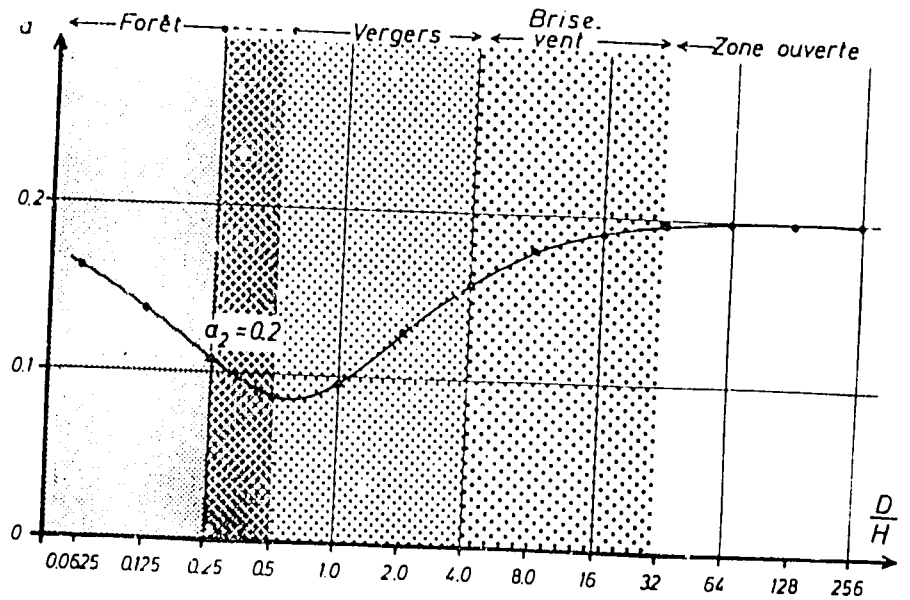
Les effets des aménagements regionaux sur le microclimat

De la même manière que pour la vitesse du vent, les brise-vent modifient les facteurs climatiques à l'échelle de la parcelle et à l'échelle de la région lorsqu'ils constituent un réseau étendu.

Les effets des aménagements régionaux sur le bilan radiatif

Un réseau de brise-vent peut modifier le bilan radiatif de la région dans laquelle il est implanté en augmentant notamment la quantité de rayonnement solaire qui est captée. En effet, le rayonnement solaire réfléchi par le couvert végétal qui est habituellement

Figure 27 Variation de l'albédo régional a en fonction de l'espacement des brise-vent successifs. Le 150e jour de l'année à 12 heures à la latitude de 44 Nord. Les brise-vent sont supposés être orientés est-ouest, ils ont 10 m de haut et 2m de large.



renvoyé vers l'espace peut être capté par les haies voisines d'une part et partiellement renvoyé vers le sol d'autre part. Une partie supplémentaire du rayonnement solaire incident est ainsi "piégée" par le réseau de brise-vent, ce qui doit conduire à une diminution de l'albédo régional. Un calcul théorique effectué par Chiapale (1975a - 1975 b) a permis de déterminer l'importance des phénomènes mis en jeu.

La figure 27 représente la variation de l'albédo d'une région protégée par une série de brise-vent parallèles de hauteur H orientés est-ouest et dont l'espacement (l) peut varier. On suppose que l'albédo du sol a_1 est egal à 0,20 (prairie) ainsi que celui des haies a_2.

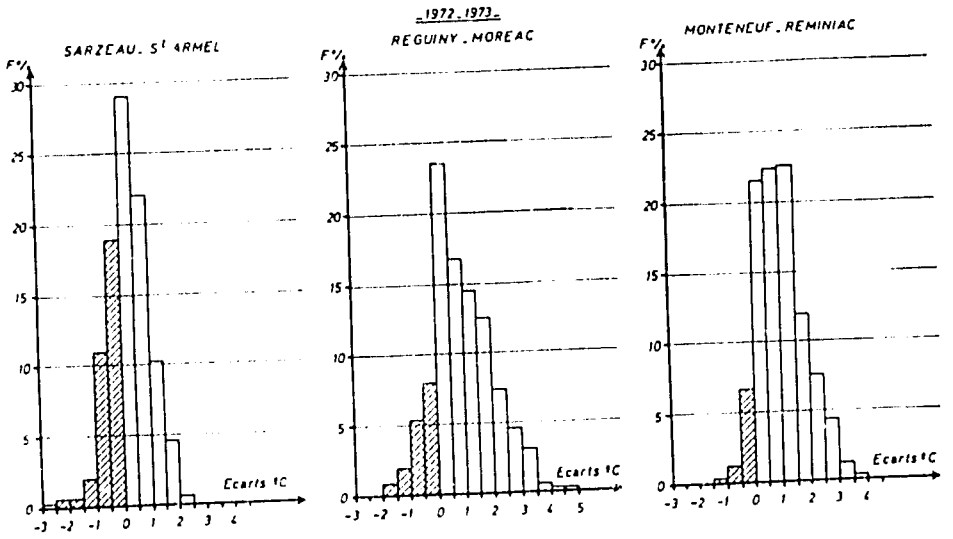
Lorsque les haies sont très espacées (l/H grand), l'albédo régional est alors égal à celui du sol. Par ailleurs, lorsque les haies sont très proches, elles tendent alors à constituer un massif forestier dont l'albédo est celui des haies. Entre ces deux extrêmes, l'albédo régional passe par un minimum voisin de 0,09 lorsque l/H = 0,6 dans l'ensemble présenté sur la figure 27.

Pour des valeurs caractéristiques d'un maillage de brise-vent, il est d'environ:

$$0{,}16 \text{ pour } l/H = 5 \text{ et } 0{,}18 \text{ pour } l/H = 8$$

Pour une belle journée ($G = 700\ W\ m^{-2}$), ceci correspond une absorption d'énergie supplémentaire à l'échelle régionale de 14 à 28 $W\ m^{-2}$, soit une augmentation relative

Figure 28 Histogrammes des fréquences d'écarts d'amplitudes thermiques entre une zone cloisonnée et une zone ouverte pour l'année agricole 1972-1973 dans 3 sites expérimentaux de Bretagne. (Les colonnes hachurées correspondant aux écarts négatifs).



du rayonnement net Rn, qui est voisin dans ces conditions de 400 W m^{-2} d'environ 3 à 6%.

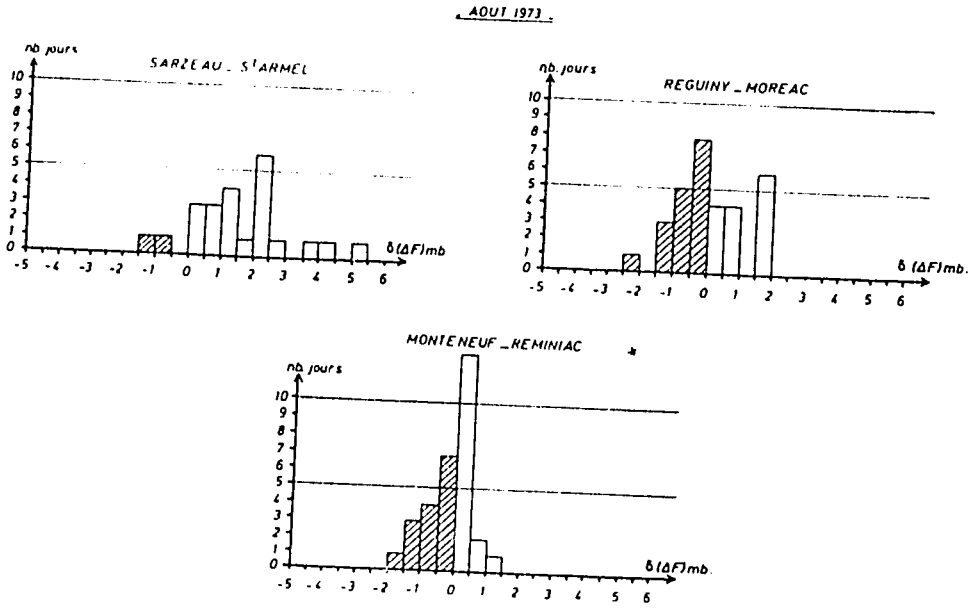
Les effets des aménagements régionaux sur les températures

Les analyses des profils verticaux de température ainsi que des simulations sur modéles ont permis de montrer qu'à l'échelle régionale, les brise-vent avaient pour effet, en général, d'accroître les températures maximales et d'abaisser les températures minimales, si bien que les lamplitudes thermiques sont accrues. Ainsi, un réseau de brise-vent n'a pas pour effet de tamponner le microclimat mais au contraire d'en accroître la 'continentalité'. C'est ce que montre par exemple la figure 28.

Les effets des aménagements régionaux sur l'humidité de l'air

Un réseau de brise-vent a pour effet de réduire les échanges de chaleur ou de vapeur d'eau entre le sol et l'atmosphère. Généralement, les brise-vent permettent ainsi un accroissement de l'humidité de l'air au voisinage du sol en limitant le départ de la vapeur d'eau émise par les plantes. Mais les brise-vent peuvent également, dans une zone sèche, empecher l'arrivée d'air humide. C'est ce que montre par exemple la figure 29.

Figure 29 Histogrammes de fréquences d'écarts de déficit de saturation, δ (Δ F) déterminés au moment du maximum de température entre une zone cloisonnée et une zone ouverte dans 3 sites expérimentaux de Bretagne au cours du mois d'août 1973 (d'après Guyot et al., 1976).



La figure 29 représente les histogrammes de fréquences d'écarts de déficit de saturation ( ) entre une zone cloisonnée et une zone ouverte dans trois sites expérimentaux de Bretagne au cours d'un mois particulirèment sec (août 1973). Le site de St Armel Sarzeau se trouve en bordure de mer alors que les deux autres sont à l'intérieur des terres.

La figure 29 montre nettement qu'en bordure de mer, le déficit de saturation est beaucoup plus important dans la zone cloisonnée que dans la zone ouverte, alors qu'à l'intérieur des terres où les pluies sont plus abondantes, un tel phénomène n'est pas observé. L'importance des écarts observés est due à deux phénomènes qui ont agi dans le même sens: l'élévation de la température de l'air dans la zone cloisonnée par rapport à la zone ouverte et la réduction de la pénétration de l'air humide d'origine marine.

Les effets des aménagements régionaux sur l'evapotranspiration potentielle

Il n'existe pas, à l'heure actuelle, de mesures permettant de connaître l'effet d'un aménagement régional sur l'ETP. Cependant, les études théoriques effectuées par Seguin permettent de montrer que l'accroissement de la rugosité régionale permet de

* Le déficit de saturation Δ F est un moyen de caractériser l'état de sécheresse de l'air. Il est égal à la différence entre la tension de vapeur saturante, à la température de l'air, et la tension de vapeur d'eau dans l'air.

diminuer le terme advectif (b Ea) de l'ETP. Ainsi, si on prend comme référence le pouvoir évaporant de l'air pour une rugosité de sol équivalente à celle d'une prairie, il peut être réduit de 50% lorsqu'on passe à la rugosité créée par un réseau dense de brise-vent. L'importance de la réduction de l'ETP dépendra alors du poids du terme b Ea dans l'ETP.

Les effets des aménagements régionaux sur les précipitations

Un certain nombre d'études ont été entreprises dans le monde pour essayer de déterminer les effets possibles des réseaux de brise-vent sur les précipitations, mais aucun résultat décisif n'a jamais été obtenu.

Les brise-vent peuvent cependant favoriser la formation de cellules convectives dans l'atmosphère grâce au découpage du territoire qui permet leur isolement. Ainsi les nuages se formeront plus vite au-dessus d'une zone cloisonnée que d'une zone dégagée dans les régions où l'humidité de l'air est suffisante.

Les effets des aménagements régionaux sur l'humidité du sol

Si les réseaux de brise-vent n'ont pas d'effet sensible sur le volume des précipitations

Figure 30 Comparison des coefficients de ruissellement Cr d'une bassin versant avec brise-vent (Penety) et d'un bassin versant ouvert (Kermaninon) (d'après Merot, 1976).

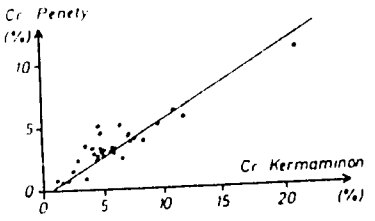
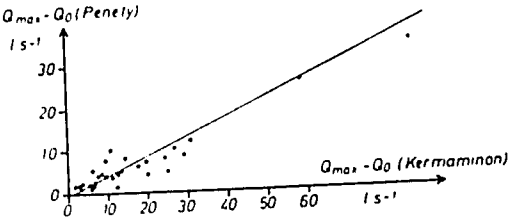


Figure 31 Comparaison des débits maximum ruisselés de crue Q max - Qo dans un bassin versant avec brise-vent u (Penety) et un bassin versant ouvert (Kermaninon) (d'après Merot 1976).



recueillies, par contre, ils peuvents limiter le ruissellement et favoriser la pénétration de l'eau dans le sol qui pourra ainsi alimenter le nappes profondes.

Le coefficient de ruissellement qui est pour chaque précipitation le rapport du volume d'eau ruisselé au volume d'eau reçu est plus faible dans une zone cloisonnée que dans une zone ouverte homologue. C'est ce que montre la figure 30 qui correspond à des mesures effectuées en Bretagne (Merot, 1976) sur deux bassins versants élémentaires, l'un étant recouvert d'un réseau de brise-vent (Penety) et l'autre étant dégagé (Kermaninon). Dans le bassin versant ouvert, le coefficient de ruisselement est

1,7 fois plus élevé que dans le bassin cloisonné. Le volume des crues est donc 1,7 fois plus élevé dans le bassin dégagé que dans le bassin cloisonné. Si l'on compare sur les mêmes bassins élémentaires les débits maximums ruisselés des crues (*), on constate que dans le bassin ouvert, ils sont pratiquement doubles de ceux qui sont mesurés dans le bassin avec brise-vent (figure 31).

Cependant, les travaux des chercheurs soviétiques dans les régions vallonnées montrent que l'effet bénéfique des brise-vent sur le ruissellement n'est sensible que s'ils sont plantés sur des talus (comme en Bretagne) où s'ils sont bordés par un fossé. Dans les régions à hiver froid, la formation de congères et la limitation du ruissellement grâce aux brise-vent permet d'améliorer la recharge des nappes phréatiques. C'est ainsi que dans les steppes de l'URRS, de nombreux auteurs (cités par van Eimern et al.,1964; Guyot, 1963) on constaté le relèvement des nappes depuis la plantation de rideaux d'arbres.

Ainsi, à l'échelle d'une région,, les brise-vent auront pour effet de régulariser le débit des cours d'eau en écrétant les crues et en limitant les étiages.

Conclusion

Cet exposé présente les principaux effets physiques des brise-vent et des aménagements régionaux et montre la complexité des phénomènes qui entrent en jeu.

A l'heure actuelle, les différents mécanismes d'action des brise-vent commencent à être bien connus, mais, par contre, l'amplitude des modifications microclimatiques qui sont produites est difficilement prévisible, car elle dépend de nombreux facteurs locaux. Aussi, dans bien des cas, il est nécessaire d'effectuer des mesures de calage qui permettent de préciser le sens et l'importance des effets des brise-vent. Ces mesures, en nombre limité, permettent alors de relier les données à un cas connu, ce qui facilite alors leur extrapolation.

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* Débit maximum ruisselé d'une crue: différence entre le débit maximum et le débit initial juste avant la crue.

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Crop protection from very strong winds : recommendations from a Costa Rican agroforestry case study

C. J. Stigter

TTMI-Project, Wageningen Agricultural University
Wageningen, The Netherlands

T. Darnhofer

International Council for Research in Agroforestry (ICRAF)
P. O. Box 30677, Nairobi, Kenya

H. Herrera S.

Agrometeorological Programme
Instituto Meteorologico Nacional
San Jose, Costa Rica

Abstract

Introduction of irrigated agriculture in Guanacaste Region (Costa Rica) during the dry season encounters a major problem in the occurrence of very strong winds. The literature was scanned for possible recommendations with respect to growing crops between rows or strips of trees under such conditions. Recommendations were formulated in this case study made for WMO with respect to shape and composition, height, length, width, direction, number and permeability of rows or strips of trees and the distance between them and on measurements and observations to be taken in trials with this agroforestry system. Finally, general recommendations are formulated for running such trials with trees, in rows or strips or in wider belts or scattered throughout the landscape, for crop protection from strong winds.

Introduction

Wind protection is a long-standing indigenous practice in traditional agriculture of many regions (Stigter 1985). In attempts to improve or establish wind protection schemes with trees, it makes sense to study the link which can be observed between traditional and relatively recent but promising agroforestry practices (Budowski 1983). And it makes sense as well to try to quantify phenomena taking place in such traditional and such promising practices alike (Stigter 1986).

In the case study in Costa Rica reported here, the National Meteorological Institute requested WMO/UNDP to assist in providing the agrometeorological input into the set-up of experiments under conditions in farmers' fields, with a system of wind barriers with trees, in irrigated crops in Guanacaste Region. No crops are usually grown in this area in the dry season due to lack of water. Irrigation would solve that problem,

but in that case the limiting factor to agricultural production becomes the occurrence of extremely strong winds (hourly average wind speeds over 70 km/hr, measured at 4 m above the ground). Protection with wind barrier systems appears most appropriate in the moderately high external input food and cash crop agricultural production system to be developed. Those in charge were aware of the fact that a shelterbelt system of trees, by its components and aims, has to be considered as an agroforestry land-use system (e.g., Darnhofer 1983). Indeed, the attempt to design a shelterbelt should only be the result of a problem-oriented diagnostic approach to the specific land-use systems, which requires inputs from a multi-disciplinary team of specialists including agrometeorologists (Darnhofer 1983). And there is no substitute for a thorough site-specific design effort, including a local cost/benefit analysis as an obligatory component (Rijks 1986).

Below we have summarized site-specific recommendations, made as the agrometeorological input for the design effort for the Guanacaste region experiments. They were thoroughly discussed with the local chief agrometeorologist – one of the co-authors of this paper – because they were meant to strengthen his input to the multi-disciplinary team established locally to design the system and the experiments.

The materials of which natural shelters are made preclude the use of wind tunnels for the direct design of an optimum shelter (Plate 1971). The effect of shelter shape and permeability on the degree of sheltering is incompletely understood. The same is true for such effects as ground roughness in front of the shelter and the effect of areal roughness that multiple shelters add to individual shelter effects. The physical forces required to cause a certain damage in a specific tree or plant are virtually unknown. Nevertheless, wind tunnel and field research have provided enough information over the past 50 years to formulate general guidelines and to prevent several serious mistakes. However, local site-specific research will certainly expand those guidelines.

To formulate our recommendations, we made use of established reviews of the extensive agronomical and (agro)meteorological research on the improvement of crops and soils by wind protection (van Eimern et al. 1964; van Eimern 1968a, 1968b; Plate 1971; Rosenberg 1975; Sturrock 1975; Radke and Hagstrom 1976; Grace 1977; Fuchs 1979). But we also used more recent reviews, including and extending new and changing emphases and insights in these fields of study (Rosenberg 1979; Hagen et al. 1981; ILACO 1981; Wenner 1983; Jensen 1985; MacKerron and Waister 1985; Pitcairn and Grace 1985; Grace 1986; McNaughton 1986).

Choices made

We conclude from recent local wind measurements in the region, using established measuring systems (van Eimern 1968c; WMO 1981), that by far the foremost problem to be expected is the mechanical impact of extremely strong winds. All other agrometeorological considerations, even those related to water use and shading, are secondary. These will come in only in cost/benefit ratio calculations once this main problem has been shown to be solvable. This reduces our case study to one in which only wind reduction effects under neutral atmospheric conditions should be considered. So we excluded considerations of water use efficiency, area occupied by the belts, shading of crops nearest the trees and damage other than from mechanical impact of air movement.

It should be noted that on the subject of mechanical damage to crops, new insights appeared about a decade ago (Grace 1977). Mechanical effects are now considered to

be of more importance under many conditions (MacKerron and Waister 1985; Pitcairn and Grace 1985; McNaughton 1986).

The choice to use multiple tree breaks appears justified by the increase in roughness over a larger area in addition to separate wind break effects (Jensen 1985), and by the multipurpose use of trees and their products which is economically possible (Wenner 1983). In larger scale agriculture, where irrigated cash and food crops have to be protected against very strong winds, relatively narrow rows of trees are to be preferred above wider belts as an intercrop or scattered trees/bushes (see the table). The first mentioned kind of wind protection is traditionally well known in Europe and Japan, the latter two better known in Africa (Stigter 1985) but also in Costa Rica (Budowski 1983). However, strip cropping experiments (Radke and Hagstrom 1976) are worth trying on a somewhat smaller scale or in combination with tree systems. This may even include artificial fences whose permeability can be more easily manipulated. More experience will be gained in this way on actual agronomical wind damage risk in the area. At present this is lacking completely and relatively little can be learned from the literature for the extreme conditions concerned. Below we will mainly discuss the use of tree rows and come back to strip cropping at the end of this paper.

Factors to be considered in the design of a multiple shelterbelt system are: shape, composition, height, length, width and direction of a belt, and distance, numbers and permeability in the composite system. Subsequently one has to decide on measurements and observations to be made in the field trials. Also some other more general recommendations can be made (see the review table at the end).

Physical features

We will now consider briefly the physics of air movement in shelterbelts. Gustiness and turbulence complicate the determination of the threshold wind speeds that cause damage. In the adiabatic atmosphere, turbulent energy is derived from the kinetic energy of the mean wind; and in the atmospheric boundary layer, turbulence (eddy formation) is due to mechanical interference with the steady flow of air. The gustiness of the wind is therefore largely determined by upwind obstructions and their geometrical characteristics. The smaller scale turbulence is determined by the roughness of the upwind surface in general. The larger the eddy size and the more vigorous the eddy movement, the more kinetic energy eddies contain and the more horizontal momentum they exchange vertically. This is more damaging to objects meeting such eddies.

Windbreaks not only change the average wind speed by the friction (drag force) due to their obstruction, but they contribute to eddy formation and to breaking up eddies (and slowing down their motion) in the approach flow by the friction in their pores. The first can be harmful (van Eimern et al. 1964; McNaughton 1986) and the second will be beneficial in several respects (Rosenberg 1979). When permeability increases, the eddy formation contribution of a windbreak decreases in importance, until no flow separation occurs in front of the break. But then jetting through the windbreak takes over as the damaging factor for those cases in which eddy break up and air movement slow down have become insufficient. This simplified picture may assist in understanding design recommendations, including empirical ones.

In what is called primary wind injury in plant stress typology, damage to whole plants and trees (swaying, shaking, bending, lodging, breaking), and plant and tree parts (premature fruit and flower shedding, breakage, bruises, lesions, abrasion), is basically due to mechanical stress caused by asymmetrical air pressures acting on plant parts. However, secondary injuries to leaves and roots, by repeated flexing of leaves, or by

rubbing of adjacent leaves or by soil particles, are involved as well (Stigter 1985). Such damages influence photosynthetic capacities, evaporation and disease susceptibility. As to the kind of damage to be expected in the Guanacaste region, lodging (breaking) of the stems of unprotected crops and leaf surface damage are of prime importance. However, there is now sufficient proof that mechanical excitation of plants is likely to cause reductions in growth rate, coupled with a whole suite of anatomical responses, some of which will adversely influence yield quality (Grace 1986).

This stresses the absolute necessity of observations of phenological characteristics and yield parameters in wind protection trials, to which we will come back later on.

Shape, composition and height

There are many reasons for the selection of shelterbelt tree species (Raheja 1963). We limit ourselves here to agrometeorological aspects of rows of protecting trees. Then height H is a major factor, because protection length of the area behind a narrow tree belt is a function of H/z_0, with z_0 a factor quantifying roughness of the surface under the approach flow (Hagen et al. 1981). From this point of view, the optimum height has to be a compromise between maximum possible height and resistance against mechanical wind damage of the tree species. Wind damage of the highest trees, as well as jetting through the trunks area, may be reduced by two to three storeys of trees, diminishing in height on the windward side. This influences the choice of composition and shape of the belt, and determines partly its permeability as well. It has the advantage of leading to a triangle shape with an almost vertical lee edge and an angled windward edge. This contributes to reducing the generation of damaging eddies at the windbreak top by deflecting the air; and to management of permeability (Raheja 1963; Gandemer 1981; Onyewuto 1983).

The latter factor is more important in our case. At extremely high wind speeds, one should use the minimum permeability one can afford. At the same time one should allow for enough throughflow (assisted by underwood manipulation) at the bottom to prevent overtopping of too much air. This contributes to reducing the formation of dangerous eddies.

Length, width and direction

Too large a width complicates permeability problems, uses too much land and does not contribute to mitigation of eddy effects, which occur primarily when height is greater than width (Gandemer 1981). As to the configuration of belts, protection of crops at four sides or in circles might be preferable when strong winds occur from different directions, but this has drawbacks in mechanized agriculture. The choice is thus for long belts, preferably 100 m to 1 km long, as much as possible perpendicular to the strongest winds. In our case of persistent trade winds, this is a very acceptable solution.

In trials where shorter windbreaks have to be used, lateral flow should be prevented. Establishment of porous cheeks at both ends and both sides, of the same composition as the main belt and each about the same length as the height of the highest trees in the belt, may solve the end effect problem and contribute to the prevention of lateral flow between the belts in a multiple system (Gandemer 1981).

Distance, number and permeability

Permeability of one narrow belt of trees should be considered separately from permeability of a system consisting of a number of such belts at distances between 10 and 20 H.

The resulting protection at and below the height of the protected crops is not identical or nearly so when the number of belts is very small or very large. For single belts, recommendable minimum permeability, even for extremely strong winds, is likely to be somewhat lower than hitherto accepted. It is on the order of 20% (Gandemer 1981; Hagen et al. 1981; Jensen 1985) at the top half or two-thirds of the break (depending on crop height) with preferably an increase of permeability towards the bottom half or third (Gandemer 1981; Onyewotu 1983).

It is evident from the measurements interpreted by Hagen et al. (1981), that in case of an overall 20% porosity, the quiet triangular standing eddy zone (Plate 1971) or recirculation zone (Hagen et al. 1981), which can be detected at lower permeabilities behind belts, will start closer to the belt and much closer again below that permeability. And the wake zone beyond it, which may become more harmful to crops than the original approach flow (van Eimern et al. 1964; McNaughton 1986), will start closer to the belt as well. Decreasing permeability with height permits some more throughflow at the lower wind speeds near the bottom, and therefore simultaneously contributes to higher safety in the wake flow closest to the belt (Gandemer 1981). The outer bound of the wake flow is dictated by the more energetic processes in the wake, and so its extent does not vary very much with permeability up to 50% (McNaughton 1986).

The fact that the quiet zone is triangular and therefore the wake flow, which is accelerated by the flow above break height, is situated above that zone, shows the advantage of a large height difference between protecting belt and protected crops.

It has been shown with much evidence earlier (van Eimern et al. 1964), and recently well summarized by Jensen (1985), that a small number of identical windbreaks slightly diminishes shelter effect behind the rearmost break of such systems, in the whole range of distances from less than 10 H up to 20 H. So the resulting permeability of the whole composite system has become higher. Between the tree rows the situation will depend on permeability of single rows and distances as well. It will at smaller distances be more protective for the permeability distributions advocated above. This applies especially to the wake flow zone, which is likely to be the more problematic (Gandemer 1981). This points to a choice of distances not much higher than 10 H in our case. To this will certainly be added an increasing decoupling of all protected areas from the main flow, so an ever increasing overall protection, when the number of rows becomes substantial, that is when it covers from one to many kilometers. An areal roughness has in this way been established from this composite system of narrow tree rows (Jensen 1985). The same effect of decoupling would be obtained with interspersed trees, bushes etc. higher than the crops to be protected and over a considerable area (Hagen and Skidmore 1974; ILACO 1981; Jensen 1985).

Measurements and observations

As mentioned earlier, where mechanical damage from strong winds is the primary limiting factor, the agronomist member of the team should pay primary attention to phenology, growth and yield parameters and visual or even microscopic observations of actual mechanical damage. This will make it possible to observe differences between unprotected crops and protected ones at different distances from belts. On the meteorological side, cup anemometer measurements should be made as an indication of what is going on, although errors exist (MacCready 1966; Busch and Kristensen 1976). It should be noted, however, that turbulence and gustiness are not quantifiable with cup anemometers. Determinations of average wind speeds, preferably as 10-minute to half-hourly averages at 20 cm above the crops, are therefore not more than indicative in

simultaneous comparisons of protection at different places. Wind profile measurements will normally be useless because of the existing streamline deflections.

In fact the non-meteorological observations mentioned will be much more indicative of integrated consequences of mechanical stress than wind measurements can be at the moment. This situation will remain until more basic knowledge has led to increased understanding, which should make it possible to develop more relevant measuring methods. Indications of maximum speeds in gusts, with pressure anemometers, could already now be very helpful in risk assessments prior to introduction of agriculture and during the trials. As soon as mechanical-stress-induced yield (quality) reductions appear to remain under acceptable thresholds, water use efficiency determinations will become of the highest importance in irrigated agriculture or under advective conditions.

Permeability should be recognized as the most important single parameter describing narrow shelterbelts. A quantification of differences in permeability can be made by comparing relative minimum wind speeds just above crop height at the same distance from the same or different belts (Bean, Alperi and Federer 1975). In our low permeability cases this distance should be of the order of 2 H. This might well be the most fruitful use one can make of cup anemometers in our case. Determinations of absolute values for permeability are much more difficult and can physically only be made by measuring pressure drops across belts. Visual observations are only of limited value and photographs may assist but cannot indicate differences due to foliage flow characteristics, which are of high importance.

Final remarks

The main recommendations made above have been summarized and compared with wider belts and scattered trees and bushes in Table 1. We believe we have shown that the existing literature yields information and results from which sensible recommendations can be derived. This strengthens the agrometeorological input into the trials needed to determine the agricultural potential of the extremely windy dry season in the Guanacaste region.

Experiments with strip cropping should be included from the beginning in order to gain more insight into the consequences of wind stress. Recommended distances are here again 10 H and recommendations on measurements and observations made above apply to such experiments as well. The difficulties that Radke and Hagstrom (1976) had in interpreting some of the results they review on strip cropping arise from their lack of consideration of the influence of porosity of the strips as a function of height. Whether in strip cropping, in using narrow tree rows or in mixed experiments, cost/benefit ratio determinations are absolutely necessary to understand the proper gain from the multipurpose role of trees and from yield (quality) increases due to the trees/crops applied for protection from wind.

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Table 1 Recommendations on windbreaks for crop protection.

Windbreak characteristic	Rows / strips	Wider belts	Scattered trees and bushes
Shape and composition	High slope triangle with straight lee (trees with underwood); double or triple rows; least damage-prone trees and crops	Open	Creates fewest eddies of damaging shape
Height	Not adding to tree damage; Large distance between tops of protecting and protected crops		
Length	As long as possible from farm management point of view	Depending on kind of protection wanted	Wide area
Width	Narrow, with few rows of trees/crops	Smaller than length	Wide area
Direction	Perpendicular to prevailing damaging wind or in network arrangement	With angle to damaging winds but more direction independent	Wind direction independent
Distance	10 H (very strong winds/strip cropping); 20 H strip (strong winds and advection conditions); porous cheeks against end effects	Large between components	Large enough for crop growth in between and under trees
Number	Many because multiple windbreaks decouple protected area from main flow	One	Many to decouple the protected area
Permeability	Somewhat higher at the bottom but without tunnelling effects, decreasing with height to a minimum of about 20% for strongest winds	Open, without jets occuring	
Measurements and observations	Windspeed (20 cm above protected crops) with very strong and other damaging winds; evaporation/soil moisture under strong winds and advection; other damaging factors (such as transported sand) under spe- cific conditions of windbreak use. In all cases: crop phenology, visual or microscopic damage to crop parts, economic yields in comparison with unprotectd crops		
Other Recommendations	Determination of cost/benefit ratios; quantification of permeability, relatively (at distance of 2 H) and absolutely (e.g. photographic approximation, plant material density mapping); determination of multi-purpose use of trees and their products		

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Wind reduction and soil water availability near a 'Caatinga shelterbelt'

P.C.E. Frota, A.D. Ramos and E. Carrari

Agricultural Research Agency of Ceara (EPACE)
Av. Rui Barbosa, 1246 Fortaleza, Ceara, Brazil

Abstract

This research was done in the Experimental Farm of Research Unity of Central Country – Ceara (EPACE), in the semi-arid region Northeastern Brazil, at 200 m altitude and geographic coordinates 4° 50' S and 39° W. It used a belt of natural caatinga, with mean height of 4 m and 20 m width, remaining after clearing of the area to get improved pasture for goats. Measurements of wind speed, evaporation and soil water content were done using the proper equipment set at the following distances after the windbreak: 4,8 and 16 m. Wind speed decrease was measured in the range of 77 to 94% and evaporation reduction had a variation from 0,5 to 2,4 m.

Introduction

The state of Ceara, in the semi-arid region of Brazil, presents strong water deficit characteristics in most of its territory and during considerable time periods (Hargreaves 1974; Golfari 1977). The vegetation is mostly poor in wood-producing species. The small water volume held in the soil is subject to high losses due to evapotranspiration. On the other hand, evapotranspiration depends greatly on solar radiation intensity, temperature, photoperiod, atmospheric moisture and winds (Mota 1975), which are related to edaphic factors and vegetative cover.

Control of wind speed by shelterbelts creates a microclimate that may reduce the water deficit, increasing the duration of water availability in the soil, and thus protect the soil against erosion and removal of litter from the rows between the trees. Shelterbelts have played an important role in temperate and tropical countries giving protection to the crops and increasing productivity (FAO 1981).

Intensive investigations of shelterbelt influence on productivity have been made in regions where eolic action causes damage to crops. In Bulgaria, protection by a shelterbelt of *Robinia pseudocacia* 2 meters broad and 9 meters high increased volumetric production of sugar cane 32% and sugar content 1% (Dzhodzhov and Georgiev 1980).

A pasture system with a central bosquet and shelterbelts of trees on the borders gave an increase of 20% in goat productivity (Wilson 1980). The Ukraine had in 1980 over 416,000 hectares of shelterbelts giving protection to 4 million hectares of crops, resulting in increased agricultural productivity on the collective farms, as well as producing forest products (Dmitrenko 1981). Tribunskaia and Sheherbakova (1978) concluded that shelterbelts in semi-desert regions of north Caucaso-Russia saved 100 million rubles per year in agricultural product. Bedrov (1978) stated that those systems can offer extra

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income in arid zones by causing higher water retention in the soil, and so increasing agricultural productivity.

In Brazil, there have been few studies that evaluated the potential of these techniques. Most species recommended in the literature for creating shelterbelts in arid and semi-arid regions have not been tested in Brazil. Recent results have shown that some experiments with *Eucalyptus excerta, E. alba, E. camaldulensis* and *E. crebra* are promising for use in arid climates (Pires and Ferreira 1982).

Methods

We present here partial data of a research project that aims to determine the efficiency of natural caatinga vegetation used as a shelterbelt. The experimental site is in Quixad, Ceara, (05° S; 39° W; 200 m asl), a semi-arid region of north-eastern Brazil. Mean annual rainfall is 700 mm with rains during summer and autumn and a distinct dry season of 7 to 8 months. Soils were classified as non-calcic brown soils, with an ochric A horizon, clay texture, and rolling topography with 3 to 6% slopes.

A caatinga natural belt with mean height (H) of 4 m and width of 20 m remained after clearing an area for an improved goat pasture. Three sets of instruments were placed at 4, 8 and 16 m (1H, 2H and 4H) from the windward and leeward sides of the belt. Wind speed was measured at 1.5 m height; evaporation was measured by a USWB Class A pan; and soil moisture content was found by gravimetric sampling from three depths: 0.10, 0.30 and 0.50 m.

Results and discussion

Table 1 shows wind speed and Class A pan evaporation during the period from July 1984 to July 1985. (Measurements of evaporation in the period from January to May 1985 are not shown because of the frequent occurrence of rainfall.) When the data from the nearest leeward observations (4 m, 1H) are compared with data from 16 m (4H) windward (considered to be uninfluenced by the shelterbelt), reduction in wind speed varied from 77% to 94%; and reduction in evaporation varied from 5% to 39%, corresponding to values of 0.5 to 2.4 mm/day (Table 2, page 536). Data from 8 m and 16 m (2H and 4H) indicate effective influence in the lee of the shelterbelt as far as 4H or 5H, consistent with the data of Pavari (1961) for a shelterbelt of medium density.

Measurements nearest the windward edge of the shelterbelt showed a considerable increase in wind speed. This is probably due to the formation of a vortex at the leading edge of the dense shelterbelt, causing an increase in evaporation from the Class A pan (Table 1). Reduction of evaporation follows the trend of the wind speed, indicating an eolic influence, mainly during the months of mild temperatures and higher relative moisture values.

Moisture content of the soil from March through July 1985 is shown in Table 3 (windward) and Table 4 (leeward). Comparison of the mean values at 4 m and 8 m leeward with corresponding values to the windward shows that soil moisture content is always higher on the leeward side. Comparing the data from the nearest leeward point (4 m, 1H) with those from 16 m windward, mean soil moisture in the upper 0.5 m was 5.9 percentage points higher in the leeward location.

Table 1 Mean values of wind speed (V) in km/h at 1.5 m height and evaporation of Class A Pan (E) in mm, at different distances from shelterbelt

local		windward						leeward					
		(16m)		(8m)		(4m)		(4m)		(8m)		(16m)	
Months		V	E	V	E	V	E	V	E	V	E	V	E
07/84		1.63	5.9	1.45	5.4	2.93	6.2	0.10	3.6	1.13	4.4	1.43	5.0
08/84		2.86	6.7	2.67	6.6	4.97	7.7	0.20	4.3	1.58	5.5	2.15	6.2
09/84		3.45	8.2	3.22	8.4	6.50	8.9	0.40	7.0	2.50	7.5	2.81	8.0
10/84		4.27	9.0	4.21	8.9	8.04	9.4	0.74	8.2	2.89	8.7	3.59	9.0
11/84		4.62	9.1	4.51	9.1	8.71	9.4	1.04	8.3	3.07	8.6	3.93	8.9
12/84		4.18	9.4	4.16	9.2	8.69	9.7	0.85	8.9	2.96	9.1	4.07	9.3
01/85	rainy period	3.02	-	2.90	-	5.57	-	0.52	-	2.23	-	2.76	-
02/85		1.92	-	1.88	-	3.11	-	0.15	-	1.30	-	1.75	-
03/85		1.68	-	1.62	-	3.21	-	0.11	-	1.25	-	1.67	-
04/85		1.62	-	1.60	-	2.91	-	0.11	-	1.24	-	1.52	-
05/85		1.54	-	1.51	-	2.13	-	0.10	-	1.20	-	1.46	-
06/85		1.93		1.80	4.9	3.00	5.0	0.13	3.9	1.28	4.2	1.71	4.8
07/85		2.50	6.3	2.02	5.6	3.40	6.0	0.15	4.2	1.37	5.1	1.91	5.4

Table 3 Soil moisture content windward of the shelterbelt

Distance from shelter-belt (m)	Depth (cm)	Soil Moisture, percent											
		7/3	2/4	16/4	25/4	2/5	30/5	4/6	4/7	11/7	25/10	mean1	mean2
		rainy period											
4	10	16.7	15.2	16.1	17.9	15.4	11.8	12.1	11.1	11.6	14.2	14.2	16.0
	30	19.8	16.7	16.9	20.4	17.5	13.6	11.9	14.3	15.0	14.3	16.0	
	50	21.1	18.4	20.9	21.4	20.1	15.3	13.5	14.6	16.4	14.0	17.6	
8	10	15.7	14.3	16.9	19.6	18.0	15.0	11.1	13.0	12.6	15.5	15.2	16.1
	30	17.3	17.8	15.5	18.5	17.9	13.2	12.6	15.1	14.1	14.5	15.7	
	50	17.2	20.5	18.2	20.4	21.8	15.3	14.0	14.4	16.1	16.8	17.5	
16	10	13.8	15.8	15.0	19.7	15.2	12.9	13.4	10.5	10.8	14.0	14.1	15.2
	30	14.3	17.6	18.6	21.4	17.3	15.1	13.6	11.9	11.1	14.1	15.5	
	50	15.1	16.3	15.1	21.7	17.9	17.5	15.0	12.1	13.1	15.9	16.0	

mean1 = for 10 samples
mean2 = for three depths

Table 4 Soil moisture content leeward of the Shelterbelt

Distance from shelter-belt (m)	Depth (cm)	Soil Moisture, percent											
		7/3	2/4	16/4	25/4	2/5	30/5	4/6	5/7	11/7	25/7	mean1	mean2
		rainy period											
4	10	18.8	19.2	18.5	24.6	16.6	13.2	13.3	17.9	16.6	19.4	17.8	
	30	23.1	26.5	18.2	32.7	17.4	14.9	15.2	18.9	18.8	21.9	20.8	21.1
	50	33.0	25.44	22.2	33.9	21.0	27.2	18.3	23.2	20.0	22.2	24.6	
8	10	16.3	21.1	17.6	18.5	15.8	12.9	12.5	13.6	15.0	19.7	16.3	
	30	18.6	22.6	22.4	24.5	16.7	19.4	18.0	17.3	17.9	20.2	19.8	19.1
	50	24.7	22.0	25.2	29.7	20.1	18.4	16.9	18.1	17.0	20.6	21.3	
16	10	13.8	18.6	14.7	19.0	14.1	11.8	12.1	11.4	11.6	16.8	14.4	
	30	15.3	18.4	16.8	24.9	15.5	12.0	12.4	10.6	13.4	19.0	15.8	15.8
	50	16.9	22.9	18.3	24.6	18.1	13.9	12.9	11.6	13.8	19.9	17.3	

mean1 = for 10 samples
mean2 = for three depths

Table 2 Reduction of wind speed (V) and Class A pan evaporation (E) in lee of shelterbelt as compared with 16 m windward.

Months		Reduction, percent					
		4 m leeward		8 m leeward		16 m leeward	
		V	E	V	E	V	E
7/84		94	39	31	25	12	15
8/84		93	35	45	18	25	8
9/84		88	15	28	9	19	2
10/84		83	8	32	3	16	0
11/84		77	9	34	5	15	2
12/84		80	5	29	3	3	1
1/85	rainy	83	–	26	–	9	–
2/85	period	92	–	32	–	9	–
3/85		93	–	26	–	1	–
4/85		93	–	33	–	6	–
5/85		93	–	22	–	5	–
6/85		93	24	34	18	11	6
7/85		94	33	45	19	34	14

Conclusions

The shelterbelt of caatinga vegetation reduced wind speed mainly in the areas close to the shelterbelt. As a consequence, leeward evaporation was diminished, causing an increase of soil moisture.

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SECTION 8

Miscellaneous

- The climatic aspects of the 1982/1983 wildfires in Nigeria. A.B. Ogurtala

The climatic aspects of the 1982/83 wildfires in Nigeria

A.B. Oguntala

School of Forestry, Forestry Research Institute of Nigeria
Private Mail Bag 5054, Ibadan, Nigeria

Abstract

The forest-fire climate of parts of Nigeria was studied in relation to a fire incidence which destroyed thousands of hectares of forest and farm plantations in different parts of the country during 1982/83 dry season.

Over 70% of the land area of Nigeria experiences annual bush fires and economic losses as a result of the 1982/83 fire incidence alone was more than N90 million ($30.00 million).

It was observed that a declining number of rainy days in different parts of the country coupled with increasing maximum air and soil temperature and decreasing relative humidity (a favourable fire-climate or high fire - danger rating) predisposed the crops (forestry and agriculture) to fire risks. After the fire regeneration in exotic trees like Pinus caribaea *and* Gmelina arborea *was higher than of indigenous species like* Khaya ivorensis, Triplochiton scleroxylon *and* Terminalia ivorensis.

The results of the study indicate that fire incidence could be predicted from available meteorological data. A fire - prediction/control system is urgently needed for the country to prevent annual economic losses, and environmental disasters.

Introduction

In Nigeria fire has been part of the environment for centuries. The savannah covering 83% of the land is still being subjected to annual bush fires, while the rain forest is being cut down in large areas and burned during land preparation for agricultural and other plantation purposes. Apart from the human factor, frequent drought occurrences in Nigeria have been predisposing the vegetation to annual fires.

Climatic studies in southern Nigeria (Oguntala 1975; Oguntala and Oguntoyinbo 1982) indicate that there has been a significant change in the number of rainy days in parts of the country and that this has contributed to the spread of bush fires.

It has been suggested that bush fires can be predicted, by making use of climatic information (Reifsnyder 1978; Oguntala 1982). The need to control bush fires is becoming increasingly important in the tropics in view of the increasing cost of damages done by fire to agricultural and forest plantation projects.

This paper diagnoses the climatic factors that predisposed farms and forests to fire in the 1982/83 dry season. The extent of damage to crops in parts of the country is examined from both economic and ecological view points.

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The extent of bush fires in Nigeria

Table I gives the summary of various vegetation types in Nigeria. These vegetation types have varied bioclimates which are related to their structure and species composition. Out of Nigeria's 983,213 km^2 area, 73% of the land consisting of all vegetation types has medium to high fire danger rating during the dry season. Before the 1982/83 drought occurrence, the high forest had a very low fire danger rating; however, with increasing human activities in the area, and increasing drought susceptibility, the area consisting of about 10% of the land area of the country experienced serious fire occurrences during 1982/83. Traditionally, major parts of the savannah (sudan, guinea and derived) consisting of 83% of the total land area of 818,633 km^2 are burned annually. Areas which totally escape annual fires include the Sahel, fresh water swamp forest, and the coastal mangrove vegetation constituting only 7% of the land area or 69,838 km^2. The Sahel has no vegetation to be burned while the swamp/coastal vegetation is water-logged most of the year. Increasing human activities particularly shifting cultivation, grazing, and timber exploitation occur in over 70% of the land area of the country (forest and savanna) which are burned annually. Fire is commonly used in shifting cultivation practices, while cattle herdsmen use fire to clear old grasses to provide green flushes during the dry season.

The sudan and northern guinea savannah usually get burned first, while the most severe bush fires occur in the southern Guinea savannah which later spread to the high forest zone.

Table 1 Area of vegetation types in Nigeria

Vegetation Types	Area (km^2)%	Total land area
Sahel	31,463	3
Sudan savanna	342,158	35
Guinea savanna	400,768	40
Derived savanna	75,707	8
Lowland rainforest	95,375	10
Fresh water swamp	25,563	3
Mangrove forest and coastal vegetation	12,782	1
Total	983,213	100

The economic importance of the 1982/83 bush fires in Nigeria

Annual bush fires have been a part of the Nigerian land-use problems for years. Indiscriminate and malicious bush burning has resulted in colossal economic losses to Nigeria for many years. Huge losses are recorded annually of forest plantations and food crops. Wildlife is destroyed resulting in the depreciation of tourism potentials.

Over 17,000 ha of forest plantation including those of two Agriculture Development Projects were burned in the 1982/83 dry season alone (Federal Department of Forestry 1984). Assuming there is a 50 per cent recovery, this is equivalent to a loss of about N-

90 million in one fire year alone. This does not include losses in forest resources outside plantations and also wildlife resources. Table 2 gives the details of losses in one of Nigeria's 19 states. The total loss was equivalent to about N-19 million based on existing compensation rate in the state. The losses in the drier northern states of Nigeria are most likely to be higher.

The practice of bush burning in Nigeria is very common and is reducing the forest estate annually. It is causing rapid vegetation changes which ultimately encourage desert encroachment.

Table 2 Effects of drought/fire in Bendel State, Nigeria 1982/83

Crops destroyed	Area ha	No. of Trees	Estimated value N
Cocoa	8,500	141,450,000	11,560,000
Oil palm	2,500	375,000	248,000
Rubber	1,500	675,000	540,000
Cola nut	100	15,000	45,000
African pear	10	1,500	7,000
Coffee	10,000	10,000,000	3,000,000
Citrus	250	37,500	123,000
Duiket nut	100	15,000	162,000
Total	22,960	152,569,000	19,580,000

Source: Federal Department of Forestry (1984). 1 US$ = 3.5 N)

The biological impact of the 1982/83 fire incidence in Nigeria

The effects of fire on tree species in different plantations were studied in April 1983 in some forest reserves of southern Nigeria. The results are presented in Table 3. In all the reserves the percentage of trees in the plantations that were completely burned varied from 5% in *Eucalyptus grandis* at Enugu Ngwo to 87% in a 3-year-old *Triplochiton scleroxylon* plot at Sapoba Forest Reserve. The highest values of trees that were completely burned were at Sapoba Forest Reserve, (26% in *Pinus caribaea* to 87%, Triplochiton scleroxylon). Sopoba plantations were burned more than the other plantations because the trees there were younger than in the other reserves and because of the relatively higher ground flora production (seeds) which had remained uncleared prior to the fire incidence. Sapoba also has higher rainfall generally than the other sites; this factor also contributes to the development of a higher fuel load at Sapoba than in the other sites.

There were also differences in the responses of individual tree species to fire. The species with the highest resistance to fire was the 9-year-old *Pinus caribaea* with values as high as 84% at Enugu - Ngo and 74% survival at Sapoba. *Tectona grandis* at Umuahia - Bende also had 77% survival. In both species the bark of the trees gave a great resistance to the fire, burned barks peeled off, while new ones were developed. Both species are exotic trees being introduced into most parts of the country.

The trees with the least resistance to fire were the indigenous high forest tree species also being developed as plantation species, following large scale clearance of the rainforest, the natural habitat of the species (Table 3). The species include *Triplochiton scleroxylon, Kaya ivorensis* and *Terminalia superba*. These species have no natural resistance to fire, as fire has never been part of their environment, unlike the savanna species.

In most of the species, regeneration was from the base (i.e., the root stock) if the whole stem had been lost to the fire. Fire, therefore, has to be kept away completely from such plantations.

Table 3 The effects of fire on different tree species in some Nigerian forest plantations during March 1983.

Forest plantation	No. of trees	Age (years)	Mean Girth (cm)	Total burned %	Regen. from base %	Whole stem surviving %
Sapoba						
Triplochiton scleroxylon	412	6	22.7	56	22	-
T. scleroxylon	90	3	14.8	87	13	-
Khaya ivorensis	201	2	7.8	77	[illegible]	-
Pinus caribaea	156	5	18.0	26	-	74
Gmelina arborea	152	5	41.9	0	34	66
Terminalia ivorensis	232	4	18.1	74	22	-
Enugu-Ngwo						
Pinus caribaea	193	9	38.6	10	-	84
Eucalyptus grandis	196	9	34.2	5	61	34
Gmelina arborea	194	9	25.6	0	56	44
Azadirachta indica	70	9	18.3	0	51	49
Umuahia-Bende						
Triplochiton scleroxylon	185	6	20.3	38	13	49
Pinus caribaea	204	6	26.3	36	-	64

Fire climate in Nigeria

Precipitation

Precipitation is one of the elements of weather used to predict fire occurrences because of its direct relationship with fuel moisture content within plant ecosystems. In Nigeria, there is a well-defined dry season, that is a period of low or no precipitation. The length

of the dry season varies with different vegetation types in the country. The dry season periods extends from 7 - 8 months in arid northern part of the country to only about one month in the wet coastal areas of the country. The length of the growing season (rainy season) is usually short in the savanna region of the country. The number of rainless period is long and is increasing (Table 4). The decrease in number of rainy days has been increasing the susceptibility of the country to drought and storms (floods); drought because of the reduction of the growing season of plants due to lack of rainfall and storms because of the spread of the total annual rainfall has been shortened resulting in higher rainfall per day (Oguntala and Oguntoyinbo 1982). The dry season starts from August in some parts of the Sahel zone before spreading to the rain forest zone in November.

Temperature

The study of temperature characteristics in southern Nigeria during the dry season (Tables 4 & 5) indicate that temperatures as high as 35 - 37 °C were obtained in the drought period of 1982/83 in southern Nigeria. Northern parts of the country recorded higher figures. The mean dry season temperature in parts of southern Nigeria is normally about 32 °C. At Sapoba (rainforest reserve) a mean maximum temperature of 35.1 °C was obtained in 1982/83 dry season which was the highest since 1978. Temperature affects the drying factor of plants, soils and animals. It affects the evapo-transpiration process, it also speeds up the rate at which dry combustible plant matter is made available for ignition (Van Wagner 1974).

Table 4 Summary of the climate of two forest sites in southern Nigeria between 1960 and 1979. (Mean values)

Period	Total Rainfall mm	No. of Rainy days	Temperature Max. °C	Temperature Min. °C	Relative Humidity %
Ibadan (Forestry Research Institute Headquarters)					
1960-64	1452	128	26.2	21.3	75
1965-69	1340	123	25.8	21.4	74
1975-74	1211	93	26.9	21.3	74
1975-79	1677	91	26.9	21.8	75
Sapoba Forest Reserve					
1960-64	2332	153	26.5	21.6	76
1965-69	2056	150	25.6	22.5	82
1970-74	2099	142	23.3	21.6	78
1975-79	2028	132	31.1	21.1	82

Table 5 The dry seasons climate of Enugu (Ngwo) Umuahia (Bende) and Calabar (Awi) FRIN Forest Experimental Stations (November 1982 - March 1983).

Site	Month	Climatic parameters				
		Temperature		Relative humidity	Rainfall	
		Max. °C	Min. °C	%	Amount (mm)	No. of days
Enugu (Ngwo)	Nov. 1982	31	21	61	25	3
	Dec. 1982	32	22	59	1	1
	Jan. 1983	32	19	24	0	0
	Feb. 1983	35	23	48	5	1
	Mar. 1983 *	32	19	24	0	0
Umuahia (Bende)	Nov. 1982	32	23	91	41	3
	Dec. 1982	31	21	77	5	1
	Jan. 1983	31	17	32	0	0
	Feb. 1983	33	25	53	0	0
	Mar. 1983 **	37	25	54	2	1
Calabar (Awi)	Nov. 1982	31	23	83	205	6
	Dec. 1982	32	24	82	42	2
	Jan. 1983	32	19	71	0	0
	Feb. 1983	35	24	64	23	1
	Mar. 1983	36	26	64	1	1

* Fire at Engu-Ngwo
** Fire at Umuahia-Bende

Relative humidity

Relative humidity generally follows the rainfall pattern: it is usually high during the rainy season and low during the dry period. Humidities as low as 24% were obtained in the derived savanna zone of Enugu Ngwo; and the high forest zone of Bende - Umuahia had humidities as low as 32% (Table 5). In the coast-line area of Awi - Calabar, the relative humidity for the same period was 64%.

Relative humidity has commonly been used in temperate countries to give a quick assessment of the degree of fire danger. Air relative humidity influences the state of dryness of combustible plant matter.

Increased human activity in the high forest zone in the past few years – particularly massive forest clearance (for farming and other activities) – has increased the albedo and has adversely affected the microclimate of the area Oguntoyinbo and Oguntala (1978). The zone now has a fire climate favourable to fire and has been seriously predisposed to bush fires.

Predicting forest fires

In order to be able to predict forest fire weather, standard meteorological stations were set up in different forest reserves in parts of Nigeria. Data on rainfall, air and soil temperature, relative humidity, evaporation and wind speed, are obtained daily from these stations. The summary of the climatic data for Ibadan and Sapoba are presented in Table 4. A significant decrease in the number of rainy days in Ibadan during the period from 1960 to 1979 was observed. Ibadan is the northern tip of the rainforest. A non-significant decrease in the number of rainy days was observed at Sapoba. This decrease in number of rainy days which was common in most parts of Nigeria has been predisposing the vegetation to fire. The growing season has been shortened and the dry matter production particularly in the dry season has been increasing (Oguntala 1979, 1981).

The summary of the dry-season climate in forest plantations of southern Nigeria is presented in Table 5. It is characterized by abnormally high temperatures (for southern Nigeria) particularly during February/March, and by very low humidities associated with low rainfall.

An accidental forest fire started at Sapoba Forest Reserve in the late afternoon of March 1983. Microclimatic data from different plantation plots in the reserve were analyzed to determine fire weather conditions. Maximum temperature at 1800 in the forest plantation was 34 °C compared with 37 °C in the open, while the relative humidity at 1600 was 47% in the open compared with 65% in the plantation.

The fire danger index was calculated using the modified Angstrom forest fire predicting equation (Reifsnyder 1978):

$$B = 3.3 - 5R + T/10$$

where
B = fire danger index
R = relative humidity expressed as a fraction from 0 - 1
T = air temperature in degrees Celsius.

Sapoba Forest plantations had a fire danger class of 4.1 (high fire danger) when the fire started in the late afternoon.

The results of this study indicate that forest fire prediction is feasible in Nigeria and the tropics although at present it is almost non-existent (Oguntala 1982). Efforts are being made to develop more synoptic meteorological stations. This is being done in collaboration with the Federal Department of Meteorology which supplies the instruments to the Forest Research Institute. The Institute collects and processes the data. The development of a national fire danger forecasting and rating system is still inadequate, but there are great prospects for improvement of facilities to cover the entire country.

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