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9. ABSTRACT
Included here are some excerpts from an interpretive summary of the conference prepared by the participants. The summary focuses on priorities for research specifically related to the biological processes that control and now limit global crop productivity. The Resource Base (Land, Water, Energy, Labor). Enhancement of crop productivity is inseparable from the resource base. The goal of agriculture should be to increase and maintain at high levels the yield of highly nutritious food per hectare of land, per increment of water, per calorie of energy input, per unit of time, while maintaining a high-quality environment. Although more land can be put into production, much of that land is marginal and may require substantial inputs of water and fossil fuel energy to be productive. We must develop research programs for effective utilization and protection of these resources. Billions of dollars have been expended for development of new land resources through irrigation. Meanwhile, little attention has been directed toward increasing efficiency of water usage by crops. That efficiency is 30-40 percent worldwide and is a similarly low value in the U.S. On the other hand, Israel has achieved a remarkable efficiency in water utilization from irrigation that exceeds 80 percent. Soil erosion control...is needed. After 40 years of a program directed by the Soil Conservation Service of the U.S. Department of Agriculture, no more than 25 percent of the farm lands are under approved conservation practices. Despite erosion control efforts, losses are estimated at 3.6 billion metric tons of top soil annually, equivalent to 31 metric tons per hectare of tilled land. Stability of Food Production. Stability of production at high levels could be improved by nitrogen self-sufficiency in crops, identification of aspects of photosynthesis which limit carbon dioxide input, an understanding of the mechanisms of senescence, ability to predict extreme weather events at crucial times, and stable pest resistance in

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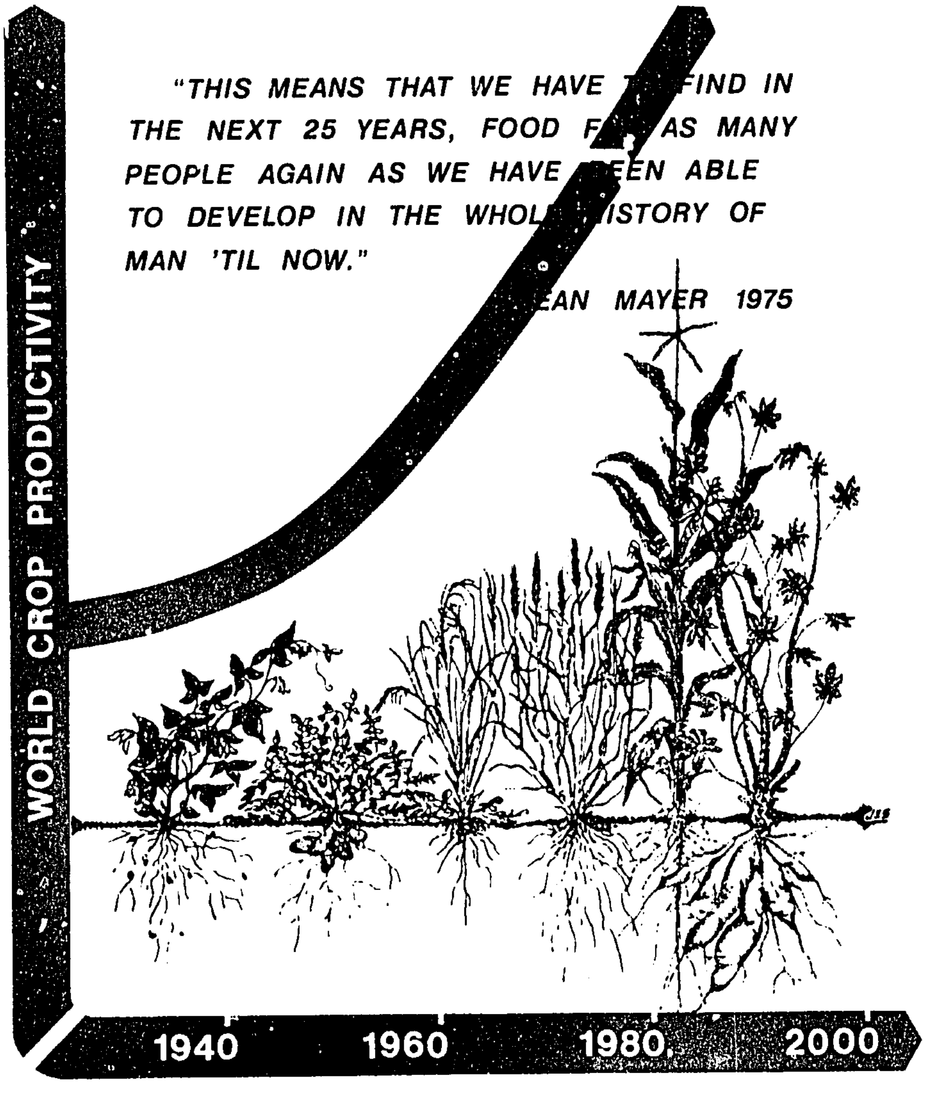
plants. Weather is the most determinant factor in food crop productivity. Decreased vulnerability of crops to weather uncertainities from season to season and to potential hazards of changing climatic patterns must be sought through genetic improvement, soil, water, and fertilizer management, chemical regulators and cropping systems that efficiently combine space and time. *The Total Food Production System.* The operational approach to maximum productivity has to be more than the traditional *ad hoc* technique. Management must be predicated on a scheme that integrates the entire system. Interacting factors such as crop cultivars, rotations, row spacing, soil nutrients, structure and moisture, temperature, sunlight, plant protection from pests, harvesting procedures, environmental concerns, and public health have led to a complexity that cannot be accommodated without sophisticated management schemes. *Improvement of Nutritional Values.* Proteins in cereal grains and seed legumes are of singular importance. Protein levels and amino acid balances are heritable traits subject to genetic manipulation. Substantial progress has already been made with the development of triticale, high-lysine maize and sorghum, and high-protein selections of rice and barley. *Photosynthesis, Biological Nitrogen Fixation, and Plant Improvement.* These processes can add substantially to the productivity of all food crops. These three areas have received only token attention in crop productivity. The U.S. lags behind other areas of the world in its research emphasis on these three basic areas. In addition, these three areas receive very limited attention at international agricultural research centers, which are predominantly commodity oriented. An international center should be established in the temperate zone to investigate the interrelationships among photosynthesis, biological nitrogen fixation, and new techniques for plant improvement. *Technology Transfer.* Much existing technology relating to agricultural production has not yet been applied. Institutional mechanisms must be developed that insure the collation, interpretation, dissemination, and application of knowledge that is already available. *Manpower, Interdisciplinary Training, International Coordination.* A global assessment of manpower resources available for crop productivity research should be undertaken. Training programs for manpower knowledgeable in the biological processes that control the production of food crops should be given high priority. *Constraints.* There are numerous environmental, socio-politico-economic and institutional disincentives for food production. The most important constraints to achieving food adequacy are the uncertain responses of human political institutions. Losses during production, handling, storage, and delivery constitute another major constraint for food adequacy. It was strikingly apparent in the Conference that there was a deficiency of information available on the fundamentals of plant growth. These include factors affecting top and root architecture and development, the root-soil complex, principles of ion and water uptake, the interrelationship of environmental stresses, the nature of pest resistance, and the action of chemical plant regulators.

CROP PRODUCTIVITY



> "THIS MEANS THAT WE HAVE TO FIND IN THE NEXT 25 YEARS, FOOD FOR AS MANY PEOPLE AGAIN AS WE HAVE BEEN ABLE TO DEVELOP IN THE WHOLE HISTORY OF MAN 'TIL NOW."
>
> EAN MAYER 1975

...RESEARCH IMPERATIVES

CROP PRODUCTIVITY - RESEARCH IMPERATIVES

An international conference sponsored by
Michigan State University, Agricultural Experiment Station
and
The Charles F. Kettering Foundation
with the support of the National Science Foundation (RANN),
the Energy Research and Development Administration,
the United States Department of Agriculture and the
United States Agency of International Development

October 20-24, 1975

Organizers: M. Lamborg, S.K. Ries, F.H. Tschirley, S.H. Wittwer

Editors: A.W.A. Brown, T.C. Byerly, M. Gibbs, A. San Pietro

Michigan-Kettering (1975) Crop Productivity-Research Imperatives,

Michigan Agricultural Experiment Station
East Lansing, Michigan 48824

Charles F. Kettering Foundation
Yellow Springs, Ohio 45387

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Any opinions, findings, conclusions or recommendations expressed in this publication are those of the contributors and do not necessarily reflect the views of the United States Department of Agriculture, the United States Agency of International Development, National Science Foundation (RANN) and the Energy Research and Development Administration.

ORGANIZER'S PREFACE

The International Conference on Crop Productivity - Research Imperatives was held October 20-24, 1975 at the Boyne Highlands Inn, Harbor Springs, Michigan. It was jointly sponsored by the Michigan State University Agricultural Experiment Station and the Charles F. Kettering Foundation. Timing coincided with the centennial year of the establishment of the first State Agricultural Experiment Station in the United States.

The Conference was planned with the recognition that an exploding population and an increasingly affluent society impose a more acute challenge to agriculture than ever before. An inadequate level of support for agricultural research in the past has left vast gaps in our knowledge of factors affecting the productivity, stability of supply, and nutritive values of food crops.

A concern of those who organized the Conference was the continued adequacy of our food supply. Also how plant scientists with input from other disciplines can best contribute to enhanced productivity and dependability on a global scale. The focus of the Conference was on the fundamental biological processes that control productivity of economically important food crops. There was the recognition that increased productivity must come with a husbanding of non-renewable resources and that a reduction in food losses would indirectly improve crop productivity by getting food already produced into use by people.

One distinctive feature of the Conference was its organization into a plenary session - workshop format. Six discussion groups addressed issues involving: Nitrogen Input; Carbon Input; Water, Soil and Mineral Input; Plant Protection from Pests; Environmental

Stress (air, water, salinity, temperature) and Plant Development Processes. The reports of the six groups discuss what were considered the most important fundamental biological processes that limit crop productivity. In addition, they identified a deficiency in the support that has been given to basic and applied plant science research on a global scale.

Secondly, the Conference participants were predominantly working scientists drawn from a wide-range of disciplines. They are recognized for their leadership and proven abilities in their respective fields. Participants constituted a blend extending from the applied field scientist to the molecular biologist. Social scientists, industry representatives, research administrators, representatives of international agricultural research centers, and graduate students were blended into each of the six discussion groups.

A third distinctive feature of the Conference was the international dimension. Biological processes that control crop productivity have a global significance. The United States is not the leader in research on all biological processes. The research imperatives that evolved from scientists of many nations considered world strategy and participation.

The Conference report was limited to the biological processes that control food-crop productivity. We recognize there are many socio-politico-economic problems relating to delivery, marketing, transportation and infrastructures in food production systems. These were beyond the intended scope of the Conference and were not considered. The impact of changing climatic and weather patterns, though recognized as the most determinate factor in crop productivity, was not a major concern of the Conference. Nutritional quality and environmental impacts were considered in arriving at imperatives. There is the assumption, however, that food producing systems exist and can yet be created in complete harmony with beauty of the landscape and an improvement of man's environment. Limited attention has been directed to operational strategies for implementation of the imperatives presented herein.

Finally, the rapid increase in world population adds urgency for enhancement of production of economically important food crops. Ultimately starvation and malnutrition can only be alleviated by achieving a balance between world population and food production. Nevertheless there is an immediate opportunity for food abundance. That which follows calls for a marshalling of resources with a focus on research imperatives identified with the fundamental biological processes that control food crop productivity.

The organizers of this Conference express appreciation to all participants and especially the untiring efforts of those who chaired the discussion groups (Ralph W. F. Hardy, Richard H. Hageman, Israel Zelitch, Dale N. Moss, William A. Jackson, Jan van Schilfgaarde, J. Ralph Shay, Boysie Day, Waldemar Klassen, Conrad J. Weiser, Howard E. Heggestad, William L. Powers, Peter S. Carlson, John E. Grafius, Donald H. Wallace); the rapporteurs (M. Wayne Adams, A. W. A. Brown, M. John Bukovac, David R. Dilley, Philip Filner, Bernard D. Knezek); editors (Martin Gibbs, A. W. A. Brown, Anthony San Pietro, T. C. Byerly), and support staff of the Michigan State University Agricultural Experiment Station and the Charles F. Kettering Research Laboratory coordinated by Vicki Hudson. The assistance of Howard Grider of Michigan State University and M. S. (Cy) Smith of the

Charles F. Kettering Foundation on financial accountability is appreciated.

The financial assistance of the United States Department of Agriculture, the United States Agency of International Development, The RANN Directorate of the National Science Foundation, and the Energy Research and Development Administration is gratefully acknowledged.

The Organizing Committee

M. Lamborg
S. K. Ries
F. H. Tschirley
S. H. Wittwer

EDITOR'S PREFACE

The Editors were charged with the responsibility to make available, in appropriately printed form and with minimum delay, the information forthcoming from this Conference to both the scientific and science-administrative global community. To discharge successfully this obligation, we chose to provide two volumes: one, Book I, the proceedings in their entirety; the other, Book II, focussed primarily on research imperatives relating to fundamental biological processes that control crop productivity. The complete volume (Book I) contains Prefaces both by the Organizers and the Editors, the Conference Imperatives prepared by the Organizers, the Imperatives generated by each of the six working groups, an Interpretative Summary written by the Organizers, salient observations at the Conference selected by the Organizers, the addresses of the four featured speakers, the entire reports of the six working groups and the names and addresses of the participants. The abbreviated volume (Book II) consists of only the first five entries indicated for Book I.

We are gratefully indebted to the Organizers for the distinctive organization and operation of the Conference which greatly eased our task of preparing those proceedings for publication. Despite the broad expertise evident within the working groups, they very quickly brought into focus the discussion of their respective problems and experimental approaches. Within the four and one-half day period of the Conference, each working group had available a preliminary report for presentation to the entire group. In particular, we gratefully acknowledge the tireless and unselfish efforts of those Co-Chairmen and Rapporteurs of the six working groups who remained at the Conference site for an additional two days to place their report into final form. We recognize that there is diversity of opinion within individual reports which we believe reflects a healthy state of the art.

The liaison between the Editors and the printer, Waverly Press, was undertaken by Martin Gibbs. The early appearance of these volumes reflects the many hours he spent in monitoring the book. We are most grateful to Mrs. Doris Gray of Waverly Press for help and patience in the production of this book.

We firmly believe that this Conference will serve to catalyze organization of additional meetings in the future.

The Editors,

A. W. A. Brown
T. C. Byerly
M. Gibbs
A. San Pietro

CONFERENCE IMPERATIVES

Issues of common concern in the deliberations of the six working groups, and other issues that transcend the bounds of any single group, emerged during the course of the Conference. These issues were identified as Conference Imperatives. It is virtually certain that the increase in food production will lag behind population growth unless these imperatives receive a higher level of support. The sequential listing is not a priority ranking.

DEVELOP MECHANISMS FOR RAPID AND EFFECTIVE TRANSFER OF AVAILABLE TECHNOLOGY.

A significiant body of agricultural technology from both biological and physical sciences, is available for immediate application. Better institutional mechanisms must be developed for collating, interpreting, disseminating, and applying the technology already known.

PROVIDE MANPOWER AND FISCAL RESOURCES ON A SUSTAINED BASIS.

It is recommended that there be an assessment of manpower resources, and that training programs for manpower knowledgeable in the processes that control the production of food crops be given high priority. Achieving the goal of substantially increasing the world food production will require a sustained increase in funding.

ENCOURAGE INTERDISCIPLINARY EDUCATION

Significant enhancement of crop productivity can be accomplished by treating the agricultural production process as a system. An institutional effort coupled with professional incentives is required to create a new generation of plant scientists with a knowledge of the basic sciences and an understanding of the principles of plant growth and crop production.

STRENGTHEN SUPPORT FOR THE BASIC PLANT SCIENCES.

Plant sciences have not received a level of support consistent with their needs and opportunities. A principal impediment to rapidly increasing food production is our lack of knowledge of the fundamental plant processes.

ITENSIFY AND EXPAND INTERNATIONAL EFFORTS TOWARD THE PRESERVATION, CONSERVATION AND INTERCHANGE OF GENETIC RESOURCES.

International mechanisms coordinated through the Food and Agricultural Organization of the U.N., have been established to conserve plant and animal genetic resources of agricultural importance. They should be expanded to include propagules, tree crops, and fungi and bacteria of agricultural importance. Cataloguing those resources and making them freely available internationally must be accomplished.

BROADEN THE RANGE OF PARAMETERS IN PLANT BREEDING RESEARCH.

Varietal improvement through plant breeding should be extended into biologic processes that have received only minor attention. There is great potential for yield enhancement by selecting for heritable characteristics such as photosynthetic efficiency, nitrogen fixation, resistance to environmental stress, and selective ion uptake.

DETERMINE THE MOST EFFICIENT BALANCE BETWEEN NON-RENEWABLE ENERGY AND HUMAN LABOR IN RELATION TO INCREASED FOOD SUPPLY.

Energy is a basic resource required to drive the food production process. Information is critically needed to determine the most appropriate ratio of non-renewable energy to the energy derived from human labor and animal draft power. This ratio will be different in various countries and ecological zones.

DEVELOP INTEGRATED PEST MANAGEMENT SYSTEMS FOR STABLE CROP PRODUCTION AT HIGH LEVELS SUITED TO VARIOUS STYLES OF AGRICULTURE.

Systems for managing pests should be developed in light of the crop, the environment in which it is growing, and the socio-economic factors for a given locale.

ESTABLISH AN INTERNATIONAL CENTER TO INVESTIGATE THE INTER-RELATIONSHIPS AMONG PHOTOSYNTHESIS, BIOLOGICAL NITROGEN FIXATION, PLANT IMPROVEMENT, AND PLANT CULTURE.

The processes identified above are interrelated. Collectively they have great potential for increasing crop productivity.

ESTABLISH A TEMPERATE ZONE INTERNATIONAL INSTITUTE FOR IMPROVEMENT AND CULTURE OF LABOR INTENSIVE FOOD CROPS.

Emphasis would be on the development of new and improved species and cultivars. They are principal sources of caloric energy, proteins, vitamins, and minerals.

RESEARCH IMPERATIVES

OF

THE SIX WORKING GROUPS

NITROGEN INPUT

J. Anderson
M.A. Bednarski
J. Bernstein
N.C. Brady
W.J. Brill
J.R. Cowles
C.W. Crum
H.J. Evans
P. Filner (rapporteur)
M.H. Gaskins
R.H. Hageman (co-chairman)
R.W.F. Hardy (co-chairman)
J.E. Harper
R.P. Hauck
G. Johnson
D.L. Keister
B.J. Miflin
O.E. Nelson, Jr.
W.E. Newton
C.A. Neyra
J. Pendleton
D. Pimentel
M. Reporter
R.L. Richards
T.R. Sinclair
R. Smith
J. Streeter
C.P. van Dijk
R.C. Valentine
J.E. Varner
G. Vest
D.K. Whigham

I. Nitrogen Input
  1. Minimize the energy and capital costs of nitrogen fertilizers
    a. Develop catalysts that work at lower temperatures and pressures
    b. Improve procedures for rotational-, inter-, and relay-cropping of legumes and cereals
    c. Develop better recycling processes to recover nitrogen from wastes
    d. A policy for natural gas allocation priority must be developed.
  2. Develop nitrogen self-sufficiency in crops
    a. Develop optimal plant-microorganismal combinations
    b. Increase transfer of photosynthetic energy from the plant to the N_2-fixing organism
    c. Seek, evaluate and develop N_2-fixing microorganisms for use in

    supplying nitrogen to cereals and grasses

3. Maximize efficiency of use of soil nitrogen and fertilizer nitrogen
    a. Improve utilization of nitrogen by plants through chemical, cultural and genetic means
    b. Modulate the rate of soil nitrogen transformations by chemical or cultural means
    c. Improve rate data for each of the steps of the global nitrogen cycle
4. Improve nutritional characteristics of product
    a. Improve protein quantity and quality in crops by genetic, chemical and cultural means

CARBON INPUT

A.H. Adelman
R. Austin
D. Bell
R.G.S. Bidwell
O.J. Björkman
C.C. Black, Jr.
J.S. Boyer
R.H. Brown
M.J. Bukovac (rapporteur)
D.T. Canvin
D.E. Fleischman
K.D. Frederick
N. Frey
D.M. Gates
D.R. Geiger
M. Gibbs
N.E. Good
G.H. Heichel
D. W. Krogmann
H.S. Ku
E.R. Lemon
B.C. Mayne
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W.L. Ogren
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G.A. Peters
B. Quebedeaux
R. Rabson
E.B. Romanoff
A. San Pietro
N.E. Tolbert
J.H. Troughton
M.N. Westwood
I. Zelitch
(co-chairman)

II. Carbon Input
1. Identify the aspects of photosynthesis which limit CO_2 input in natural environments
   a. Interception and utilization of light
   b. Increase the rate of CO_2 absorption
   c. Analyze the enzymic processes of carbon metabolism
   d. Characterize the components of dark respiration and photorespiration
   e. Explore the use of tissue cultures to increase net photosynthesis

   - f. Investigate the adverse effects of oxygen on photosynthetic reactions
   - g. Identify limitations on CO_2 assimilation by the carboxylation reaction
   - h. Identify limitations on CO_2 assimilation by light reactions
   - j. Characterize the environmental control of photosynthesis

2. Elucidate the relationship of plant development to photosynthesis
   - a. Study the translocation and partitioning processes
   - b. Investigate hormonal and chemical regulation in crop plants
   - c. Characterize the effect of develmental stage on regulation of carbon metabolism
   - d. Determine effect of leaf senescence on photosynthesis
3. Provide plant breeders with new screening procedures
   - a. Investigate the variations in net photosynthesis among genotypes

WATER, SOIL AND MINERAL INPUT

R.R. Allmaras
G.B. Baird
K.K. Barnes
G. Bowen
D.T. Clarkson
L.J. Connor
R.W. Cummings
E. Epstein
G. Farquhar
R.J. Hanks
J.B. Hanson
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B.D. Knezek (rapporteur)
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J. Malcolm
B.D. Mayberry
K. Mengel
L.D. Meyer
R.E. Meyer
A.C. Orvedal
D.C. Reicosky
L. Seatz
G. Uehara
J. van Schilfgaarde (co-chairman)
E.H. Wiser
D. Wright

III. Water, Soil and Mineral Input
1. Devise crop-water-soil management systems to obtain maximum crop output per unit water input
    a. Utilize rational design criteria for drainage, including field measurements of soil properties
    b. Assure the maintenance of soil water content sufficient for maximum crop production
    c. Develop methods of forecasting the water requirements of given crops
2. Transfer available erosion-control technology, and develop new technologies, especially for cultivated marginal lands
3. Determine whole-plant and cell water relationships affecting crop productivity, and develop methods for their manipulation

4. Devise water and soil management systems to prevent salinization and water logging
5. Develop systems of crop production compatible with community interests and with environmental and esthetic values
6. Adapt soil management practices to subsistence cultivation in developing countries
7. Design a strategy for worldwide transfer and application of the new soil taxonomy
8. Develop soil technology for crop production on problem soils (e.g. oxisols, ultisols, etc.)
9. Evolve soil management methods to improve soil characteristics assuring seed germination
10. Identify and increase the use of inexpensive local sources of soil amendments and plant nutrients, including wastes and crop residues
11. Characterize and quantify the stresses in problem soils and relate them to the results of genetic, physiological and cultural research
12. Enhance the mineral nutrient uptake of crops in saline, ion-toxic and highly fertile soils by utilizing cultivars selectively developed by plant breeders
13. Stimulate plant uptake and growth by selective use of mycorrhizal fungi and/or rhizosphere bacteria
14. Quantify the chemical, physical and biological properties of the root-soil interface and its role in mineral nutrition and water uptake
15. Investigate the root distributions and absorptive characteristics of

components of multiple-cropping systems which maximize the use of soil resources

16. Elucidate the metabolic control and integration of ion transport from the soil into the rootlet and the entire plant

PLANT PROTECTION FROM PESTS

A.P. Appleby
K.F. Baker
W.D. Bauer
D.E. Behmer
G. Bird
A.W.A. Brown (rapporteur)
J.A. Browning
A. Collmer
D. Coplin
B. Croft
J.M. Daly
D.E. Davis
B. Day (co-chairman)
D. Delmer
W. Furtick
C.A.I. Goring
A.N. Halter
C.M. Himel
W. Klassen
(co-chairman)
W. Klomparens
F.G. Maxwell
J.J. Menn
R.L. Metcalf
R.R. Nelson
E. Ortman
A. Putnam
J.R. Shay
(co-chairman)
R. Staples
G.G. Still
M.G. Wiltse
J.A. Witz

IV. Plant Protection from Pests
  1. Research necessary for development of integrated management systems for stable protection suited to various styles of agriculture.
    a. Identification and quantitation of the basic biological and physical parameters of a particular pest system
    b. Characterization or modeling of the dynamics of the individual pest systems in quantitative terms
    c. Development of an overall descriptive model of the total crop-pest ecosystem
    d. Development of a management model by expansion of the crop-pest model to include control methods

    - e. Development of an implementation model for practical crop protection
2. Increased understanding of the fundamental biology of pests
    - a. Assessment of genetic plasticity of pest species
    - b. Studies in population genetics of pests
    - c. Determination of the mechanisms of stress survival in pests
    - d. Assessment of genetic exchange among plant pathogens
    - e. Selected studies on vital processes in the developmental biology of pests
3. Breeding for stable resistance to plant pests
    - a. Development of resistant cultivars
    - b. Conservation of resistance germplasm in germplasm preserves
    - c. Investigation of host-pest interactions in germplasm preserves
    - d. Search for additional sources of resistance
    - e. Search for sources of competitive ability (e.g. allelopathy)
    - f. Identification of mechanisms of resistance and allelopathy
4. Expanded research for the further development of biological control
    - a. Search for areas where effective biological control occurs
    - b. Identification of specific biological agents responsible for control
    - c. Evaluation of biological agents in practical agriculture
    - d. Analysis of physical factors and biological agents for the stabilization of control

    e. Development of mass-culture and release methods
    f. Combinations of the biological agents to obtain the widest effectiveness
    g. Incorporation of the use of biological agents into crop production systems
5. Better pesticides and better use of pesticides
    a. Development of a diversity of selective chemicals
    b. Development of novel chemicals for specialized uses
    c. Improved strategies for utilizing available pesticides
    d. Measures for avoiding the consequences of pest resistance to pesticides
    e. Elucidation of mode of action and metabolism of pesticides
6. Innovative approaches for plant protection
    a. Genetical control methods for certain pests
    b. Remote sensing for control operations against migratory pests
    c. Controlled-release formulations of pesticides
    d. Chemicals for modifying insect behavior
    e. Innovation on a variety of fronts

ENVIRONMENTAL STRESS

F. Albani
H.R. Albrecht
J.E. Carnhan
T.T. Chang
L.J. Connor
D.R. Dilley (rapporteur)
A.E. Erickson
E.H. Everson
C.D. Foy
M. George
J.F. Gerber
R. Guderian
H.E. Heggestad (co-chairman)
H.R. Jensen
M.E. Jensen
J. Levitt
J.M. Lyons
D.C. McCune
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M. Plesnicar
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(co-chairman)
E.L. Proebsting
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D. Raveed
M.E. Saltveit, Jr.
R.H. Shaw
C. Stushnoff
C. Sullivan
C.B. Tanner
O.C. Taylor
D.T. Tingey
Y. Vaadia
M.A. Watson
C.J. Weiser
(co-chairman)
D. Wright

V. Environmental Stress
  1. Manipulate crops or their environments in ways which avoid or reduce stress injury and increase productivity
    a. Develop crop management systems and cultural practices which reduce exposure of crops to stress
    b. Reduce stress by modifying the micro-climate in the vicinity of the crop
    c. Develop treatments (e.g. chemicals) to increase stress resistance or to facilitate recovery from stress
  2. Exploit the genetic potential for developing new varieties of crops

resistant to environmental stress

   a. Collect and evaluate germplasm of crop plant species for stress resistance
   b. Develop criteria and tests for screening large seedling populations for stress resistance
   c. Increase the level of tolerance to yield-limiting stresses in food crop varieties

3. Elucidate the basic principles of stress injury and resistance, and evaluate the scope and nature of stress damage
   a. Characterize the basic mechanisms whereby stress factors injure plants
   b. Investigate the basic mechanisms of resistance to and avoidance of stress injury
   c. Achieve an understanding of plant growth and productivity under stress

PLANT DEVELOPMENT PROCESSES

A.A. Abdul-Baki
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J.K.A. Bleasdale
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K.J. Kasha
E. Kueneman
C.F. Lewis
G.C. Marten
A. Millerd
R.T. Ramage
D.C. Basmusson
J. Shen-Miller
V. Walbot
D.H. Wallace (co-chairman)
P.F. Wareing
A.H. Zakri

VI. Plant Development Processes
  1. Utilize cell and tissue culture techniques to accelerate genetic improvement of crop plants
    a. Determine how to regenerate whole plants from the cultures obtained
    b. Apply the principles of somatic cell genetics to understanding the growth of higher plants
    c. Retain mass selective screening for traits of agronomic value
    d. Employ cultures for preservation of germplasm of vegetatively propagated species
    e. Develop selection schemes which recover processes unique to higher plants

    - f. Increase genetic diversity by inducing and recovering chromosome changes in somatic cells
    - g. Encourage genetic engineering by transformation, transduction and plasmid transfer

2. Identify and evaluate the control mechanisms for whole plant development
    - a. Investigate factors limiting number and size of fruit and tubers, and their protein content
    - b. Investigate factors controlling time, intensity and duration of flowering, and affecting abscission and abortion of flowers
    - c. Develop female-flowering crop plants as tools for testing hybrid vigor from various pollens
    - d. Determine optimum leaf canopies for light and root architecture for nutrient uptake
    - e. Investigate relationship between stem growth and productivity
    - f. Study the physiology of seeds and crop cycles to obtain optimum seedling establishment
    - g. Attain a better understanding of the hormonal control of growth and development
3. Determine the physiological and genetic bases of response to environmental stresses
    - a. Probe the genetic ranges for tolerance to adverse soil conditions
    - b. Understand the physiology of winter hardiness and shade tolerance
    - c. Study inter-plant competition with a view of increasing crop densities

    d. Exploit intergeneric crosses to increase genetic ranges for stress tolerance
    e. Uncover the causes of tolerance to drought, heat and micronutrient deficiency
4. Preserve the sources and exploit the possiblities of genetic variability
    a. Collect, maintain and describe indigenous germplasm
    b. Develop outcropping systems between species and strains indigenous to extreme conditions
5. Combine the disciplines of plant genetics and plant physiology to achieve plant design
    a. Identify the physiological, morphological and architectural components of superior yield
    b. Devise screening techniques for discovering strains with such desirable components
    c. Remove management constraints on plant crop types with a combination of superior characteristics
    d. Use modeling techniques to ascertain the effect of a given change on the entire yield system
6. Continue and encourage basic research in plant development
    a. Understand in detail the genetics, biochemistry, and physiology of certain crop species
    b. Develop novel research approaches, such as remote sensing of the diverse phenotypes in a field

INTERPRETATIVE SUMMARY

INTRODUCTION

This summary focuses on priorities for research specifically related to the biological processes that control and now limit global crop productivity. The pre-designed Conference structure of six working groups and their interaction in plenary sessions provided maximum opportunity for intellectual exchange among scientists of many disciplines. It was from these interacting groups that the research imperatives had their origin. Each working group developed a report that addressed the critical issues for its area.

Contributions made by each of the working groups and the distinguished speakers have been synthesized into this Conference summary. That which follows represents a distillation of thought and comment that pervaded the discussions of a diverse array of scientists of many disciplines from many nations. The focal point was on food crops and what might be done with fundamental biological processes to enhance their productivity.

THE RESOURCE BASE (LAND, WATER, ENERGY, LABOR)

Enhancement of crop productivity is inseparable from the resource base. The goal of agriculture should be to increase and maintain at high levels the yield of highly nutritious food per hectare of land, per increment of water, per calorie of energy input, per unit time, while maintaining a high quality environment.

An alternative is to enlarge or improve the resource base. This is possible with time and technology, but there are limits. Expansion of the land base and an increase in water input can increase total food output, as can an increase in productivity per unit land and water input. Preservation and improvement of the land base for enhancement of crop productivity should remain an option. The problem is, however, that land resources available for expansion are not where the people are. Our best hope for the future must be to enhance crop productivity with the resources at hand.

Arable land, water, and fossil fuel energy are finite resources. Although more land can be put into production than is now being cultivated, much of that land is marginal and may require substantial inputs of water and fossil fuel energy to be productive. We must develop research programs for effective utilization and protection of these resources. Failure to do so will result in a diminution of potential productive capacity.

Billions of dollars have been expended for development of new land resources through irrigation. Meanwhile little attention has been directed toward increasing efficiency of water usage by crops. That efficiency is 30-40 percent worldwide and is a similarly low value in the United States. On the other hand, Israel has achieved a remarkable efficiency of water utilization from irrigation that exceeds 80 percent.

Soil erosion control, a research imperative of the Water, Soil and Mineral group, is an example of the need to protect our resources. After 40 years of a program directed by the Soil Conservation Service of the United States Department of Agriculture, no more than 25 percent of the farm lands are under approved conservation practices. Despite erosion control efforts, losses are estimated at 3.6 billion metric tons of top soil annually, equivalent to 31 metric tons per hectare of tilled land.

Improved efficiency of fertilizer uptake is another example of the need for resource conservation. Crops in temperate zones utilize 50 percent or less of applied nitrogen, and less than 35 percent in the tropics, especially for rice production. Greater fertilizer efficiency can be achieved through the use of improved cultivars with enhanced capacities for ion uptake. Modulation of nitrification and denitrification also offer great possibilities.

Unemployment, inflation and inadequate food supplies are continuing global concerns. Partial resolution of those problems could come from technologies that are labor intensive with production maintained at high levels, and with minimum input of capital, management, and non-renewable resources. A good example is the production of hybrid cotton in India where tens of thousands of workers are required to hand pollinate the flowers but yields are doubled. Ultra-low volume knapsack sprayers for pest control in agriculturally developing countries, or multiple cropping systems in the tropics, and reduced tillage and surface interseeding of crops in temperate zones are other examples of the labor intensive high production crop technologies with a minimum of non-renewable resource input.

There must be a continuing search for ideas that provide alternative options for land and water use, and for fertilizer, energy, and labor inputs. Establishing a temperate zone international agricultural institute for improvement and culture of labor intensive crops, which is listed as a Conference imperative, would be of importance in developing cropping systems that have a high yield but are sparing of non-renewable resource inputs. The emphasis should be on vegetable crops (beans, peas, potatoes, cucurbits, tomatoes, root crops, onions, crucifers) intensively grown and locally consumed. Vegetables are principal sources for calories, proteins, vitamins, and minerals for hundreds of millions of people. Their production is high, they are labor intensive, and sparing in fossil fuel inputs. Seldom are these important crops considered in statistical tables compiled on world food production.

STABILITY OF FOOD PRODUCTION

Yield variabilities from year to year and area to area are principal causes of food shortages. Accordingly, stability of food production at high levels should be a global research imperative. Long term stability should not be sacrificed for short-term productivity. Stability of production at high levels could be improved by nitrogen self-sufficiency in crops, identification of aspects of photosynthesis which limit carbon dioxide input, an understanding of the mechanisms of senescence, ability to predict extreme weather events at crucial times, and stable pest resistance in plants. We should have the knowledge to manipulate crops and their environments to avoid or reduce injury from environmental stress and from pests. Finally, our genetic resources must be preserved and exploited for their variability. For example, interspecific and intergeneric crosses of crops indigenous to areas having extreme environmental conditions could be used to great advantage in reducing stress injury.

Weather is the most determinant factor in food crop productivity. Production stability at high levels can be achieved only as environmental stresses are minimized. Decreased vulnerability of crops to weather uncertainties from season to season and to potential hazards of changing climatic patterns must be sought through genetic improvement, soil, water, and fertilizer management, chemical regulators and cropping systems that efficiently combine space and time.

THE TOTAL FOOD PRODUCTION SYSTEM

The operational approach to maximum agricultural productivity has to be more than the traditional *ad hoc* technique. Management must be predicated on a scheme that integrates the entire system. Interacting factors such as crop cultivars, rotations, row spacing, soil nutrients, structure and moisture, temperature, sunlight, plant protection from pests, harvesting procedures, environmental concerns, and public health have led to a complexity that cannot be accommodated without sophisticated management schemes.

Most plant breeders of the past have emphasized yield and disease resistance, to the exclusion of many other factors that affect productivity and nutritive value. A broader set of parameters should be incorporated into crop breeding programs.

Most entomologists have employed chemical insecticides, without being aware that some of them reduce plant growth and yield. Weed control specialists have used herbicides that increase susceptibility to insect and disease pests. Agronomists have recommended no-till crop production techniques without being fully cognizant of trade-offs such as increased pest problems that may require higher pesticide usage.

Further breakthroughs in agricultural productivity will be possible only if the total complex agricultural system is considered in proposing new research strategies. Interdisciplinary efforts aimed at effective management of the total food production system will be required.

IMPROVEMENT OF NUTRITIONAL VALUES

Enhanced productivity of food crops is closely linked to the improvement of their nutrient content. Proteins in cereal grains and seed legumes are of singular importance. Protein levels and amino acid balances are heritable traits subject to genetic manipulation. Substantial progress has already been made with the development of triticale, high lysine maize and sorghum, and high protein selections of rice and barley.

People of many nations with the most crucial food problems and rapidly expanding populations are predominantly vegetarian. There is substantial evidence that increased protein levels and improved amino acid balances of cereal grains, together with adequate caloric intake, would provide a nutritionally balanced diet for many of the world's hungry people. This would have a sparing effect on cereal grain consumption. Genetic improvement of the nutritional status of food crops should not be restricted to cereals. Equal opportunity exists for potatoes, legumes (field beans, mung beans, chick peas, pigeon peas), cassava, sweet potato, and a multitude of fruits and other vegetables. An effort should be made to improve the protein levels and amino acid composition in food crops concurrently with increased efforts for enhanced stability and productivity.

PHOTOSYNTHESIS, BIOLOGICAL NITROGEN FIXATION AND PLANT IMPROVEMENT

Photosynthetic efficiency and biological nitrogen fixation are closely interrelated biological processes that, along with genetic improvement, underpin crop productivity. As a new technology is achieved in one, that new advance will affect the other two. If appropriately managed, modification of these processes can add substantially to the productivity of all food crops. Important in such studies would be improvements in the architecture of both the roots and tops of major food crops and the potentials of multiple cropping systems. Somatic fusion offers a new technique for acceleration of genetic improvement.

These three areas (photosynthetic efficiency, biological nitrogen fixation, new techniques for genetic improvement) have received only token attention in crop productivity. The United States lags behind other areas of the world in its research emphasis on these three basic areas that relate to future potentials for crop productivity. In addition, these three areas receive very limited attention at international agricultural research centers, which are predominantly commodity oriented. Accordingly, an international center should be established in the temperate zone to investigate the interrelationships among photosynthesis, biological nitrogen fixation, and new techniques for plant improvement. Emphasis would be on the research imperatives of this Conference which relate to the biological processes of nitrogen input, carbon input, and the major plant developmental processes. Such a center would recruit the manpower to provide research competence extending from the very basic sciences to the operational transfer of the technology to a food crop.

TECHNOLOGY TRANSFER

Much existing technology relating to agricultural production is known that has not yet been applied. The most rapid increases in crop productivity can result from the immediate application of known technology. For example, improved soil and water management techniques can be implemented broadly in agricultural areas. The first priority should be to utilize currently available principles and practices on potentially productive soils in the proximity of needy populations. The principles inherent in the new Soil Taxonomy make information derived in one location more useful and reliable in another. Conversely, technology in some disciplines of crop production (protection from pests, for example) changes rapidly and soon becomes obsolete.

Institutional mechanisms must be developed that insure the collation, interpretation, dissemination, and application of knowledge that is already available. There is an urgent need for improving transfer of information within and among disciplines at the institutional level. It must come in discrete increments, from physics and chemistry to basic studies on biological processes controlling crop productivity, to performance under field conditions, to production practices at the operational level.

Rapid technology transfer in the past has been most successful in those cases where visual evidence of improvement was readily apparent. One reason for the ready adoption of chemical pesticides and plant growth regulants is the striking differences that are quickly discernible as a result of treatment. Growers will quickly accept and apply technology which they can observe to be beneficial and economically rewarding. Extension Services will need to step up the pace of information transfer requisite for rapid adoption of the new technologies.

MANPOWER, INTERDISCIPLINARY TRAINING, INTERNATIONAL COORDINATION.

Projected food requirements for the future dictate an increase in the scientific and technical manpower needed to achieve increased crop productivity.

A global assessment of manpower resources available for crop productivity research should be undertaken. Training programs for manpower knowledgeable in the biological processes that control the production of food crops should be given high priority. There should be an institutional effort to create a new generation of plant scientists with the knowledge and techniques of the basic sciences as well as an understanding of the fundamentals of plant growth and crop production.

Achievement of the goal of substantially increasing world food production will require an interdisciplinary research effort that treats the production process as a system. For example, basic research in carbon and nitrogen fixation must be accompanied by research efforts in physiology, development, genetics, and culture of involved crops. It is manifestly impossible to extrapolate from research at the molecular or cellular level to field performance. A good example is the encouraging trend, in teaching and in field practice, in crop protection. A total systems approach is being viewed rather than separate treatment for entomology, nematology, pathology, and the weed sciences.

While interdisciplinary efforts and team approaches are championed for the solution of complex problems, there should be some constraints on how such teams are put together and oriented. Not all good plant scientists adapt to a team approach. Some of the most significant scientific achievements in crop productivity have come from individual efforts rather than organized groups. Such efforts should be recognized and encouraged.

Enhancement of production of food crops must become a world-wide goal. The need is a global one. Many production practices require adaptations to fit local situations. Accordingly, international communication and coordination is required to maximize the efforts of research and to avoid needless duplication. In that sense, international symposia and conferences should be encouraged. The coordinating role of the Consultative Group for International Agricultural Research Centers and their associated networks is endorsed.

CONSTRAINTS

This Conference focused on biological processes that control food crop productivity. Adequacy of food supplies, however, is more than production technology. After production, it's getting the food where the people are and providing an income so they can buy it. Poor people do not have and cannot buy enough food.

There are numerous environmental, socio-politico-economic and institutional disincentives for food production. The most important constraints to achieving food adequacy, or even abundance are the uncertain responses of human political institutions. Improved technologies relating to the control of biological processes as determinants in food crop production eventually must be accepted and put into practice at the level of the food producer. There must also be an economic incentive at the farm level.

Losses during production, handling, storage, and delivery constitute another major constraint for food adequacy. The introductory section of the report of the working group on Plant Protection from Pests suggests that a major factor in reducing the amount of food available is losses to pests between harvest and consumption. Such post-harvest losses must be recognized, even though this Conference addressed only issues relating to production.

There are also constraints in research methodology. Detection devices and associated instrumentation that will quickly monitor at the micro- and macro-scale levels such processes as respiration, net photosynthesis, protein synthesis, biomass accumulation, and specific enzyme activities are critically needed for use by both plant breeders and plant physiologists.

It was strikingly apparent in the Conference that there was a deficiency as to information available on the fundamentals of plant growth. These included factors affecting top and root architecture and development, the root-soil complex, principles of ion and water uptake, the interrelationship of environmental stresses (heat, drought), the nature of pest resistance, and the action of chemical plant regulators.

These limitations are all reflected in an inability to model effectively plant growth. Attempts to model the productivity of food crops have faltered because the knowledge of basic biological processes is inadequate. In the meantime, plant protection scientists have taken the lead in modeling efforts with some crops.

The Conference addressed key issues relating to food production and concentrated on the research needed to achieve a significant increase in productivity. However, participants recognized that increased food productivity is futile if global population growth continues at its present rate. Historically the food production curve has paralleled population growth during an era when natural resources were not limiting. There is now a universal awareness that nonrenewable resources are finite and that, in the absence of alternatives, the demands of an increasingly affluent population will steepen the slope of the depletion curves for these resources. As fossil fuels, water, minerals such as phosphorus, and arable land become more limiting, it will be increasingly difficult for food production to be increased to keep pace with current rates of population growth.

The most important product of the Conference may have been the enthusiasm and elation of the conferees for the opportunity to associate with representatives of widely diverse disciplines. Furthermore, the frequent observation that basic research on biological processes must be accompanied by basic research on crop yield physiology, crop development and genetics was encouraging. Also, it became evident to the basic and applied scientists in attendance that information of particular biological processes in the laboratory, may not necessarily correlate with productivity in the field.

Finally, this Conference identified and placed priorities on research imperatives deemed necessary for further knowledge of the biological processes that control crop production. Attention must now be directed toward assuring their implementations and application to the various crop production systems of world agriculture.

SALIENT STATEMENTS FROM THE CONFERENCE

Sterling Wortman:

"Increasing the productivity and profitability of small farms represents a recognition that this is a primary solution of the world food problem". (The corollary is) "Large-scale mechanized farming is not a solution to the food problem of the poor countries".

"Agriculture at last has been recognized as the basic industry of Agrarian Nations".

"We have come to realize the limited transferability of agricultural technology from temperate climate to tropical and subtropical regions".

"...advances of the past century....permit a worldwide assault on hunger and proverty -- with a reasonable high probability of success... The penalties for failure will include immense human suffering, growing unrest and violence, instability of governments...".

"Most agricultural research has been provincial, and it still is".

"The scientists of the world... are considered... to comprise the single most conservative element among those who must be involved in alleviation of world hunger - more conservative than either government or farmers".

Nyle C. Brady:

"The new rices... respond well to nitrogen fertilization, but generally yield better than the traditional varieties even when no fertilizer is used".

"Only 25 to 30 percent of the farmers in the developing nations have adopted the new high yielding rice varieties and the technology associated with them".

"Systemic insecticides...are four-fold more efficient and...urea nitrogen fertilizer is twice as effective when concentrated in the root zone (of rice) rather than broadcast on the surface".

Ninety percent of the world's very low income people utilize rice for at least one-fourth of their diet.

Jean Mayer:

"This means that we have to find in the next 25 years, food for as many people again as we have been able to develop in the whole history of man till now".

"The world sea catch has faltered in the past three years and may well have, in most oceans, reached the limits of growth".

"In rich...temperate countries losses (preservation and distribution) appear at the consumption level. Military refectories and the school lunch program operate with as much as 40 percent of the food served appearing in garbage bins... In poor countries...one-third of the food may be lost in storage. ...less than one percent of the budget (of the FAO) is devoted to postharvest technology".

"The world has, as yet, no policy on food reserves".

"A...general reordering of the (world's) priorities is essential. We must (1) give a much greater emphasis to agriculture than it has been accorded in the past; (2) make all countries more conscious of the need to balance resources and population; (3) pay attention to the type of social policy... that will ensure that all benefit...".

"We must make all countries more conscious of the need to balance resources and population".

Reid A. Bryson:

"We may look back at the last 1000 years and see what happened after a decline of temperatures such as the last 30 years. At no time...has such a decline lasted less than 40 years. Therefore, it is unlikely that the trend of the last 30 years terminated last year".

"...Only 7% of world grain production move in international commerce".

"Hemispheric ice and snow increased by 15 percent - 1/6 of the increase...during the Ice Age - (in the winter of 1971-72)".

"The United States once had a drought like 1974 that lasted 200 years". ..."It is possible to have a drought last 200 years in the corn belt".

"Interglacial periods...last an average of 10,000 years, plus or minus a thousand years. We have been in the present one 10,800 years!".

NITROGEN INPUT:

Projections for nitrogen demand for crop production are from 40 x 10^6 metric tons in 1974 to 160 x 10^6 metric tons by 2000.

"About 2 percent of domestic natural gas consumption is used to manufacture fertilizer nitrogen and of the energy required to produce the three major fertilizer nutrients, 87 percent is consumed by ammonia synthesis".

"The photosynthetic inefficiency of domesticated legumes and most cereals is a major limitation for biological N_2 fixation and probably utilization of fixed nitrogen".

"The addition of fertilizer nitrogen to N_2-fixing legumes decreases N_2 fixation and does not increase total nitrogen input".

"Crops are inefficient in their uptake and use of fertilizer nitrogen with only 50% of applied fertilizer nitrogen taken up by non-legume crops such as corn and wheat and only 30 to 40 percent by paddy rice".

"A 50 percent improvement in the efficiency of use of fertilizer nitrogen would shave the world bill for nitrogen fertilizer by three billion dollars".

"The legume-rhizobia N_2-fixing associations do not provide all of the nitrogen required by legumes and in the case of soybeans, provide an average of only 30% at a rate of 75 kg N_2 fixed per ha per season".

CARBON INPUT:

"Little of the increased (crop) yield has come from enhanced capacity or efficiency of the plant's photosynthetic factory".

"Net photosynthesis in some plants increases when storage organs...are formed".

"Senescence of leaves, especially since it often occurs while the food product is being produced, appears to limit yields in many crops".

"Variation in rates of net photosynthesis per unit leaf area among genotypes have not generally been analyzed (to determine the cause of the variation)".

"It is not known whether senescence occurs because of competition for assimilates and inorganic nutrients or because of a 'death signal' controlled during development".

"In some environments, C_4 species require one-half as much water per unit of dry matter produced as do C_3 species".

"Models, if they are to be useful, must deal realistically with the complexities of the environment in which plants grow".

"In wheat...., cultivated varieties have lower rates of leaf photosynthesis per unit leaf area than do wild species, but the leaf area per plant is much greater".

WATER, SOIL AND MINERAL INPUT:

"We should be able to.....develop --- management strategy that enhances the utilization of the water resources in a manner compatible with energy conservation, environmental quality maintenance......, effective labor utilization and food production".

".....55% of the energy required to grow an irrigated grain crop is used to deliver the water to the farm".

"The bulk of the arable land not yet developed is not located where the major concentrations of population are found".

"...in western Minnesota, it was found that intercropping of soybeans and corn modified the microclimate such that total grain yield was increased by some 25%; in Montana a few rows of tall wheatgrass spaced across a grainfield increased snow catch for better water storage".

"On the U.S. mainland, erosion by water is the dominant conservation problem on 72 million hectares of cropland and about 13 million hectares of non-Federal pasture and rangeland".

"The effect of conversion of tropical forests into cultivated land must be evaluated in terms of hydrology, soil stability, and cultivated soil fertility".

"It is estimated that in the USA, 90% of all water...consumed from that withdrawn from streams and ground-water storage for use, is consumed in irrigated agriculture".

"Utilization of existing knowledge can in the short run accomplish...more than (can) expanding basic knowledge".

"...slow growth initially may set a pattern which may never be regained during the remainder of the growing season".

"Grazing by animals offers the only potential for converting the natural plant crop of these (non-tillable) lands to food useful to man".

"Increases in plant growth following fumigation sometimes cannot be accounted for by control of known pathogens or pests".

"Our ignorance of this vital zone (root-soil complex) is nothing short of appalling and for obvious reasons. The system we are discussing is inaccessible, and the processes of gaining access to it tend to alter it severely, at the very least, and usually, to destroy it".

ENVIRONMENTAL STRESS:

"...most facets of agricultural research are not amenable to a 'crash program' approach which intermittently pour research dollars and effort into programs".

"Combinations of stresses constitute the primary limiting factor(s) for increasing and expanding production in many, if not most, of the world's food crops".

"...world rice production would decrease by 45% or 137 million metric tons if there was a global fall in temperature of 0.5° C in the 0°-20° latitudes and a 1.0° C fall in the 20°-40° latitudes".

"Several promising (rice) lines have been hybridized to recombine drought resistance with yield increases which, to date, range up to 50% or higher".

"World hunger will be a problem even if we produce enough food unless we can improve distribution".

"Agricultural practices to overcome environmental stress should emphasize approaches that do not require large amounts of energy, water, or other finite resources".

"We cannot answer two seemingly simple questions: How do stresses injure plants? How do some plants avoid or tolerate stress"?

"Minor modification of crops or microclimate which are within the realm of our current biological and technological capabilities could markedly increase crop productivity under stress".

PLANT PROTECTION FROM PESTS:

"...crop losses caused by insects and diseases in the USA have increased both absolutely and as a percentage of crop value since the 1940's".

"...pests in the United States and the world destroy one-third of the potential harvest".

"In many situations the post-harvest losses due to pests can exceed the loss they have imposed before the harvest".

"...in only 3-10 years many resistant crop varieties become obsolete because the pests develop new strains and biotypes that overcome the plant resistance mechanisms".

"On the average the time from conception to first realization of a new technology is 19 years".

"...inadequate knowledge of the pests themselves is a major constraint on the development of superior control methods and of integrated management systems for crop protection".

"...stabilization of losses from plant pests at an acceptable economic threshold level through integrated plant protection remains the underlying principle of biological control".

"A diversity of narrow-spectrum insecticides is preferable to a limited number of broad-spectrum compounds for insect control because it diminishes the chances of mortality among the natural enemies of the pest".

"Insecticide-resistant populations are now known in more than 150 species of plant-feeding insects and mites and in more than 20 species of fungal diseases of plants".

PLANT DEVELOPMENT PROCESSES:

"The accelerated progress required for feeding rapidly expanding world populations depends on bringing biochemists and plant physiologists into direct and active participation with those teams whose mission is genetic and cultural improvement of crop productivity".

"Maximum economic yield...is achieved primarily by two multiple-gene directed processes, namely photosynthate accumulation and partitioning".

"Although continuous divisions do occur from protoplasts of a few species, the lack of such proliferation for most crop species remains a serious limitation to capitalizing on these methods in crop improvement".

"...cell and tissue culture will probably be very effective with some plants and in attacking some problems. They will certainly not be a panacea for solving all plant improvement problems".

"Plant development...is limited by lack of fundamental knowledge of the mode of action of hormones and of how the several hormones interact to control plant organ development".

"Factors affecting root architecture and development and their relationships to root functions in uptake of nutrients and water are poorly understood".

"Much of the realized gain in crop productivity of current as compared with past cultivars is derived from closer between-row and within-row spacings. Higher plant population densities do not give increased yield for the old cultivars".

"The mechanisms controlling the partitioning of photosynthates and nutrients demand immediate attention".

"Many important genes will only be expressed...in very specific environments, and some...only in combination with certain other genes".

"For the most part, plant improvement through breeding has been based on empirical tests without an understanding of the basic physiological processes being manipulated".

"While urging the implementation of team research, we suggest constraint in how such teams are put together and how they are oriented. Not all people work well together. Some extremely productive scientists work best when not constrained by the needs of an organized group".

INTRODUCTION
OF
KEYNOTE SPEAKER

John E. Cantlon
Michigan State University

It is a distinct honor to have the responsibility of introducing the keynote speaker for this International Conference on Crop Productivity. In reflecting on the importance of this occasion, I was struck by the observation that in the short period of the lifetimes of many of us in this room, we have been uniquely exposed to an array of very significant challenges, e.g.:

- The challenge of how to deal responsibly with nuclear energy.
- The challenge of how to build a sustainable, economically feasible energy supply after oil.
- The challenge of having made a reality out of global economics without either understanding its ramifications or learning how an individual nation can cope with them.
- The challenge of discovering we must learn to live with tough environmental constraints upon the complex technologies on which we have become dependent.
- The challenge of having substantially lowered human mortality rates without discovering concomitantly socially acceptable means for lowering human birth rates.

All five of these challenges are essentially new to our generation - at least in the global context from which we now view them.

The challenge that provides the theme of this Conference, however, that of enhancing crop productivity, has its roots back in the far distant past - so long ago that the very ground on which we meet today was relatively fresh glacial till scarcely yet forested when man first began to modify the crops that produce his food supply.

A remarkable thing, of course, is how far we have come in this task - yet how little we truly know about how to use modern science to change the base productivity of man's crop systems.

Even more remarkable, in view of the urgent human population generated world hunger challenge, is how low in national and international priorities is increased support for the science that will underlie the next major steps in enhancing crop productivity.

Our keynote speaker is a man whose professional life has been devoted to aspects of this central challenge to man's future well being. Dr. Sterling Wortman is currently Vice President of The Rockefeller Foundation in New York City - an organization that has a long and internationally respected tradition of supporting and conducting successful and significant research on plant productivity. It gives me great pleasure to introduce your keynote speaker, Dr. Sterling Wortman.

WORLD CROP PRODUCTIVITY: CHALLENGES TO SCIENCE

Sterling Wortman

The intensification of agriculture worldwide has become, for the first time in history, a matter of concern in international diplomatic, financial, and scientific circles. Hopefully, there is emerging a new era of global collaboration in the mobilization of knowledge, of financial resources, and of management capabilities to achieve new breakthroughs in crop and animal productivity. This growing interest is fueled by a broadening awareness of the seriousness and complexity of the world food situation - and of the extreme proverty with which hunger is associated.

The timing of the discussions scheduled for this Conference could hardly be better: you will be dealing with those biological processes which are at the very heart of man's efforts to secure for people everywhere more adequate and stable food supplies and the rising standards of living so directly related to agricultural productivity.

Indications are that accumulated advances of the past century would now permit a worldwide assault on hunger and proverty - with a reasonably high probability of success. In all likelihood, such a bold undertaking could not have been launched a decade ago nor even five years ago. But it can be done now if men and nations, their international agencies, and their scientists have the wisdom and the will to act in concert.

The penalties for failure will include immense human suffering, growing unrest and violence, instability of governments, plus tightness of markets and higher food prices everywhere.

A successful international effort could, if wisely organized and pursued, buy time for necessary reductions in population growth rates and contribute importantly to a reduction of suffering and of international tensions, to a new sense of hope for the hundreds of millions whose future now is bleak, and to a new sense of satisfaction among the many who wish to help.

THE ACCUMULATED ADVANCES

Perhaps it would be useful to recount, even if briefly, some of the important advances of recent decades which would now permit that effective assault on poverty and hunger.

First, the growing seriousness and complexity of the poverty-food-population problem worldwide is becoming understood. Before World War II, Asia, Africa, and Latin America were all net exporters of grain. Since then, nations of those regions have been importing increasingly large quantities. The first forecasts that I have found of food deficits projected to the end of this century date back only to 1963, when L. R. Brown (1) presented his paper entitled, "Man, Land, and Food." It was not until 1967 that a comprehensive analysis of the situation was undertaken. Some 125 U.S. scientists, after months of work, published their findings in a three-volume report to the President entitled, "The World Food Problem." (2) That study remains a classic one, its findings still generally valid - and still generally ignored - in the view of a U.S. National Academy of Sciences committee which reviewed it a year ago. Since that 1967 report of the President's Science Advisory Committee, a number of other important analyses have been presented, including FAO's Indicative World Plan, (3) and the findings of the World Food Conference of 1974(4). Emerging awareness of the situation is based on studies largely of the last decade. If we recall how recently this concern has developed, we should find it reassuring that the food problem is receiving the amount of attention it does on the highest political levels.

Second, agriculture at last has been recognized as the basic industry of agrarian nations. A decade ago many if not most development authorities advocated industrialization (as the supposed means for providing employment for the masses), as the primary way by which a poor agrarian country could leap into the twentieth century. Now, it is increasingly realized that if productivity of hundreds of millions of farms, most tiny by American standards, can be raised substantially, with higher incomes for hundreds of millions of farm families, the domestic markets for products of urban industry can be created. Increased demand for goods and services in the countryside will lead to quickened economic activity in the rural trade centers.

Most of the world's subsistence farmers today depend for a livelihood on production of basic food crops and animal species long neglected by governments of their countries. An increase of production of basic food crops in the developing countries themselves will contribute both to the needed increase in absolute amounts of food and to the widespread purchasing power which will allow the hungry, access to greater and more varied food supplies. Agricultural development in any agrarian nation is a principal component of, if not a prerequisite to, general economic progress.

Third, we have come to realize the limited transferability of agricultural technology from temperate climate to tropical and subtropical regions. A decade ago many politcal authorities assumed that technolgy generally could be freely transferred, and all that was required was to put existing information to use. Much agricultural technology is highly transferable but, generally speaking, the biological components are not.

New high-yielding, more highly profitable crop and animal production systems must be devised to fit the peculiar combinations of soil, climate, plant-pest complexes, and consumer preferences of each of thousands of localities. New production systems must be devised for every crop for every season of every region of every nation and be adopted by hundreds of millions of farmers, many of whom are uneducated and in remote areas. The myth of general transferability of agricultural technology has been set aside.

There now exists a new network of international agricultural research and training centers to deal in the developing regions with some problems of the many crop and animal species so long neglected, see page 68, Table II. Moreover, a number of the emerging countries are embarking on large-scale development of their agricultural science capabilities, each of several programs involving scores of millions of dollars.

Fourth, chemical fertilizers are now being produced in absolute quantities sufficient to allow their use to be extended to the vast areas of the food crops, even in developing countries. Total world chemical fertilizer production following World War II was about 7.5 million tons. That had tripled by 1955, had doubled again by 1965. World production now is approaching 80 million tons per year. Once priced so high and in such limited quantities that they could be used only on luxury crops, fertilizers can now be increasingly used on food crops. This shift is accelerated as scientists develop varieties - with associated production systems - which are efficient in utilization of nutrients, water, and solar energy.

Fifth, it has been learned that farmers, even those who are uneducated and have tiny landholdings, are willing to change to new, more productive systems if they can. A decade ago it was conventional wisdom that such farmers were too conservative, too ignorant, to be expected to shift to high-yielding, more complex systems. That myth too has been set aside.

Scientists or administrators who once could blame failures of production programs on supposedly ignorant and apathetic farmers now must look to the weaknesses of their programs.

Sixth, it has been demonstrated that governments can take effective action if they will. Time will not permit a recitation of the growing number of reasonably successful national agricultural production efforts, but among them are India's High-Yielding Varieties Programme of the 1960's, the Turkish Government's introduction of semidwarf wheats into her coastal regions, the Philippine Government's current campaign with rice, entitled "Masagana 99," the remarkably successful programs of Japan and Taiwan, and that of the People's Republic of China (5,6).

Seventh, many of the financial institutions necessary to handle large-to-small volumes of credit - the World Bank, the regional banks, the national agricultural banks, the local rural credit banks - are in place or are being created. Moreover, most major banks and international assistance agencies have in recent years altered their priorities to focus on agricultural and rural development, a welcome change in strategy.

Eighth, the recent emphasis by a growing number of institutions on increasing the productivity and profitability of small farms represents a recognition that this is a primary solution of the world food problem. It gets at both sides of the hunger equation: increased food production and purchasing power among the poor.

The growing concern of national authorities for problems of the rural masses, - the small farmers and other rural dwellings, can be illustrated by recounting the remarks of a governor of a state in Mexico, made about two years ago.

He recalled that the Mexican revolution, early in this century, was triggered because "the granaries of the landlords were full, and the bellies of the people were empty". Now, he says a similar situation exists, in that a relatively small fraction of the population is enjoying the comforts of life, the masses of the people are not benefiting and many see no hope of doing so. Moreover, the poorer people know it - as a result of improvements in communications, especially radio and television. Mexico, he said, is setting on a powder keg - as it was at the time of the earlier revolution.

The agrarian nations must give effective attention to improving the productivity of the rural people, assisting them in obtaining higher real incomes and standards of living, otherwise rural unrest will grow and governments will fall. Growing more food on large farms which the hungry could not obtain would simply give Mexico once again a situation where granaries were full, bellies empty, and the country set up for unrest.

Greater agricultural production in the United States or other developed countries is a non-solution to the world food problem. Nevertheless, increased productivity in North America, Europe, and elsewhere, is extremely important. Many countries must continue to rely on these few areas of surplus production for needed supplies. There will be growing international sales, important to achievement of balance of payments. Abundant food supplies are a prerequisite to maintenance of reasonable food prices everywhere. And, for humanitarian reasons, food stocks must be available to meet emergency requirements anywhere.

Large-scale, mechanized farming is not a solution to the food problem of the poor countries for two reasons: it is potentially less productive per unit-area per unit-time than is the labor-intensive system of gardening that can be practiced by farmers with small holdings. Moreover, it often creates food supplies which the poor cannot afford to purchase.

That large-scale, mechanized farming is not as potentially productive *per unit area* as is labor-intensive "gardening" can be illustrated with an example from the People's Republic of China. When an American team of plant scientists visited the Kirin Academy of Sciences of Agriculture and Forestry - the Kirin provincial agricultural research institute - in September 1974, we were shown a field of corn which had been *superimposed* on a field of wheat. The wheat had been planted the first of April. Near the end of April, when the wheat had emerged, corn was planted between appropriate rows of wheat. Later, the wheat was harvested while the corn continued to grow. Yields of both wheat and corn reportedly were depressed in such a system, but the combined yields were said to be some 40 percent greater than could be obtained with a single crop of either wheat or corn. The Chinese could not afford to be penalized 40 percent for use of a mechanized monoculture.

Many other examples of greater productivity of gardening techniques (relative to monocultures on a per unit-area per unit-time basis, could be drawn from experiences in Asia with multiple cropping.

Large-scale, mechanized agriculture has its place. As practiced in the United States and many other countries, it is extremely productive *per man-year of farmers' time*, and in such economic systems where labor costs are high it results in low costs per unit of harvested product. But, large scale, mechanized farming is not, generally speaking, the solution to the food problems of developing countries.

Ninth, the drawdown of surplus supplies of food and feed grains in the 1960's, and more recently in the 1970's, seemingly has convinced a number of authorities of the developing countries that they must give attention to the development of their own agriculture and rural areas. Any confidence they may have had in the availability of low-cost or free external food supplies has been jolted, severely and repeatedly. If these jolts result in significant action by governments on problems of their own rural people, the disappearance of the surpluses may well be considered the most favorable event of recent years, so far as alleviation of the world food problem is concerned.

Tenth, in recent decades much has been done to build a scientific and technological base on which countries in need can draw in bringing agricultural advances to their own farms.

EXTENDING THE AGRICULTURAL REVOLUTION

An opportunity exists to extend and intensify the agricultural revolution - a revolution which already has resulted in large gains in yield of virtually all crops in temperate climate regions and of most estate crops in tropical and subtropical areas. Basic to an extension of the revolution will be a substantial increase of biological research efforts coupled with a deliberate focus on those problems of highest priority.

Clearly, an extended and improved science base is only one of the requirements. Road systems must be extended as must power grids marketing systems and systems of credit. The unique capabilities of industry, unavailable elsewhere at any price, must be utilized to the maximum. Finally, population growth rates must be reduced.

Accompanying it all must be the emergence and widespread understanding of a strategy which will bring results at an accelerating pace.

It is particularly important that the scientific community take the lead in identifying and articulating that strategy, making it know in terms that the non-scientist can understand. Most authorities of most nations, those who will make the important decisions regarding agricultural development or the support of science, are neither agriculturalists or scientists.

THE SPECTRUM OF RESEARCH REQUIRED

One of the difficulties in dealing with

the subject of research, at least for me, has been the lack of adequate terminology. Perhaps we should consider agricultural research in terms of the needed forced-pace production campaigns, borrowing in part from the military. A spectrum of research efforts is called for - operational, tactical, strategic, supporting, and basic.

OPERATIONAL OR FARM LEVEL

This involves the identification - through continuing experimentation on farms - of the specific combinations of crop and animal production practices that will provide maximum productivity and profitability on those farms. Much of this vast amount of research - or innovation as some would call it - has been done by farmers themselves, as in the United States.

In the developing countries many farmers have little education and are unaware of the vast array of technologies which they might employ. They cannot experiment or innovate as do their more sophisticated and educated counterparts of other nations. Therefore, in the poorer countries, scientists must direct development of the local farm systems, and for the most part this involves work on representative farms of each region of each nation. Perhaps 70 percent of the world's agricultural technical manpower must be engaged in "operational" experimentation.

TACTICAL

In each nation, supporting the farm-level experimental and demonstrational efforts, there must be one or more teams of scientists usually working at regional experiment stations, to identify or develop components for local farming systems. These components comprise new varieties, fertilizer-use guidelines, methods for control of locally prevalent diseases and insect pests, new crop- or animal-production practices, and other materials or techniques.

STRATEGIC

This category of research is aimed at the solution of those major problems affecting several areas of a country, or a region of the world, or at the development of entirely new approaches to the removal of major barriers to improve production of particular crop or animal species.

Such research should be in direct support of scientists engaged in technical research in several regions of a single country or in several countries - efforts aimed at putting scientific advances immediately to widespread use as they are developed. Most of the main lines of research at the international agricultural research institutes and at central experiment stations of the larger nations would be of the strategic type.

SUPPORTING

These fundamental but purposeful investigations generally are undertaken and financed because of probable usefulness of the findings in ways at least partially known. Much of the supporting research related to the world food effort is being done by national agencies or at universities of the developed countries. One might include in the supporting category such efforts as work on biological nitrogen fixation and its potential extension to the grasses, on photosynthesis or respiration of economic crop plants, or on the nature of organisms causing plant or animal diseases. These are among the main subjects which you will be discussing this week.

BASIC

This is research undertaken primarily to extend the frontiers of knowledge with no predetermined use in mind - development of knowledge for the sake of knowledge. This is an important category of research on which all supporting, strategic, tactical, and operational advances depend.

AN EXAMPLE: WHEAT

Work on wheat improvement will serve to illustrate the spectrum of research efforts. From "basic" work in the field of genetics came the capability of scientists to understand the mechanisms of inheritance of the several species of *Triticum*, to understand their relationships, and to devise plant breeding techniques for the improvement of spring- and winter-bread wheats and the durum wheats (7). From basic work in plant physiology came an understanding of nitrogen uptake, of requirements of major and minor nutrients, of factors affecting photosynthesis and respiration. The earliest work probably was undertaken for the primary purpose of extending knowledge, though there may have been hope and belief that this knowledge could somehow be usefully employed.

As the utility of basic work in genetics, physiology, and chemistry was recognized, efforts (of the "supporting" type) were intensified in many countries to improve the wheats by developing plant types which could utilize more efficiently solar energy, water, and nutrients. Attention was given to the nature of disease organisms (such as rusts), the nature of host plant resistance, and factors affecting grain quality. These are but a few of many examples of "supporting" research on wheat. Note only that they are purposeful investigations of broad applicability and of great importance.

Building on advances in many fields of basic and supporting research, it was possible in Mexico for scientists to begin creating improved varieties and practices for the low latitude areas, as was being done concurrently by scientists of nations elsewhere. Work was initiated on means of incorporating into new varieties wide adaptation to climatic conditions, and to devise means of reducing danger from diseases through creation of multiline varieties. These are but a few examples of "strategic" research which was undertaken.

In several important wheat-growing countries, teams of scientists are working to identify improved wheat varieties adapted to local conditions and to determine effective practices related to fertilizer application or the control of locally prevalent diseases or insect pests. Such "tactical" research was undertaken with introduction of the semidwarf wheats into India and Pakistan in the mid-1960's. For example, at the Indian Agricultural Research Institute, and in localities elsewhere in the country, experiments were conducted to determine appropriate rates and dates and depths of planting, rates and dates and placement of required fertilizers, and amounts and timing of irrigation water needed. Literally scores of experiments were installed, almost at a feverish pace, to determine as quickly as possible the appropriate components for farm-level wheat production systems. This was forced-pace, "tactical" research at its best.

Finally, and we must not underestimate its required volume, is the experimentation carried on at the farm level, both by technicians and by farmers themselves - the so-called "operational" research or innovation.

At any particular research center or station, one actually will find an assortment of these types of research, and it is not suggested that any category of research should be the exclusive responsiblity of scientists at any particular level in the system. It is important to recall, however, that effective work at the strategic, tactical, and operational levels, wherever it is occurring, is possible only because of past advances in research of the basic or supporting types. Conversely, support of "basic," "supporting," or "strategic" research will be of no value to mankind unless its benefits reach the farmer through the "tactical" and "operational" research avenues.

The entire system must exist and function. A substantial start has been made internationally toward that end.

THE CHALLENGES TO SCIENCE

In the brochure describing this Conference, it is stated that attention will be given to the "biological processes that enhance plant productivity." Surely no more competent group of scientists could be assembled to assess the research imperatives in these areas. You will be dealing with the three major sets of biological processes involved: those that affect the efficiency of the plant in utilizing energy, nutrients, and water, and their conversion to desired plant products; those affecting nutrient supply; and those related to disease and pest control. Presumably you will also consider, in relation to these subjects, the importance of having an adequate knowledge of the genetics of each of the major economic species, of the importance of wide adaptation in crop plants, and of the need to screen the world's germplasm for sources of resistance to diseases and insect pests, for sources of tolerance to drought and other types of stress, and sources of improved photosynthetic efficiency. You will in effect be looking primarily at research needs of the basic or supporting types. Let me challenge you to consider - for each set of biological processes - the requirements at the strategic, tactical, and operational levels required to complete the system and to bring to people of the developing countries the benefits of any advances made.

The description in the brochure also says that this Conference will give attention to "those aspects of science and technology which hold greatest promise for enhancing (crop) productivity." One might then ask "what are those aspects?" Let me mention a few in the hope of stimulating your discussions.

1) In recent decades, most agricultural research has been provincial, and it still is. Funds for agricultural research have often been restricted to work applicable to immediate or to local or regional needs, with little for work on far-reaching or longer term approaches. But, the world is entering a new era of international cooperation. Opportunities now exist for scientists to think in international or global terms with some hope that required international collaborative research might be arranged.

2) The opportunities, indeed the requirements, for interdisciplinary work to achieve solutions of some of the major

biological problems are becoming known. Increasingly in the biological sciences, as in the physical sciences and engineering, real teamwork on real problems, with an emphasis on rapid progress toward well-defined goals, will be demanded. The time-frame in which all of us will be working is entirely too short for any other posture.

3) The scientists of the world - you and I - are considered by many other authorities to comprise the single most conservative element among those who must be involved in alleviation of world hunger - more conservative than either governments or farmers. It is alleged that we think smaller, are less willing to become involved in concerted, directed, team action, and have less of a sense of strategy than do many others.

AN ILLUSTRATION OF THE CONSERVATISM OF SCIENTISTS

In the mid-1960's, seed of semidwarf Mexican wheat varieties reportedly was smuggled into Turkey from Pakistan by a technical assistance representative, and was given to a Turkish farmer to try on his farm on the Mediterranean coast. The variety, which had been given good yields in neighboring countries, also was outstanding in the initial farmer's test in Turkey. Farmers from the surrounding area, on seeing the unusually high yield of the Mexican semidwarf, petitioned the government for a permit for commerical import of more seed, so that more farmers could try it.

Reportedly the scientific community opposed the import of even a few hundred kilograms, on the grounds that such varieties had not been properly tested within the Turkish national system. But, the pressure from the farmers was too great, the import license was granted, and some 100 farmers planted it in the following year. Results were so spectacular and enthusiasm of the farmers so high, that the Minister of Agriculture decided to import 50,000 tons of seed of the new varieties!

There reportedly was an uproar from the Turkish scientific community who felt that planting of such a large quantity of such locally-untested varieties represented an unrealistic gamble for Turkey.

United States Agency of International Development (USAID), which had indicated it would provide loan funds for the purchase of seed by Turkey from Mexico turned to us at The Rockefeller Foundation for counsel. Their question was "Should Turkey import 50,000 tons?" We in the New York office were not competent to answer such a question so we called Dr. Borlaug who was meeting with other wheat authorities in Minnesota. After consultations, they suggested that Turkey import no more than 5000 tons! They had no fears about the usefulness of the varieties, but they were concerned that there would be insufficient time to instruct large numbers of farmers how to plant the dwarf varieties (dwarf below-ground as well as above-ground) 5 centimeters deep with grain drills rather than plowing it in at around 10 centimeters deep, as was the usual practice.

The Minister split the difference, importing some 22,000 tons of seed, including relatively small amounts of high yielding varieties from the Pacific Northwest area of the United States. With help for several months of experienced extension agents and farmers from the United States, Turkey successfully planted over 18,000 tons of that seed!

Clearly those of us at The Rockefeller Foundation were more conservative than people in the Ministry of Agriculture of Turkey, and perhaps some of Turkey's academics were even more conservative than we were.

To a plant breeder, 50,000 tons of seed seems like an *enormous* amount - and it is, relative to the handful of seed with which most tests of varieties are launched. But, as the Minister pointed out, Turkey at the time was planting each year about 1.25 *million* tons of wheat, seed, and to import and plant *only* *50,000* tons of seed of dwarf varieties seemed not to be an undue risk.

The difference in the views by scientists and development authorities of 50,000 tons of seed, illustrates why scientists are considered by some others to be so conservative.

Certainly biological scientists must begin to exert much greater leadership in defining, articulating, and implementing the strategy for extending the agricultural revolution. They have the clearest understanding of the biological basis for agricultural change and are responsible to a large degree for progress to date. Unless biological scientists assume greater leadership, it will go to others by default.

Let me urge you to foster, particularly at your own institutions, interdisciplinary approaches to research wherever that is required. And, let me suggest you push for development of a strategy of forced-pace agricultural development toward which scientists of all nations can contribute in a joint effort far more complex than the space programs, and far more important, no doubt, to far more people.

Finally, as you examine priorities or

imperatives for research on biological processes, let me urge that you make your findings known in terms that those who control funds and action - mostly non-scientists - can understand, that you explain the importance of such work in the campaign for a better life for all in the years immediately ahead.

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RICE RESPONDS
TO SCIENCE

Nyle C. Brady[1]

The world food problem, or crisis if you will, is real. While for most of us our next meal is taken for granted, for hundreds of millions of people their next meal may not be forthcoming. Some say that this state of affairs is not markedly different today from that of a century ago or even a decade ago. There have always been some people who were hungry - who were uncertain as to where their next meal was coming from - and some who were starving.

But the situation today is different in two respects. First, the number who are faced with malnourishment, if not downright starvation, is an order of magnitude greater than was the case even a quarter of a century ago. And secondly, the food "shock wave" of the past two years has not only damaged the poor nations for whom hunger has become a way of life, but also has had decidedly unsettling effects on the more affluent nations. Even North American citizens who in the past dealt more often with food surpluses than food scarcity, found themselves in 1973 and 1974 scrambling for food at unprecedented prices. Worldwide concern culminated in the United Nations-sponsored World Food Conference held in Rome in November 1974(1). The headlines and editorial attention received by this conference suggest that at no time in history have more people, rich or poor, been as seriously concerned with food supplies as at present.

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[1] Introduced by E. R. Lemon

EVENTS OF THE '60'S

Even to the casual observer, the present food situation is surprising, to say the least. In the early 1960's as much attention was given to the problems of excess food as to food deficits. Crop acreage controls, two price marketing systems, and special international trade agreements helped food-exporting nations to maintain a balance between supply and demand. The less affluent nations showed no signs of alarm. The advent of new high yielding wheats and rices offered what to many was a panacea. The term Green Revolution" was coined to describe what the new "miracle" seeds could do to free man from the ugly spectre of hunger. Self-styled forward looking planners turned their attention to so-called second generation problems concerned with factors such as marketing, land reform, and income distribution. In spite of unprecedented population increases, food production per capita remained steady and even increased slightly. There seemed to be a general consensus that the food production problems were near solution. Only the 1966-1967 droughts in India caused anyone to question the validity of these impressions, and these lean years were handled readily by drawing upon reserves from the United States, Canada and Australia. The worldwide granary of food stocks was ample to meet what appeared to be an unusual and isolated case of food scarcity.

DROUGHTS BRING TRAGEDY

The drought of '72 in Russia and China, floods and droughts in India and Bangladesh, and the severe droughts in Central Africa drastically altered this food supply and demand picture. Suddenly, the worldwide food stocks were badly depleted. The nations with traditional surpluses were hard pressed to meet commitments. Food prices reached unprecedented levels. In the United States, export controls were used to slow down the upward spiral of food costs to the American consumer. The energy crisis and concomitant fertilizer and pesticide shortages aggravated the situation, especially in the less affluent nations.

While the more affluent nations have been shaken by the events of the past few years, the developing countries have been drastically affected. Per capita food production decreased, especially in India and Bangladesh, where the density of population is among the highest in the world. Food prices doubled or even tripled in some developing countries and the very poor in those countries found that the proportion of their family income used to purchase food increased dramatically.

GREEN REVOLUTION REEVALUATED

The latest food supply crisis has opened to question the validity of the Green Revolution as a tool for increased food production in the developing world, particularly in view of its strong dependence on chemical inputs and fossil fuels. Revolutionaries indentify it with a conspiracy on the part of the chemical-supplying capitalist nations to enslave economically the low-income populace of the world. Analysts and biologists question the soundness of the new technology since it is so energy-dependent (2). They view the new technology as superimposing a western style, monoculture-based agriculture upon farmers and societies who neither want it nor need it. Environmentalists caution against those practices associated with the new technology which could lead to a deterioration of environmental quality in the developing world similar to that which has occurred elsewhere (3). Lastly, there remain the disappointed disciples of the Green Revolution who, disillusioned because of its lack of widespread success, are at a loss to explain why only 25-30 percent of the farmers in the developing nations have adopted the new high yielding rice varieties and the technology associated with them (4).

Favorable weather in late 1973 and 1974 stimulated world food production and there appears to be a temporary global respite from the threat of widespread hunger and starvation. In selected countries, however, the problems are still acute. For example, in Bangladesh, substantial food aid has not prevented widespread hunger and starvation. Likewise, in the drought stricken countries just south of the Sahara in Africa untold suffering has occurred. Even in the more fortunate of the third world countries, national food stocks remain low suggesting a critical dependence on a day by day supply of food. These facts emphasize that the basic problem of food production is still far from solved.

The events of the past quarter century and particularly of the last 15 years have emphasized several truisms including two that have impressed me deeply. First is the fact that science can help man feed himself. Even if the Green Revolution is not quite as green as it was thought to be, the products of science have demonstrated food production potentials far beyond those currently being accomplished by today's food producers. There are reasons to hope that a true green revolution is achievable.

The second truism is the fact that the development process is a complex one and cannot be easily achieved. World food sufficiency requires more than the development of a few simple rice and wheat varieties and more than the fertilizer and other chemical imputs necessary for the top performance of these varieties. It requires new technologies that will work in the wide variety of ecological conditions under which the world's food supply is produced. And it requires a number of intricate physical, biological, social and economic inputs, each in the proper proportion, and a support infrastructure that takes time, resources, and broad-scale planning to achieve. Lastly, it requires public policies which will not only allow, but also foster the overall food production system to function effectively.

RICE AND THE BACKGROUND OF THE INTERNATIONAL RICE RESEARCH INSTITUTE

May I turn now to rice and to the International Rice Research Institute (IRRI). No

Table I. Rice consumption, population and arable land, 25 major rice consuming areas, 1970.

	Rice consumption per capita	Calories from rice	Protein from rice	Population	Arable land
	kg/year	%	%	million	hectare capita
South East Asia[a]	112	57	48	256.3	0.170
East Asia[b]	115	46	32	168.0	0.056
South Asia less India[c]	142	67	55	121.3	0.270
"Rice" India[d]	118	57	45	230.8	0.258
"Rice" China [e]	108	53	41	491.7	0.157
Other rice dependent[f]	113	48	40	15.8	1.027
Average/Total	115	55	43	1283.9	0.186
Rest of the world	.3	5	4	2439.0	0.482

[a] Indonesia, Thailand, Philippines, Malaysia, Vietnam, Laos, Khmer, and Singapore.

[b] Japan, Taiwan, Korea, Hongkong.

[c] Nepal, SriLanka, Bangladesh, Burma.

[d] Andhra Pradesh, Assam, Kerala, Madhya Pradesh, Orissa, Tamil Nadu and West Bengal.

[e] Kiangsu, Anhwei, Chekiang, Fukien, Hupeh, Hunan, Kiangsi, Kwangtung, Kwangsi, Szechwan, Kweichow, Yunnan.

[f] Madagascar, Surinam, Senegal, Gambia, Mauritius, Liberia, Sierra Leone.

References 1[illegible],1[illegible]

thinking person can fail to have an interest in rice. It provides at least 25 percent of the food for 1.7 million people. In some heavily populated countries of Asia, more than 2/3 of their calories and more than half of their protein comes from rice (Table I). Nine-tenths of the really poor people of the world have rice as their primary or secondary food staple. Most of them live in the tropics and subtropics where monsoon climates provide surplus water during at least part of the year. And rice is the only major food crop which will produce abundantly under these conditions.

IRRI was the first of a series of international centers dedicated to the proposition that science had a crucial role to play in helping to increase the world's food production (Table II). Established in 1960, IRRI's first buildings were dedicated in 1962. The IRRI was supported initially by The Ford and The Rockefeller Foundations and by the Philippine Government which invited the Institute to make the Philippines its home. IRRI now receives support from not only these Foundations, but also from the United Nations Development Program (UNDP), the World Bank, and seven national aid agencies.

The more important characteristics of IRRI were summarized by its first Director, Dr. Robert F. Chandler, Jr. (5):

1) It is "a complete plant science research institute devoted exclusively to rice."

2) It emphasized from its inception problem oriented research without at the same time entirely eliminating more basically oriented research.

3) Its program implementation required "a team approach to the solution of rice-growing problems."

4) It had a truly international staff, scientists from seven countries making up the initial staff complement.

Table II. Background data on 10 International Agricultural Research Centers

Center	Location	Research
IRRI (International Rice Research Institute)	Los Banos, Phillipines	Rice under irrigation; multiple cropping systems; upland rice
CIMMYT (International Center for the Improvement of Maize and Wheat)	El Batan, Mexico	Wheat (also triticale, barley); maize
CIAT (International Center for Tropical Agriculture)	Palmira, Colombia	Beef; cassava; field beans; farming systems; swine (minor); maize and rice (regional relay stations to CIMMYT and IRRI)
IITA (International Institute of Tropical Agriculture)	Ibadan, Nigeria	Farming systems; cereals (rice and maize as regional relay stations for IRRI and CIMMYT); grain legume (cowpeas, soybeans, lima beans, pigeon peas); root and tuber crops (cassava, sweet potatoes, yams)
CIP (International Potato Center)	Lima, Peru	Potatoes (for both tropics and temperate regions)
ICRISAT (International Crops Research Institute for the Semi-Arid Tropics)	Hyderabad, India	Sorghum; pearl millet; pigeon peas; chickpeas; farming systems; groundnuts
ILRAD (International Laboratory for Research on Animal Diseases)	Nairobi, Kenya	Trypanosomiasis; theileriasis (mainly east coast fever)
ILCA (International Livestock Center for Africa)	Addis Ababa, Ethiopia	Livestock production systems
ICARDA (International Center for Agricultural Research in Dry Areas)	Lebanon	Probably a center or centers for crop and mixed farming systems research, with a focus on sheep, barley, wheat and lentils
AVDRC (Asian Vegetable Research and Development Center)	Taiwan, Republic of China	Mungbean, soybean, tomato Chinese cabbage, sweet potato, white potato

Source: reference 17

Table II.(cont'd)

Coverage	Date of initiation	Proposed budget for 1975 ($000)
Worldwide, special emphasis in Asia	1959	8,520
Worldwide	1964	6,834
Worldwide in lowland tropics, special emphasis in Latin America	1968	5,828
Worldwide in lowland tropics, special emphasis in Africa	1965	7,746
Worldwide including linkages with developed countries	1972	2,403
Worldwide, special emphasis on dry semi-arid tropics, nonirrigated farming. Special relay stations in Africa under negotiation	1972	10,250
Africa	1974	2,170
Major ecological regions in tropical zones of Africa	1974	1,885
Worldwide emphasis on the semi-arid winter rainfall zone		
Asia	1973	1,608

5) It had truly international program concepts and scope which involved training as well as research.

6) It was given freedom of action by its donors and governing board.

A NEW PLANT TYPE

Some remarkable achievements were accomplished during the first decade of the Institute. Perhaps the most significant was the development and dissemination of a new rice plant type for the tropics. Traditional Indica Type tropical varieties were tall (160-180 cm), had droopy leaves, tillered sparsely and were generally unresponsive to fertilizers. Invariably, before harvest, such varieties lodged which in turn reduced the potential yield markedly. Also, they were generally photoperiod sensitive thereby restricting their zones of adaptability.

IRRI scientists capitalized upon the pioneering research accomplished in China, India, Indonesia, and other Asian countries to develop a completely different plant type (5). The new rices are relatively short - semidwarf - (90-120 cm) and stiff-strawed, making them very resistant to lodging even when heavily fertilized. Their leaves are comparatively upright which decreases mutual shading thereby increasing the efficiency of utilization of solar radiation. They have high tillering ability and a high grain to straw ratio. They respond well to nitrogen fertilization, but generally yield better than the traditional varieties even when no fertilizer is applied.

New rice varieties with these favorable characteristics had double or even triple the practical yield potential of the traditional varieties. For the first time, farmers in the tropics had Indica type rice varieties with yield potential equivalent to those being grown in the temperate zones such as in Japan where the Japonica type rices are grown.

Farmers' yields of 4 to 6 metric tons per hectare were obtainable and yields on experiment stations of up to 10 tons were achieved. Compared with national yields of 1.2 to 2.0 metric tons per hectare, these new yield levels were exceedingly attractive (Fig. 1).

The first IRRI variety - IR-8 - was released in 1966, only four years after the first crosses were made between short-statured varieties coming from China and taller varieties from the tropics. IR-5 was released in 1967, IR-20 and IR-22 in 1969, and IR-24 in 1971. Similar progress was being made by

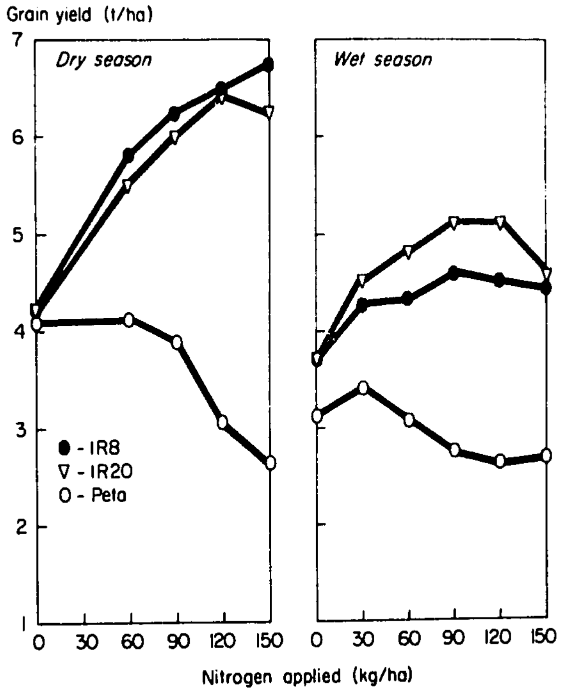

Fig. 1. Effect of levels of nitrogen on the grain yield of IR8, IR20, and Peta a traditional variety at four locations (IRRI, Maligaya, Bicol, and Visayas). Data are averages for 1968-73 cropping seasons.

scientists in other countries. For example, scientists in the People's Republic of China claim to have released six high-yielding short-statured varieties between 1959 and 1963 (4) and by 1973 6.7 million hectares were sown to the new rices (6).

The new plant type soon became a major component of rice breeding programs in the tropics. Breeding lines with the new plant type and high-yielding ability were promptly supplied to cooperating scientists working in national programs. Lines from crosses made at IRRI were evaluated under different ecological conditions throughout the world and were released as varieties by the cooperating scientists in a number of Asian countries.

Table III. Increase in production associated with the use of high-yielding varieties, Asia and the Mid-East (18).

Crop Year	Increase in			
	Production		Value	
	Wheat 1/	Rice 2/	Wheat 3/	Rice 4/
	t		millions of $	
1965/66	0.01	0.01	0.4	1.3
1966/67	1.5	1.0	58	148
1967/68	10.9	3.3	436	463
1968/69	18.3	5.5	732	784
1969/70	19.3	9.6	772	1,365
1970/71	22.1	12.7	884	1,798
1971/72	24.0	16.5	960	2,329
1972/73	28.2	20.7	1,128	2,933

1/ 13 countries 2/ 12 countries

3/ Wheat priced at $75/metric ton

4/ Rice priced at $100/metric ton

Source: reference 18

The number so released has now reached nearly 40. In addition, the new IRRI lines made available to cooperating scientists were soon incorporated with hundred of lines in national breeding programs. Many of these lines have been released and are in use today. An estimate of the economic value of production from these new varieties is shown in Table III.

GERM PLASM BANK

As a basis for the rice improvement program, IRRI scientists early in the Institute's history began the systematic collection and preservation of rice cultivars from around the world. By 1971, more than 14,000 samples had been collected. Today, this germ plasm bank contains more than 35,000 accessions and is still growing (7). Cooperating scientists request eight to ten thousand samples a year from this collection.

PRODUCTION RESEARCH

While plant breeders were developing the new varieties, other studies were under way at IRRI which contributed greatly to practical rice production. For example, a practical and relatively inexpensive means of controlling grassy weeds in paddy rice was discovered and tested, using 2,4-dichlorophenoxyacetic acid (2,4-D) one of the world's least expensive herbicides (8). The economic control of insects using paddy-applied granular insecticides was demonstrated as was the fact that the insecticides lindane, diazinon and DDT degraded more rapidly in the paddy field than under the drier upland conditions (8).

Yield increases of 12 to 30 kilograms of the new rices for each kilogram of nitrogen fertilizer demonstrated the real practicality of applying chemical fertilizers to rice. The significance of other soil deficiencies and toxicities was examined. Large areas of zinc deficient soil were identified and practical means of ameliorating the deficiency were developed (9).

The influence of solar radiation, temperature, and other climatic variables on photosynthesis and on the growth and yield of rice were studied. Solar radiation during the 45 days just before harvest was found to affect strongly grain yields (10). The optimum temperature requirements and the photosynthetic capacity of rice varieties were found to vary widely (8).

DISEASE AND INSECT CONTROL

Studies of insect pests and diseases of rice have received major attention since IRRI's inception (5). Marked genetic diversity in the resistance of rice cultivars to diseases and insect pests was soon recognized. Entomologists and plant pathologists have screened thousands of varieties and lines under greenhouse, screenhouse, and field conditions. They have identified sources of resistance to the majority of the economically significant diseases and insects of rice. Cooperating plant breeders have incorporated this resistance into IRRI breeding lines and in turn into the breeding materials of national research programs. This has caused a marked increase in the number of crosses made annually at IRRI. This number was 1,100 in 1972 and increased to nearly 3,000 in 1974 (7).

The planned program of incorporating greater insect and disease resistance into the high yielding varieties' has borne fruit. In 1973 IRRI released one variety (IR-26) which has at least moderate resistance to seven of the major rice insects and diseases. This was followed in 1974 by IR-28, IR-29 and IR-30 and in 1975 by IR-32 and IR-34 which have equally good resistance to major rice pests. These new varieties are being planted in the Philippines. Furthermore, they have been tested in other Asian countries and are available for use there.

FARM MACHINERY

In labor surplus economies which characterize most of the developing countries, the need for mechanization in agriculture is not immediately apparent. In these countries, the need is real but it is related not to saving labor, but to saving time. Proper timing of cultural operations is needed to realize the full potential of the new high-yielding rice varieties. Early land preparation to permit direct seeding of rice on moist soil without having to wait for the flooded conditions necessary for transplanting can save up to six weeks in some areas. This permits time for an additional crop to be grown and insures increased efficienty of utilization of scarce water and fertilizer supplies. Likewise simple harvesting and drying machinery can save irreplaceable time during periods of peak labor requirements. Additionally, fertilizer efficiency depends upon proper placement in the soil, a requirement that can best be met by small machinery.

IRRI engineers and economists have made studies of areas where machinery would be most helpful to the small farmer (11). The engineers have designed and fabricated a number of machines which after thorough testing are being manufactured by local firms in the developing world. Among the more successful of these units is a 5-7 horse power tiller, a small rotary weeder, a small hand propelled direct seeder, three small threshing machines, and a one-ton batch drier which uses rice hulls as a source of energy.

FARM MANAGEMENT STUDIES

Practical farm management problems have been approached by agricultural economists who have integrated their efforts with those of the biological scientists so that the research efforts of the biological scientists could be applied directly to the solution of practical farm problems. The work of IRRI's economists stressed from the outset the factors affecting the adoption or non-adoption of modern technology and the consequences of this adoption. Adoption was most rapid in irrigated areas and with farmers who were able to procure chemicals and financial inputs. The adoption of the new technology including mechanization did not decrease total labor requirements, however, since increased labor for weeding, harvesting and threshing offset decreased labor utilization resulting from mechanization (5).

TWO MAJOR ACHIEVEMENTS

IRRI's first decade was characterized by two major achievements. First, it was necessary to establish credibility, not only with the scientific community but with decision makers concerned with research, education and economic development policies. It was necessary to convince leaders of both the developing nations and the more affluent countries that science could provide major contributions to the solution of the world food problems.

Policy changes have suggested that this goal has been at least in part achieved. There appears to be a conviction that a science-based technology developed in and relevant to the developing world is essential for agricultural development. The more affluent donor nations have set up a worldwide network of international agricultural research centers of which IRRI is a part. National leaders are giving greater attention to science as an integral part of agricultural production programs. Encouraged by inputs from outside donirs, national agricultural research programs are being strengthened and expanded. There seems to be a general recognition that locally effective technology must be developed and that adaptive research is essential to develop that technology.

The second major IRRI achievement of the first decade was to provide the scientific basis for a technology which would pay off quickly and handsomely. This was accomplished by concentrating on rice production where the yield could be most easily increased. Consequently, heavy emphasis was placed on irrigated rice culture where water levels could be controlled. Also, initially there was heavy dependence on the use of pesticides to control rice pests and diseases. This early research emphasis on irrigated rice was justified since this approach gave the best opportunity for immediate pay-off. Also, it demonstrated the yield potential of tropical rices and suggested yield levels that could be attained if some of the constraints were removed.

Evidence of success in the second achievement is seen in the rates of adoption of new high yielding varieties and of the associated technology. In irrigated areas, the rate of adoption has been high. For example, in Pakistan, where a large proportion of the rice is irrigated, the adoption rate has been good (Table IV). Likewise, the adoption rate is high in the Philippines where most of the rice is either irrigated or is grown under non-irrigated by bunded[1] conditions where depths of paddy water are controllable. In contrast, in Thailand, where a high proportion of the rice is grown under condition of uncontrolled flooding or of upland unbunded culture, the adoption rate is low.

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[1] In bunded rice culture individual small fields are leveled and surrounded by dikes in a terrace-like arrangement which holds rain or irrigation water on the land.

Table IV. Proportion of total rice area planted to high-yielding varieties

Country	Crop Year 1966/67	1968/69	1970/71	1972/73
	Percent			
Bangladesh	negl.	1.6	4.6	11.1
Burma	-	3.3	3.6	4.2
India	2.5	7.3	14.9	24.7
Indonesia	-	2.4	11.2	18.0
Korea (South)	-	-	-	15.6
Malaysia	14.7	20.1	30.9	38.0
Pakistan	negl.	19.8	36.6	43.4
Philippines	2.7	30.4[1]	50.3	56.3[1]
Thailand[1]	-	-	1.5	4.9

1/ Based on unofficial estimates of high-yielding varieties area.

[illegible]

THREE-PRONGED RESEARCH APPROACH

Having demonstrated to the scientific community, to decision makers, and to farmers that it was possible to improve greatly rice yields where water, insects, diseases, and the supply of fertilizer nutrients could be controlled, IRRI scientists have now turned their attention to problems where such control is difficult if not impossible. This research has three foci:

1) to ascertain better the nature and extent of the constraints on the production of rice.

2) to develop technology which will either remove the unfavorable conditions or will permit the rice plant to overcome or adapt to them.

3) to couple the research at IRRI with activities in national agencies in areas of mutual interest, thereby strengthening and

reinforcing the efforts of each.

CHARACTERIZING RICE PRODUCTION CONSTRAINTS

The significance of rice production constraints due to the physical environment is obvious, especially when taking into consideration the uncontrolled water levels in rice-growing regions of the world. Currently available evidence suggests that in 30 to 40 percent of the rice growing areas in Asia, flood waters commonly exceed 0.5 m at some time during the growing season. Under these conditions, the new short-statured, high-yielding varieties are not suitable. The implications for rice investigators are obvious (Fig. 2).

The quality of rice soils is also receiving greater attention. Studies are under way to classify these soils according to their capability for rice production and to identify and quantify areas of problem soils. The latter include saline and alkali soils, highly acidic soils, acid sulfate soils, and soils containing toxic or deficient levels of elements such as iron, manganese, aluminum and zinc. Preliminary investigations indicate the presence of large areas of problem soils which must be dealt with before rice yields can be increased.

In agro-climatological studies designed to better characterize the climates in which rice is being grown, particular attention is being given to rainfall patterns as they relate to crop production potentials. Such data are needed, not only for rice production but also for the development of better cropping systems involving rice.

The biological and socio-economic constraints on rice yields in the farmers field are being determined by teams of agricultural ecomonists, agronomists, and statisticians. Field experiments are undertaken on farmers' fields to learn why farmers cannot obtain the same yields

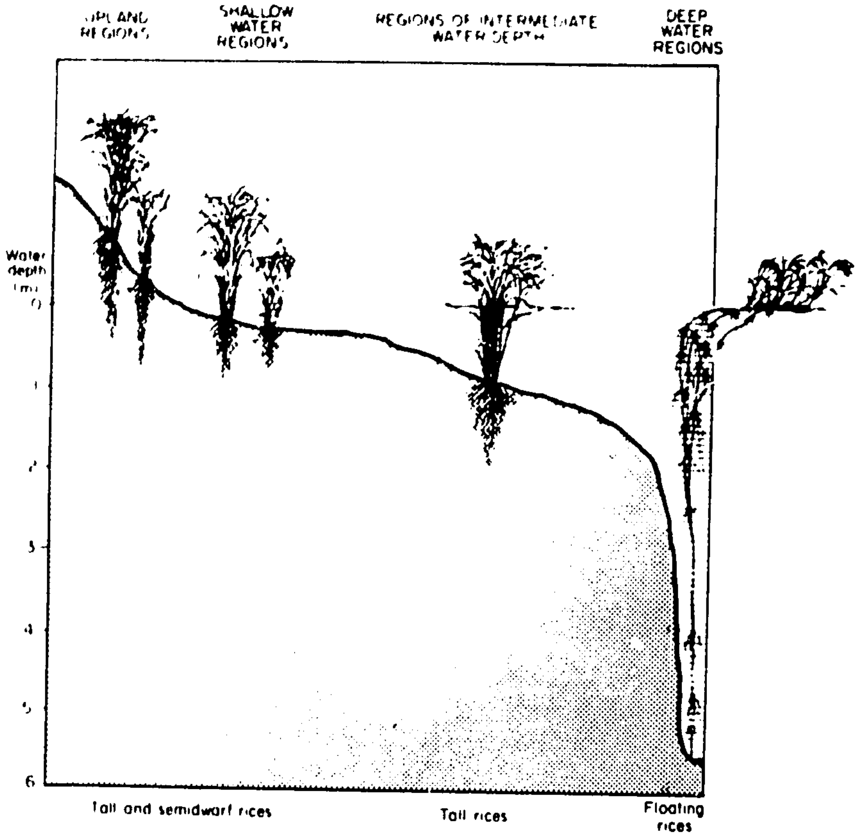

Fig. 2. The world's rice land classified by water regimes and predominant rice types. (20)

on their farms as can be obtained by the researchers. Such trials are conducted in the Philippines and through a cooperating network of scientists in other Asian nations. These studies should establish more clearly in each ecological region under study the major problem areas which sould continue to receive priority attention by scientists both at IRRI and within national programs (Fig. 3).

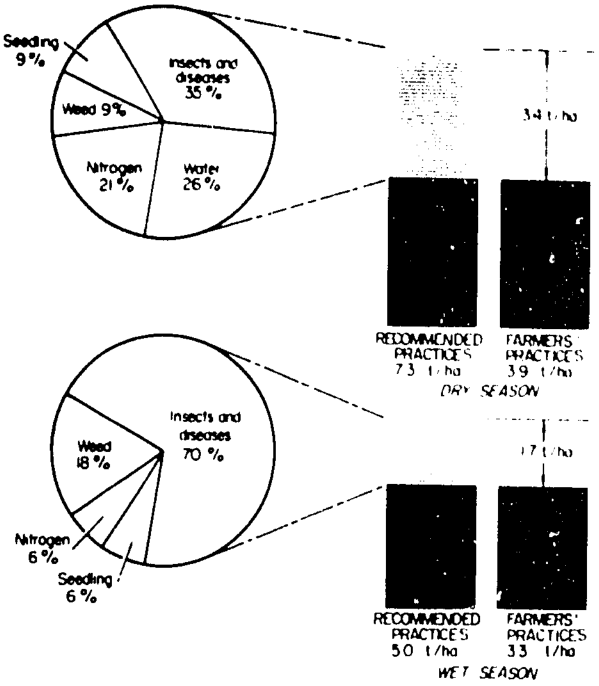

Fig. 3. Differences between yields when farmers follow their usual practices and when they follow IRRI recommendations. Factors which constrain yields in farmers' fields are shown in circles. Data taken on a total of 15 farms over three crop seasons, 1972-73, Laguna province, Philippines.(12)

MAJOR CURRENT RESEARCH AREAS

GENETIC EVALUATION AND UTILIZATION (GEU)

IRRI scientists are focusing on research to increase rice production in upland, non-bunded areas, deep water areas, problem soil areas, cold water areas and in areas of high disease and insect pressures. Through an enlarged

GEU program, (Fig. 4), they are systematically screening the more than 35,000 accessions in the IRRI germ plasm bank for genetic resistance to each of these major yield constraints. Promising accessions which pass the screening tests are included as parents in the 3000 crosses made each year. Thousands of selections from progeny of these crosses will be further tested and screened to provide lines for inclusion in observational nurseries and finally in replicated yield trials of each of the cooperating national research programs.

The incorporation of insect and disease resistance into new high yielding lines has received high priority during the past few years. A measure of the success of this effort is shown by comparing the pest resistance of the 185 entries included in the annual replicated yield trials. As late as 1969, only 10% of these lines had resistance to more than one of the major disease and insect pests. By 1973, 70% of the entries had at least moderate resistance to five or more of these pests(12). Such progress has accelerated the release of

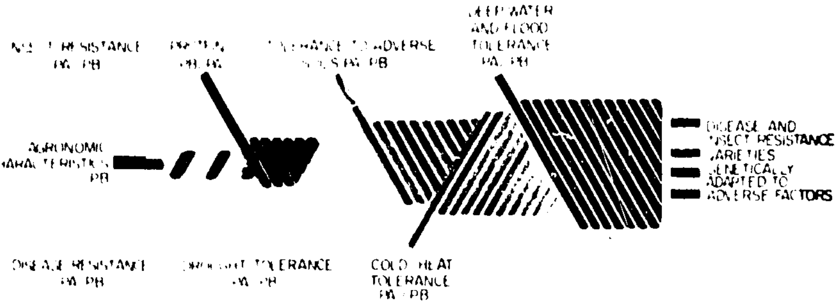

Fig. 4. Plant breeders (PB) and problem area scientists (PA) are working together as interdisciplinary teams to develop disease- and insect- resistant varieties that are genetically adapted to withstand a range of adverse factors (12).

new varieties -- six were released during the past 18 months. All of these have reasonably good field resistance to seven of the major disease and insect pests. Also, IRRI lines with multiple pest resistance are furnished to cooperators in national programs; more than 11,000 such seed samples were dispatched during 1974 (7).

Research in deep water rice is being carried out in cooperation with the Government of Thailand where a promising national program is already under way. This research is expected to provide both improved tall, deep water rices and shorter statured rices which are flood tolerant. Some promising lines have already been identified from this program.

Drought resistance is also being incorporated into new IRRI lines. This characteristic is essential for non-bunded upland rice and is needed in lowland areas where the rainfall is variable and uncertain. Thousands of germ plasm bank accessions and breeding lines are being screened for drought resistance and for their capacity to recover from drought. The best varieties and lines will be tested in the Philippines and cooperating countries of Asia, Africa, and Latin America.

Rice varieties with marked tolerance to each of the major adverse soil conditions have been identified. These are being crossed with high-yielding lines known to have resistance to 6 or more of the major insect and disease pests. Similar success has been achieved with cold tolerant lines. Within the next few years, high yielding rices with tolerance or resistance to each of the major yield constraints should be available.

Research is under way to improve the protein content of rice, a justifiable objective in view of the fact that in some areas as much as 80% of the protein for human consumption comes from rice. Improved lines with protein contents 1/5 higher than those of traditional varieties have been developed and are being field tested (13).

To assure adequate field testing of promising lines from IRRI and from cooperating countries, an enlarged and systematized international testing program was organized in 1975. Selected scientists from cooperating countries help develop and implement plans for several hundred field trials to compare the performance of the best lines available. These trials are strategically located in cooperating countries to assure that the selected lines are tested in the different agroclimatic zones in which rice is grown. Some of the trials deal only with a given desired characteristic of rice, such as resistance to tungro or to the brown planthopper. Yield

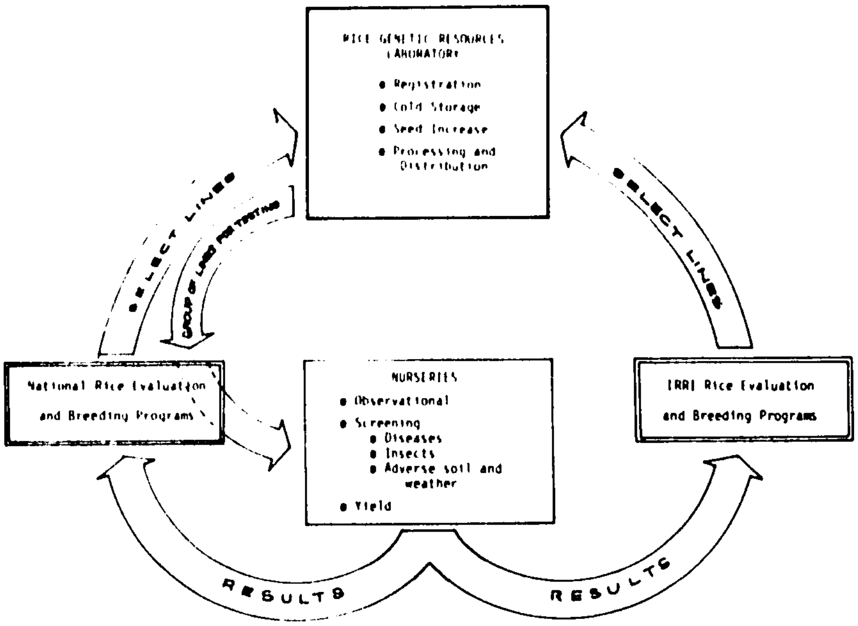

Fig. 5. Flow of genetic materials through the International Rice Testing Program which IRRI scientists coordinate.

and a number of other performance characteristics of advanced lines are tested in other trials. This international testing program will greatly accelerate the evaluation and utilization of the most promising lines coming from the GEU programs of IRRI and of national agricultural research agencies (Fig. 5).

IMPROVING FERTILIZER AND PESTICIDE EFFICIENCIES

Inflation has greatly increased the prices for fertilizer and pesticides, thereby reducing the probability of use of adequate amounts of these important chemicals, especially by the smaller and lower-income farmers. If the efficiency of these chemicals can be improved, the quantities needed can be reduced concomitantly with a reduction in the financial risks of farmers who use them. IRRI scientists have demonstrated greatly increased efficiency of these chemicals, when they applied in the root zone of the rice plant. (Table V). Systemic

TABLE V. Effect on rice yield by applying nitrogen concentrated in mudballs to the root zone with nitrogen applied by the topdressing method used by farmers. IRRI, 1974 dry season (average 2 varieties)

Fertilizer rate	Yield when N applied as		Efficiency of N	
	Mudball	Top-dressing	Mudball	Top-dressing
kg N/hectare	tons/hectare		kg rice/kg N	
60	8.0	5.8	53	23
100	8.4	6.6	38	31

Source: Reference 7

insecticides so applied are four-fold more efficient than surface applications to the paddy field. Similarly, urea nitrogen fertilizer is twice as effective when concentrated in the root zone rather than broadcast on the surface in the traditional manner. Combinations of fertilizer and pesticide placed in the root zone are quite satisfactory. A prototype of a small manually operated fertilizer-pesticide placement machine has been developed at IRRI and is being tested (7). The technology associated with the placement of both pesticides and fertilizers is important because it offers the possibility of markedly decreasing the quantities of these chemicals needed.

IRRIGATION WATER MANAGEMENT

IRRI's concern for the small farmer is exemplified by efforts to improve the on-farm delivery of irrigation water. Unfortunately, most large irrigation projects in rice growing countries of the tropics provide abysmally inadequate means of delivering water to the farm at the time the farmer wants it and in the quantities required for good crop yields. Furthermore, the farmers have no organized means of participating in decisions on the timing or methods of delivery of irrigation water.

IRRI scientists are working with national and regional irrigation authorities, and with cooperating farmers, to evaluate thoroughly the biological, economic and social implications of the current systems of on-farm delivery of irrigation water (7). Alternative improvements in these systems have been planned and initiated, and are now being evaluated in terms of biological and economic returns and of sociological benefits. These are in turn compared with the costs of alternative means of water delivery.

BIOLOGICAL FIXATION OF NITROGEN

High costs of chemical fertilizer have dictated a focus on biological fixation of molecular nitrogen in rice paddies. Nitrogen fixation by blue green algae had long been known to support long term yields of rice. Studies are underway to ascertain genetic differences among different strains of algae in their nitrogen fixing capacity. Also, IRRI microbiologists have discovered a high rate of fixation of elemental nitrogen in the root zone of paddy rice plants. Experiments suggest a fixation under certain conditions as high as 60 kg per hectare per cropping season (12). The fixation process is being examined to determine the mechanism and the factors which affect it to exploit the practical implications of this free fixation of atmospheric nitrogen.

CONTROLLED ENVIRONMENT STUDIES

IRRI scientists are able to determine the effects of climatic variables such as light, day length, humidity, and temperature on the growth and development of both the rice plant, and of insects and diseases which attack rice. This is made possible by a newly inaugurated phytotron, a gift of the Australian Government (12). This facility will be used to simulate climatic conditions not found in the Philippines, but significant in other rice-growing areas. This bioclimatic laboratory is also useful for studies of the life history and epidemiology of rice diseases and insect pests.

RICE CROPPING SYSTEMS

Approximately 25 percent of IRRI's research efforts is devoted to the improvement of rice cropping systems, a research and training program which has been increased markedly during the past two years. Primary attention is devoted to the development of systems to maximize the utilization of available soil, water, and climate resources. Simple cropping systems are emphasized which permit two crops to be grown annually where in the past only one has been grown. The new short season high-yielding rices and a direct-seeding technique will be used to advantage to permit the first crop to be grown and harvested in time for a second crop of rice or an upland crop to follow the first rice crop (Fig. 6). There are millions of hectares in the tropics where such a cropping system may have merit and be potentially feasible. This possibility must be thoroughly explored.

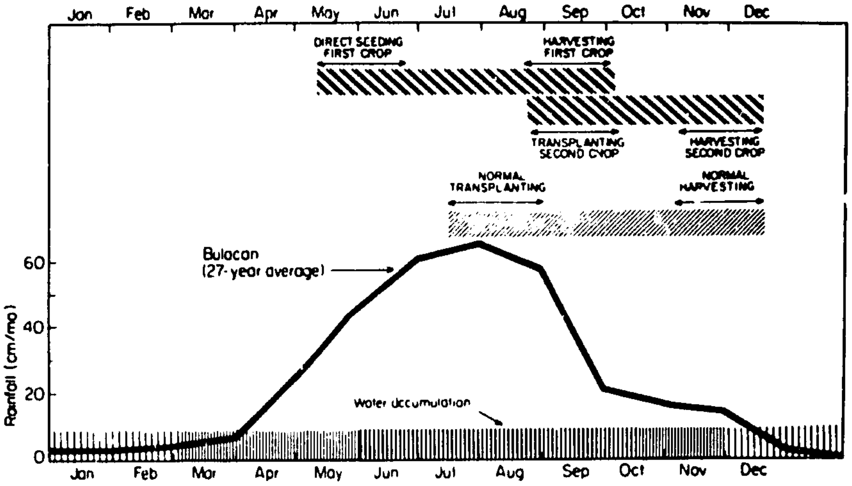

Fig. 6. Rainfall pattern in Central Luzon Philippines, normal single crop pattern (lower bar) and double cropping pattern (upper two bars) made possible by direct seeding and short seasoned.

Other more complex rice cropping systems will be developed and tested in different agro-climatic regions. Systems currently used successfully by farmers will be studied to ascertain their effects on the control of weeds and other pests. Opportunities for introducing crops and technologies aimed at increasing the effective use of water and soil resources will be investigated. The economic and social implications of each of the biological systems used will be ascertained. Eventually, models will be developed to predict the suitability of different cropping systems in given ecological situations and in different social and economic environments. Close intergration between the economist and biologists will be required for these efforts.

To test selected cropping systems in different agro-climatic environments, scientists from cooperating countries have been invited to participate in a region-wide research network. They serve as co-planners and co-investigators in this network, each carrying out one or more experiments of common interest. In this way, research results will be obtained under a variety of soil and climatic conditions, and these results will be quickly communicated among scientists participating in the network.

SUPPORT STUDIES

A number of studies are underway to provide a better understanding of the processes and phenomena related to the production of rice (13). Genetic studies are performed to determine the gene sources of characters such as dwarfism, resistance to different diseases and insect pests, and level of proteins in the seed. Physiological studies include measurements of photosynthetic rates as influenced by solar radiation, moisture stress and variety. Differences among varieties in tolerance to low and high temperatures at different growth stages have been determined in the phytotron. These observations help the plant breeders select parents for the GEU program.

The major components of rice yields have been determined in both field and greenhouse studies. Grain number per unit area is the primary yield component, although filled grain percentage and average grain weight are significant factors. Together these three components account for more than 80% of the yield variability (Table VI).

TABLE VI. Contribution of three yield components to the grain yield of rice.

Variables	Contribution to Total Variation in Yield %
Grain No./meter^2 (N)	60.2
Filled grain percentage (F)	21.2
N and F	75.7
N and average Grain Weight (W)	78.5
N and F and W	81.4

Source: Reference 13

Grain quality studies have concentrated on the development of chemical and physical methods measuring differences in human preferences for different rices (13). Amylose content, supplemented with gelatinization temperature and the consistency of a gel formed in a weak potassium hydroxide solution, have proved most satisfactory. Starch synthesis in developing rice grains is also being studied. Nutritional studies in preschool children and with Streptococcus zymogenes have demonstrated the superiority of high protein rices over those with low protein.

Biochemical studies on seed and plant metabolism are providing a better understanding of factors affecting seed dormancy, germination and the filling of rice grains. These studies provide information on enzymic controls of starch formation and of germination (13).

Studies of the chemical kinetics of flooded rice soils have helped explain field responses of rice (14). The availability of essential elements other than zinc is increased by flooding, suggesting the desirability of flooding a few weeks before transplanting on zinc deficient soils. Allowing the soil to dry out after applying nitrogen fertilizers and then reflooding results in nitrogen losses by denitrification. The kinetics of this process under different soil and environmental conditions are being studied.

INTERNATIONAL COOPERATION

COOPERATION WITH DEVELOPING COUNTRIES

IRRI scientists cooperate with their counterparts in national programs in developing countries in three ways. First, they collaborate in implementing rice research projects which are of considerable international importance but which cannot be done in the Philippines. Research on deep water rice in Thailand and Bangladesh, and on the gall midge insect in India are examples. Neither of these problems exists in the Philippines, and yet IRRI scientists in collaboration with their national counterparts can help solve them.

Secondly, networks of cooperating scientists were established to implement projects which require experimentation and testing in a number of agro-climatic zones. Such networks are concerned with cropping systems, agro-economic constraints, and GEU international testing, and they will provide valuable research information. Additionally, these networks develop mechanisms for international collaboration and communication.

The third means of cooperation with national research agencies is through joint action to develop the research capability of the national research agencies. A cooperative agreement between IRRI and the national research organization establishes the bases for the cooperation and identifies the extent of assistance IRRI is to provide. Normally this assistance requires the inputs of one or more IRRI scientists to be stationed in the cooperating country. Also included are training opportunities at IRRI for a number of young scientists from the national research agency. The projects are commonly funded by outside donors.

COOPERATION WITH THE MORE DEVELOPED COUNTRIES

Collaboration with scientists in the more economically developed countries has been useful to IRRI in the past and will likely be even more useful in the future. With a cadre of only 35 senior scientists, IRRI cannot possibly provide the research depth needed to attack the many rice production research problems that exist. Instead, IRRI teams up with scientists or with laboratories in Europe, the United States, Japan or Australia to do so. For example, we are collaborating with British scientists to determine the biochemical bases for host resistance to certain insects, and to test the field applicability of some insect attractants. British and American scientists are cooperating with IRRI to ascertain further the significance of rhizosphere fixation of nitrogen, and to determine the mechanism of this process and factors affecting it. A Canadian biochemist assists the Institute in research to determine the phytotoxic effects of certain edible legumes on subsequent crops.

Discussions are under way with Australian and British scientists covering research on drought tolerance and on methods of measuring it. Agroclimatological studies are being undertaken in cooperation with Dutch and American scientists. Indian nutritionists work with IRRI's food chemists to learn about the nutritional quality of rice.

FUTURE COLLABORATION

There are a number of other research areas which must receive the attention of basically oriented scientists in the more developed countries. Fundamental physiological processes including photosynthesis and respiration must be better understood. This knowledge may help the applied researcher raise the maximum efficiency of net solar radiation utilization from the current 5 to 10 percent to at least double these figures. Likewise, an understanding of the mechanism or mechanisms for biological fixation of nitrogen could help free cereal grain producers from dependence on chemically fixed nitrogen.

Basic research is essential to speed up the tedious and time consuming plant breeding process and to improve the combining ability of parents, both of those of the same species and those involved in wide crosses from different but closely related species. Cell culturing techniques which by-pass the normal sexual reproduction methods of plant breeding must be refined. Practical techniques to increase the success of wide crosses and to accelerate the process of breeding and selection could expedite the GEU research program.

The process of protein synthesis and factors affecting it should receive attention, especially in relation to genetic differences among rices. Likewise, we must gain a better understanding of the biochemistry of starch formulation, the nature of amylose in the rice plant and its relation to eating quality.

The ecological factors affecting pest control must receive more attention, especially in relation to cropping patterns in which rice is grown. Likewise, reasons for phytotoxicity noted in certain crop combinations and sequences must be ascertained.

There is one other type of research needed to complement, supplement and in some cases guide the research done by the biologist. This is socio-economic research that relates to the overall production, processing, marketing and consumption system. Starting with the rain or snow that falls on the land and ending with food in the bellies of the consumer, this overall system must be viewed in the light of people, and of the constraints and accelerants they present. The likes and dislikes of farmers may determine their willingness to grow a short statured variety or to use a pre-emergence herbicide. Consumer preference will determine, more than nutritional quality, the demand for new varieties or new crops. And public policies, particularly those relating to prices, will determine whether the farmer can afford to adapt a new practice or whether he will take the risk to do so. While such research is not the subject of this Conference, it must be done simultaneously with the biological research if we are to maximize the results of the latter.

International research centers such as IRRI depend upon collaboration with scientists in the more developed world to implement much of its supporting biological and socio-economic research. University professors on sabbatic leave are being invited to do research at these centers and joint projects are being undertaken. Such collaboration will likely increase in the future.

SUMMARY

Changes in the world's social and economic climate over the past decade have had and continue to have profound effects on science and scientists. One of the main effects is to move science towards a greater problem solving orientation. This reorientation is welcomed by those concerned with world food production, which together with population control, is mankind's greatest challenge to survival.

Rice is a pivotal crop in man's struggle to feed himself since 90% of the world's very low income people utilize this crop for at least one fourth of their diet. Research is vital to increased rice production.

The International Rice Research Institute, established in 1960, has helped revolutionize rice production technology. Varieties with yield potentials double or even triple those of traditional tropical rices have been developed and are being used widely throughout the world. Cultural technologies to utilize fully the potential of these rices have also been developed.

The impressive achievements of the first decade or so of the Institute helped to increase yields of rice grown under controlled irrigated conditions where adequate chemical inputs were available. Efforts are now concentrated on the development of rices and technologies suitable to areas with less favorable soil, water and climatic conditions and with less exacting chemical requirements to control pests.

International linkage with the developing nations will facilitate the prompt utilization of the research findings by both scientists and farmers in cooperating rice-growing nations. Similar linkages with scientists in the more developed world will permit greater in-depth research pertaining to the many constraints to rice production.

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AGRICULTURAL PRODUCTIVITY
AND
WORLD NUTRITION

Jean Mayer

INTRODUCTION: POSSIBLE DEFINITIONS OF PRODUCTIVITY

The word Productivity cannot be entirely taken for granted. It is true that, in a vague way, everyone can agree that in order to feed a nation -or the world-production needs to increase. Inasmuch as the arable land area-or at least that fraction which can be cultivated most easily -is limited, this in turn means that "productivity" in general must increase. But any attempt to define the word does require more specific thinking. My predecessor on this platform, Dr. Sterling Wortman (1), initiated this thinking process yesterday when he contrasted productivity per farmer, which is very high in the U.S., with productivity per acre, which is surpassed by many areas with more labor-intensive agriculture. In fact, there are many other ways to look at productivity. That which seems to me in practical political terms to be most important to the U.S. farmer (though rarely used in such meetings as this) is income per farmer still farming, whether he is growing grain, soybeans, tobacco, cotton, cattle, poultry or fruit. No consideration is given as to whether he is contributing to the sound nutrition of the American people, correcting the deficits in agricultural production of other industrial nations or insuring the possibility of relief for the poor countries. Nor is any consideration given to the fact that the type of capital intensive, low labor requiring agriculture which our land grant colleges have helped to develop and extend, by driving unnecessary labor and less affluent farmers off the land, is saddling our cities with the insupportable burden of receiving a stream of poor people faster than an increasingly automated industry can absorb them. In a production-, non-service oriented society, this means that an increasing burden of unemployment and welfare is inevitable, a conclusion, the inevitability of which the title of a recent book "Studies of the Great Rural Tap Roots of Urban Poverty in the United States" (2) makes apparent. We are forced to conclude, as we look at the cost of crowding, unemployment, welfare, pollution and crime in our cities, that maximum productivity *per farmer* does not necessarily mean maximum productivity *for the country* as a whole.

Finally, in modern agriculture high productivity in certain commodities (e.g., grain, soybeans, meat) which can be obtained with low labor utilization, is preferred to the higher labor requiring fruits and vegetables; in addition, in the other components of agribusiness (manufacture, distribution, food services), the profits are increasingly in selling "convenience" rather than foodstuffs alone. This leads to steadily increasing processing and (nutritionally speaking) overprocessing of our food supply which means that we may have more and more food available without necessarily getting more nutrition. Our pandemic of cardiovascular disease is directly attributable in part to excessively high intake of salt, saturated fats and cholesterol. Our miserable dental health is directly related in part to excessively high intake of sugar. Our mounting toll of cancer of the colon may well be directly attributable to a diet from which fiber is absent as a result of our milling practices. The low intake of vegetables and the appearance of nutritional deficiencies, such as zinc, in middle class children fed a diet of overprocessed foods and soft drinks also show that higher productivity in agriculture and the food industry is not tantamount to improved nutritional health. In some ways (unless we curb advertising or counterbalance it with more vigorous nutrition education) it may lead to less satisfactory nutrition. Surely, in the last analysis, a definition of world productivity which entails the betterment of nutrition for all is one we can all agree upon.

I. IMPORTANCE OF PRODUCTIVITY

Even when we have considered the reservations above, it is, nevertheless, true that without a increase in productivity - per acre and per farm worker - the world is unlikely to be well fed or indeed to be fed at all. The population of the world is increasing too rapidly, particularly in poor countries; and changes in consumption patterns in rich countries (whether or not these result in improved health in these countries), are putting increased pressure on the available world food supply.

The population of the world is increasing more rapidly than ever. It took almost all of the history of Man (5 million years or more) to reach, in 1850 A.D., one billion people. It only took 70 years to reach, in 1920, a count of 2 billion, 40 years to reach, in 1960, 3 billion. And it has only taken 15 years to reach, this year, 4 billion people. From now on, even with birth rates falling in major areas of the world, we are going to see an even more rapidly growing world population, reaching perhaps as much as 8 billion in the year 2,000 A.D. or shortly afterwards, with the bulk of the increase taking place in the poor countries of Asia, Latin America and Africa. This means that we have to find, in the next 25 years, food for as many people as we have been able to develop in the past history of Man. Clearly, productivity has to be increased. Furthermore, we have to improve, rather than just maintaining present levels of consumption. It seems to be a universal observation that when the wealth of nations increases (whether in "free enterprise" or in "socialist" countries), there develops an increased appetite for animal products which, in turn, considerably increases the demand for cereals, soybeans, fish meal and other "primary" agricultural commodities. The efficiency of conversion is poor: of the order of 25 percent (in calories of animal products per calorie of feed) for feed based milk and eggs, 16-18 percent for poultry, 12 percent for pork and appreciably less for the stage of beef production which takes place in the feed lot. (Range growth is "free" in the sense that it is non-competitive with man, except inasmuch as pastures can be cultivated directly for human food). Thus, in the United States and Canada, over 900 kilograms of cereals of the 1000 available per person or 90 percent are used for animal production, with the percentages only slightly lower for such countries as France or Germany, or indeed, the Soviet Union. This compares with the situation, for example, in the People's Republic of China, where it appears that 160 kilograms of cereals, out of 205 available per person, are used directly as bread, rice or other grain based food. This trend towards higher conversion of grain into animal products is likely to be extended to new countries, such as Brazil, Eastern Europe or the Koreas as these improve their economic status, thus putting additional pressure on food supply. Incidentally, this massive increase in animal product intake is not necessarily "good" for us: the mounting toll of cardiovascular diseases, which maintained the U.S. adult life expectancy at a near constant level for the past 25 years in spite of a 10-fold increase in medical expenditures, is related in part to an excessive intake of such animal products as beef, pork and eggs.

At present, the estimate is that about 75 percent of the increased world demand is directly attributable to population growth, at least 25 percent to changes in food habits. There is no reason to suppose that these factors will not keep on operating for some time to come.

II. PRODUCTIVITY NOT THE ONLY CONSIDERATION

Even the most enthusiastic "producer" is likely to agree nowadays (however reluctantly) that some attention has to be paid to considerations other than production alone in any plans and projections for economic development.

a) INTERACTION WITH ENVIRONMENT. Whether or not as many producers claim, environment enthusiasts exaggerate environmental concerns, the fact is that certain aspects of economic growth have already become counterproductive. The fisheries situation is a case in point. After increasing from 1945 to 1972 by a compounded 10 percent per year, the world sea catch has faltered in the past 3 years and may well have, in most oceans, reached the "limits of growth". It seems generally agreed that of 22 major varieties of table fish now produced, all 22 are overfished, with the South Indian Ocean the only area left with some growth left for fisheries. The overfishing is aggravated by pollution, resulting from contamination with agricultural pesticides and especially from spills of hydrocarbons, the latter the consequence of the world's greater demand for and enormously increased traffic in energy. Yet it appears from the tone of the continuing deliberations of the "Law of the Sea" Conference that nations are unwilling to come to terms with the limitations resulting from the clash between increased demands and limited resources. The traditional fishing nations want to do no less fishing, and new fishing nations want to do more. The solution may lie in replacing the "hunting" stage of marine food production by an agricultural stage, aquaculture and mariculture.

On land, trade offs may have to be considered. In a first stage of the use of agricultural chemicals, modern methods actually improve conservation, by permitting more food to be grown on a smaller surface of the land. The stone walls found in many of the woods in New England are mute witnesses to the fact that in the nineteenth century, even with a much sparser population to feed, it took the whole landscape to grow the food required. The opening of the West, and mostly the improvement in technology (the elimination of the land needed to feed working horses, the increase in yield of areas under cultivation) has permitted the return of many areas of New England to natural pastures and forest. As the use of agricultural chemicals continues to grow, however, environmental drawbacks begin to appear. How the various requirements for production, conservation, recreation, and health are balanced is a matter for political choice, which should result in a number of land use and regulatory measures consistent with a national (and perhaps some day, a world wide) policy.

b) IMPORTANCE OF EFFICIENT AND EQUITABLE DISTRIBUTION.

Production alone cannot feed the world. The food produced must be preserved and it must be available to all. Certainly, nutritionists are very conscious of the fact that since the "World Food Crisis" has started impinging on the consciousness of both governments and public opinion, the glamor in solution seeking has been in the search for increased production, with inadequate attention being paid to preservation and distribution.

Food is naturally perishable. Unless it is properly preserved, a very large fraction of the new crops may be wasted. In the rich countries, which tend to have temperate climates with cold winters and efficient canning and refrigerating facilities, the loss is minimized (though in a country such as ours, other losses appear such as waste at the consumption level). As an example, military refectories and the school lunch program operate with as much as 40 percent of the food served appearing in garbage bins; the waste in restaurants is almost as bad). In poor countries, often hot and humid, as much as one third of the food may be lost in storage. Yet attention given to post-harvest technology in poor countries is inadequate. I have been told by an eminent food technologist, a member of the FAO Staff, that less than 1 percent of the budget of that international organization is devoted to post-harvest technology.

Equitable distribution is essential. If the food available to a country essentially goes to the rich, or to better off farmers and the large cities, with little left for partly employed rural populations and the poor in the cities, production statistics may become highly unreliable as guides to the state of nutrition of the population. Indeed, there have been a number of historical examples of situations where overall agricultural production went up at the same time as malnutrition spread. The type of agricultural development is major factor there. If the growth of production is obtained on a capital intensive, highly mechanized basis, rural employment may decrease as food production grows. In the absence of any alternative source of employment, whether in the countryside or the cities, the rural poor may starve in the village, or if they "leave the land" and flock to the cities, may suffer from malnutrition in the spreading shanty towns which, increasingly, surround the coastal cities in the developing continents. Certainly, a type of agricultural development which combines certain aspects of new technologies (better varieties, use of agricultural chemicals and irrigation) with a delay in mechanization and continued use of large amounts of labor is in general conducive to better nutrition. Thus, in spite of lower per capita Gross National Product and, in the case of the People's Republic of China, a lower rate of economic growth, both Taiwan and the People's Republic seem to have done much better, in terms of eliminating malnutrition, than Brazil, Colombia or even Mexicc

c) IMPORTANCE OF INTERNATIONAL COOPERATION.

It should be unnecessary to point out that political considerations and, in particular, the lack of international cooperation, are, at present, at least as responsible for the continued presence of malnutrition in many areas, as lack of productivity. Consider a few examples of such failures.

1. The world has, as yet, no policy on food reserves. Among difficulties still to be resolved are the fears on the part of U.S. and Canadian farmers that "reserves" will turn into "surpluses" and will depress food prices; and the unwillingness of certain countries, notable the USSR and the People's Republic of China to cooperate fully in the census of national grain reserves or in yearly crop forecasts. These are all the more necessary in that these two countries, and the USSR in particular, are the most variable importers from year to year.
2. The world has put insufficient pressure on potential producers of fertilizers, such as the countries of the Middle East and Nigeria, to use their (presently wasted) flare gas and their (largely unused) accumlating wealth to produce the massive amounts of fertilizers required to modernize production in poor agricultural countries. Nor have adequate measures been taken to prevent exploitive profiteering by fertilizer producers and traders in periods of world shortage, thus aggravating the already disastrous effects of the excessively rapid rise in price of oil and other necessary basic materials.
3. The world has been very slow in setting up a famine early-warning system and in agreeing on famine prevention, relief and rehabilitation methods.

III. QUALITATIVE ASPECTS OF PRODUCTION.

a) ECONOMISTS AND FOOD PLANNING. Man does not live on calories, or even calories and protein alone. The state of nutrition of the world is highly dependent on the availability of a large number of nutrients, many of which tend to be forgotten in international discussions. As an example, the Rome Conference (3) preliminary documents and final reports tacked on considerations of Nutrition as an afterthought. A non-nutritionist attending the Conference could well have concluded that the normal diet of man is made up of the three main cereals, soybeans, sugar and beef - with no consideration being given to "secondary" cereals, vegetables, fruits, legumes other than soy, fish, milk and eggs for home consumption, and small animals. Yet all of these are essential to good family nutrition. This is largely the result of economists' biases in planning.

Economists have a tendency to be exclusively interested in two types of "food" commodities: those that are easily counted; and those that move in channels of national and, even more, international trade. Bags of cereals and soybeans, and heads of cattle fall in the first category. Cereals, soy, sugar and meat shipment fall into the second. Fruits and vegetables are difficult to count. In general, they travel only locally. They are largely consumed by the producers. Legumes, again, are largely consumed at home. When fresh, they may travel somewhat farther than fresh fruits and other vegetables, but the market is again regional. The few rabbits, the hens for family egg production, the milk produced by the family cow, the fish caught by some member of the family (including the children) again have no "economic" importance. They are rarely included in any "economic" survey. Yet, their impact cannot be underestimated. If "increased production" through elimination of small farms, specialization of labor or monoculture practices results, as it often does, in a decrease of traditional methods of production of such "protective" foods, the deterioration in the state of nutrition may be precipitous, even as "production", "income" or "per capita gross national product" are increasing. This is particularly true if the increase in wealth is accompanied, as it so often is, by the buying of refined cereals and sugar to replace "indigenous" foodstuffs. The replacement of subsistence agriculture by a cash-based agriculture, in a cultural environment in which there is no traditional spending of much (indeed, of any) earned money on food can be a nutritional castastrophe unless extremely vigorous educational efforts are carried out simultaneously.

b) MICROECONOMICS OF NUTRITION.

It should also be noted that much of the malnutrition present in the world occurs in families in which there is enough food available but where for one reason or another it does not go to those members who most need it. Two well studied examples are the spread of Kwashiorkor following the disastrous spread of cassava in Africa and the consequent feeding of small children on a diet high in calories but excessively low in protein; and the "commerciogenic" malnutrition resulting from the abandonment of breast feeding in many areas of the developing world and the replacement of breast milk by expensive substitutes, usually both inadequate in amounts and prepared with water of dubious sanitary quality (4).

c) NUTRITION MEASURES NOT DEPENDENT ON FOOD PRODUCTION

Finally, it is worth noting that some of the most urgent measures which can be taken to eliminate malnutrition are not dependent on food production but on social organization. Vitamin A deficiency blindness, which affects tens of thousands of children annually, can be eliminated by massive dosages of Vitamin A twice a year. Goiter, which affects millions of persons in the world, can be prevented by iodine enrichment of salt or by iodine preparation injections.

IV. CONCLUSION

We can only conclude that a general reordering of the priorities of the world is essential.

a) We need to give a much greater emphasis to agriculture than it has been accorded in the past. Too often, agriculture has been "deglamorized" with bright youngsters in rural environments being made to feel that any profession - physician, lawer, civil servant, businessman - is more glamorous than agriculture. Even within universities, the School of Agriculture has been generally intellectually isolated (5). It may be added that the problems of food preservation have been given an even lower priority than those of production even though the quickest way to make more food available is to preserve that already produced. Poor agricultural countries, in particular, should concentrate more on agricultural development at the expense of prestige projects of lesser urgency.

b) We must make all countries more conscious of the need to balance resources and population, not through the application of the morally repugnant "lifeboat ethics" or "triage" approach but through balanced economic, social and intellectual development. An encouraging fact is that in those areas where agriculture has progressed rapidly in the past twenty years (e.g. People's Republic of China, Taiwan, North and South Korea, the Punjab, Tunisia), birth rates have gone down.

c) We must, in our agricultural development plans, pay attention not only to ecological preservation but also to the type of social policy, including employment and salary policy, which will ensure that all benefit from increased productivity and prosperity. Community organization ("building from below") is an essential component.

d) Finally, as regards food and as regards oil, we are rapidly evolving towards a more interdependent world. This should impose on all, exporting countries, "old rich" countries, "new rich" countries, buyers and aid recipients, a greater measure of responsibility than has often been apparent.

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SHOOTING
AT A
MOVING TARGET

by
Reid A. Bryson[1]

I think it stupid of the weather
to put white snow on purple heather,
dry the corn at summer's height,
freeze the crops on autumn night.

I think it awful of the monsoon
to fail at all (likewise the typhoon),
to move the desert south in Mali,
and flood upon the Isle of Bali.

But I must make it most emphatic
that the climate is not static,
that the change is here to stay
(until it goes the other way)!

Since I started listening to you people, two words have come up over and over: "optimizing" and "maximizing." You're going to optimize yields. You're going to maximize yields. You're going to do this and that and the other thing. I know what you're trying to do - to get as much food produced as you can to feed a hungry world: an admirable goal. There is, however, one point that relates directly what you plan to do to what I want to say today. You talk about optimizing, and in a sense, you're saying "let's make bumper crops the normal thing." And of course, you all recognize - as every farmer does, that to get a bumper crop you must have good weather. When you adapt a plant to get maximum yield you are, in essence, adapting it to maximum yield at the normal weather, whereupon the normal weather is optimal. Well, ladies

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[1] Introduced by E. H. Vause

and gentlemen, you're shooting at a moving target, because the climate is not fixed; it changes. It can change rapidly. It can stay changed for a long time, and so if you are doing something that requires a number of years to achieve, like adaptation to a certain climate, you want to consider the fact that perhaps by that time, the climate will have changed. We are in a time of rapid change. It is the variability of the climate that I want to discuss with you today. Let's start by taking a long perspective and look back at the past. Let's look at the last 13,000 years in Minnesota (Fig. 1). Now where do we get such a long weather record? Well, we get it by looking at plants. This record was reconstructed from pollen profiles from a few miles south of Minneapolis by a

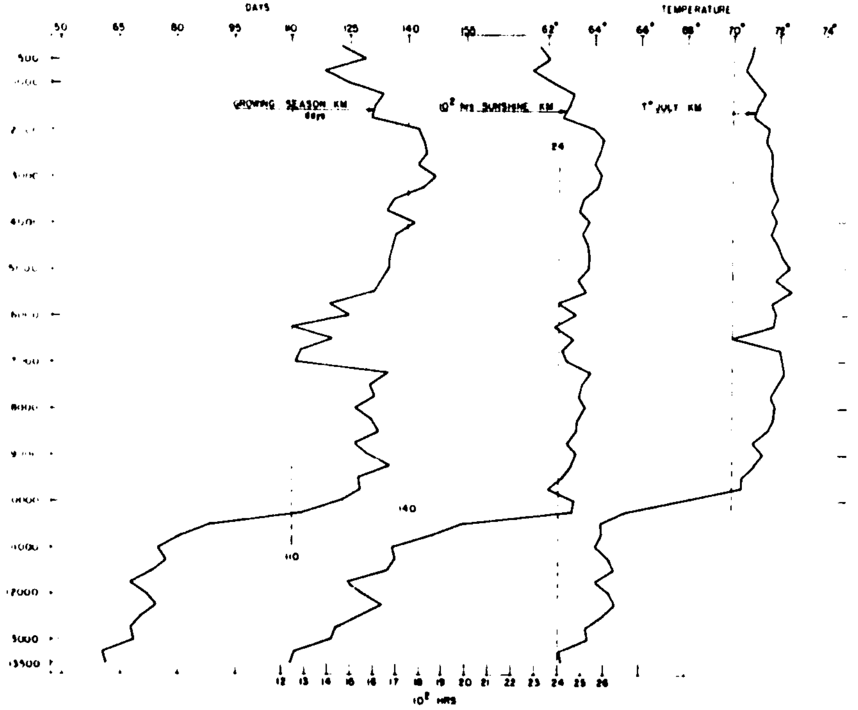

Fig. 1 - Reconstructed climatic profiles for the Kirchner Marsh Area (KM), Dakota Co., Minn. derived from pollen profiles by the transfer function technique. (1)

statistical technique we devised a few years ago (1). And so we can look at what has happened to some of the variables that are significant to plants by looking at the record that the plants themselves have left behind. You see on the right-hand side of the fiture what has happened to the mid-summer temperature over the last 13,000 years. Now notice, back about 10,800 years ago, the rather dramatic, rapid change in summer temperatures. That was the end of the ice age climate. It took another 5,000 years for the bulk of the ice to disappear, in a post-glacial climate. Since that time, in Minnesota, the July temperatures haven't changed very much, on the order of 1°F. But don't let that fool you because summers are largely solar radiation weather and the rest of the year isn't the same. You'll notice, in the middle, that the number of hours of sunlight is a little more variable (Fig. 1, center curve). You can see that during the ice age it was somewhat cloudier. It got a little sunnier in the post-glacial period. Notice that in the last 2,000 years it has been getting a little cloudier, with a little less sunlight. Now look over on the left at the number of days in the growing season: Still more variable. The growing season was short at the time of glaciation, on the order of 60 days, which is about the same as the tundra of northern Canada today. Then it increased, but you will notice that the length of the growing season, even in the post-glacial climate, can change rapidly. Look, for example, at that section about 6,000 years ago; there was a significant change that lasted a couple of thousand years. It started rapidly, it lasted 2,000 years, and ended rapidly. And the last 2,000 years have been different also.

Interestingly enough, the research that has been done by marine geologists in the last few years has shown that the last dozen or so interglacial periods, such as the one we are now in, last an average of 10,000 years plus or minus a thousand years. We have been in the present one 10,800 years!

Now, let us return to another aspect of the climate that is significant to agriculture: the moisture variables. On the right of Figure 2 is the precipitation during the growing season. In this 13,000 year record, you can see that it does change rather dramatically. Back about 6,000 years ago, Minneapolis had a "climate"

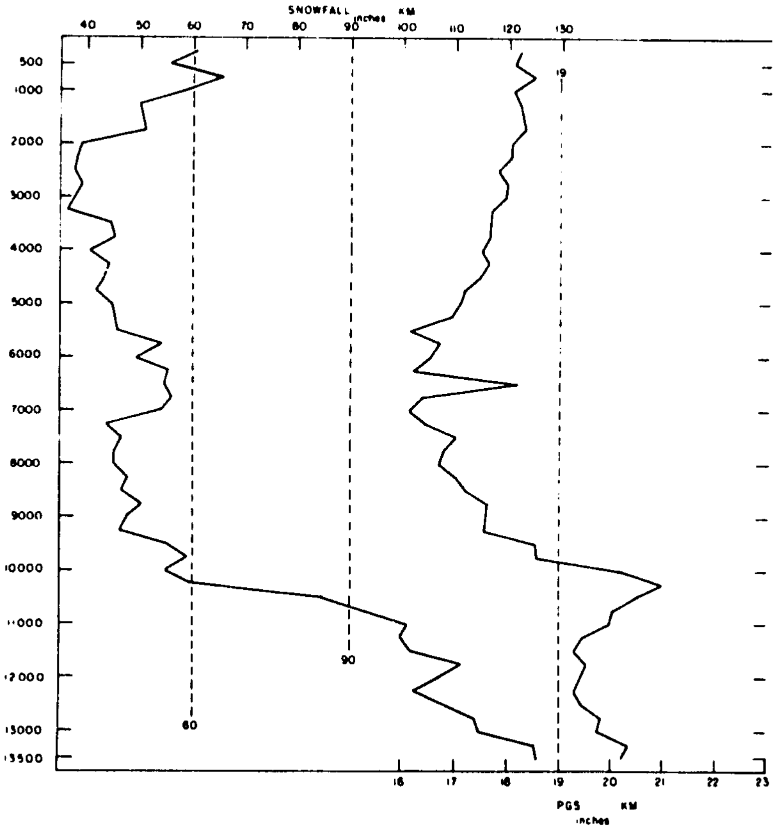

Fig. 2 - Same as Fig. 1 for precipitation during the growing season (PGS) and annual snowfall.

(if you put the temperature, the sunshine and everything together) very much like Huron, South Dakota. Now that's quite a significant difference, agriculturally. The snowfall has also varied. Back during the ice age, there were over 110 inches of snow in Minneapolis, not surprising for an ice age. But notice what's happened in the last 2,000 years: the snowfall increased from 40 inches up to 60 inches. The last 2,000 years have been different, haven't they?

Now, there are some things you need to know about how this kind of record relates to other parts of the world. We see that the summers haven't changed very much in this inter-glacial period that we're in. The winters have changed more. But the changes in temperature at these latitudes are not very important. Figure 3 is simply to give you a little lesson about climatic change (2). On the left is the variation of winter temperature, latitude by latitude, over the last century and on the right, the variation of summer temperature. You'll notice that the summers don't vary as much as the winters do. And you'll also notice that at our latitudes the temperature hardly changed at all. The changes are in the Arctic. The important thing is that the changes in the Arctic have an impact on the rest of the world, because it is the difference between the Arctic and the rest of the world that dirves the atmosphers, determines the circulation pattern, and in that way, determines where the rain falls. Figure 4 is a schematic diagram based on real data to show you a relationship that is most important (3). Circling around the northern hemisphere is a cap of westerlies which we call the circumpolar vortex. When the Arctic cools off relative to the tropics (the tropics hardly change, so that any change in the Arctic is a change in the difference of temperature between Arctic and tropics), the cap of cold air and westerlies expands. Around the outer edge of that cap of cold air, the circumpolar vortex, are some whirls which we call the subtropical anticyclones. They are the big desert makers of the world. If the circumpolar vortex expands, those deserts, produced under the sinking air of the subtropical anticyclones, shift southward and thereupon suppress the monsoons. You know, as agriculturalists, that the hungry half of

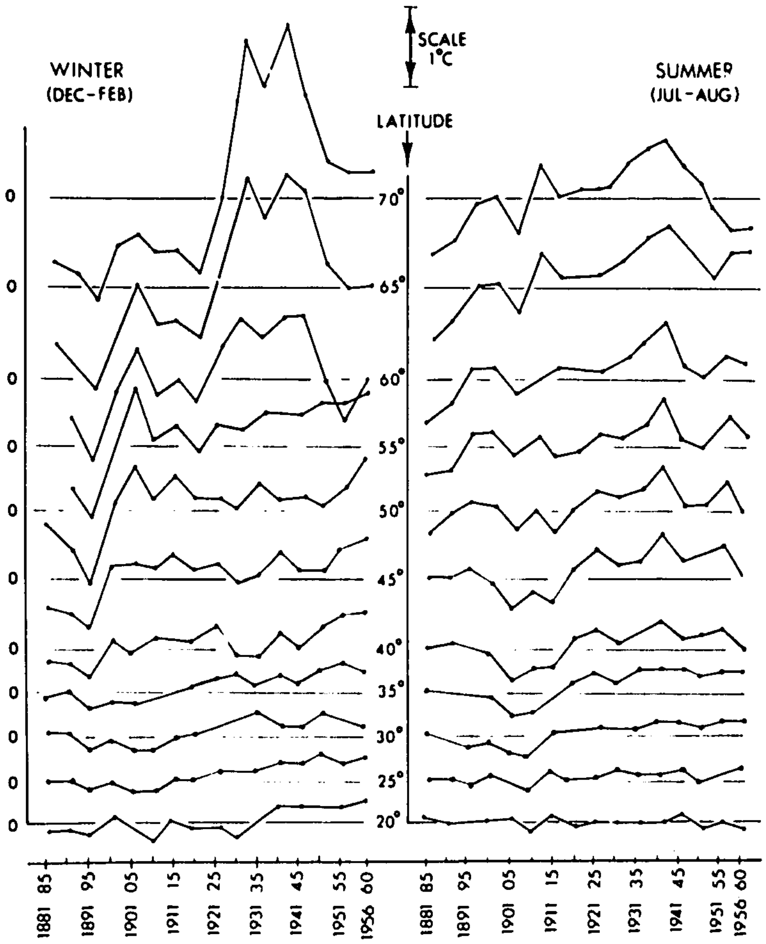

Fig. 3 - Five year mean temperature anomalies, by latitude, for the Northern Hemisphere. The climatic variation is most pronounced in winter and at high latitudes. Zero on the ordinate is the average of that latitude (0 departure). (2)

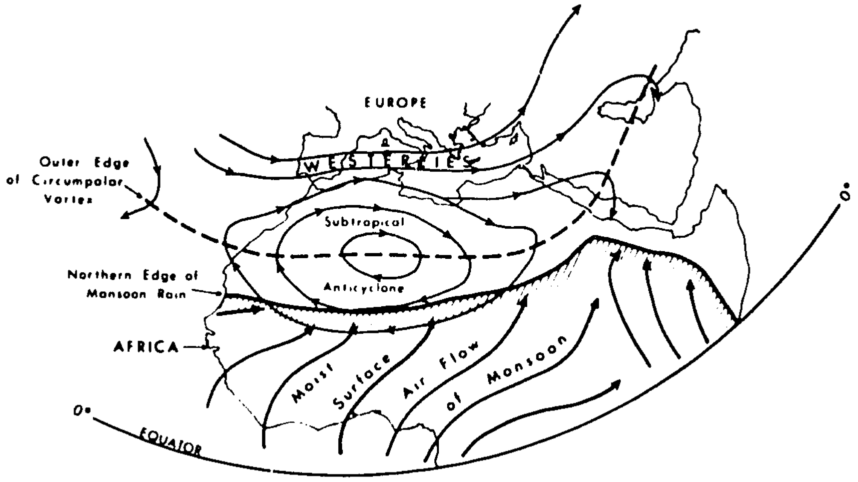

Fig. 4 - The subtropical anticyclones - clockwise eddies which produce the great subtropical deserts - are at the outer edge of the westerlies of the circumpolar vortex. The monsoon rains, between the anticyclones and the Equator, follow the anticyclones north and south with the seasons. If the anticyclones do not move as far poleward in summer as usual, the monsoon rains are also less extensive and the deserts reach closer to the Equator. The light arrows over northern Africa and Europe represent air-flow in the mid-atmosphere and the heavy arrows extending northwards from the Gulf of Guinea represent the air-flow near the ground. (3)

the world lives in the monsoon lands. So if you're talking about feeding the world, you're talking about a problem that focuses as much on the monsoon lands as it does on anything else. Producing the food somewhere else isn't going to make the difference between life and death for large numbers of people. As you know, only about 7% of world grain production moves in international commerce. It's what the subsistence farmer himself can produce that means more in terms of millions eating or not eating.

Let's look then at the question of what happens in high latitudes and the consequence in the monsoon lands of the world (4). If the Arctic expands, the monsoons should be suppressed. (You'll see later why it's important what the Arctic is doing.) Let's go to the Arctic and see if it ever expanded. The northern edge of the boreal forest in central Canada is about latitude 61 north and longitude 101 west. At its northern edge, the boreal forest is a closed canopy spruce forest, with an occasional birch, and tamarack. Fifteen km farther north the forest is gone and there is nothing but tundra. The next forest you see if you head in this direction will be in Siberia. There is a very sharp boundary at the edge of the Arctic biota, and the sharp biological boundary is also a sharp climatic boundary (Fig. 5). It is the southern boundary of arctic air in summer. North of that boundary arctic air prevails every month of the year, and only tundra plants grow. Farther south, near the northern edge of the United States we find the southern edge of Arctic air, on the average, in winter. It comes down to the southern border of the boreal forest. You may also notice in Figure 5 that the corn belt is the region occupied by southern air in the summer and by Pacifi air (dry air from the west) in the winter, but has an early spring. It is a very subtle climatic system that defines the corn belt. At the norther edge of the boreal forest, we find evidence of climatic change, of those times when the Arctic expanded. In the tundra beyond the present day forest over a band 150 miles north-south and over a 1000 miles east-west, there are numerous remnants of a paleosol; a beautifully developed forest, podzol (using the old terminology - I don't speak "Seventh Approximation"). These beautifully developed soil profiles were not formed under tundra, because if you dig in the charcoal layer that caps the paleosol, you find spruce cones, spruce needles, and tamarack.

That soil was developed under a forest. Radiocarbon dates on the charcoal layer show that this border, the far northern extent of the boreal forest, suddenly ceased. When the Arctic expanded the trees died and fires eliminated them. And on top of the paleosol (where there

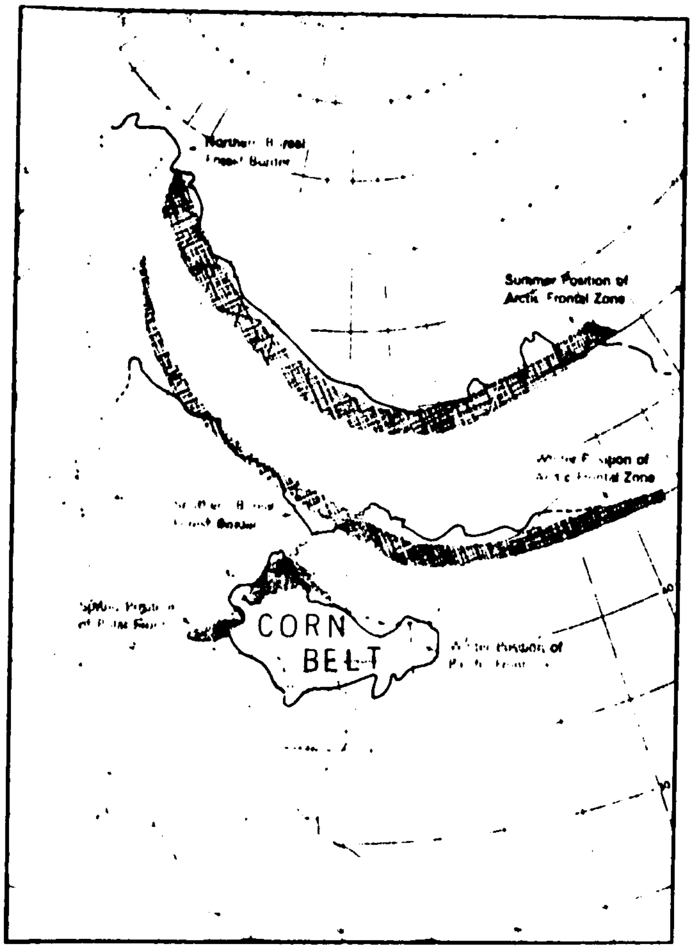

Fig. 5 - The coincidence of the "boreal forest" and "corn belt" biotic regions with climatically defined airmass regions. (4)

is blown-in sand so another soil can develop), you find an Arctic brown soil. In other words, the climate changed from that which would support forests to that which would not, as the Arctic expanded 3600 years ago.

Now, if what I told you is correct, then that expansion of the Arctic should be matched by a failure of the monsoons. I'm a field scientist, so if I want to get an answer, I usually go out and start digging holes to find a fossil soil, or pollen. Figure 6 is the result of digging a hole in a lake in Rajasthan (5). An analysis of the pollen, using our transfer function technique to see what the climate was, gives us a 10,800 year record of summer monsoon rainfall in Rajasthan. During the Ice Age when the Arctic was obviously expanded, there was no monsoon in northern India. It was a total desert of drifting sand dunes. When the Ice Age climate ended 10,800 years ago, the rains came, the water table rose in the sand dunes, and fresh water lakes formed in some depressions in the sand dunes. Cat-tails grew by the lakes. Nine thousand four hundred years ago there was farming in the area. That region of stabilized sand dunes and freshwater lakes was occupied about 5,000 years ago, by the Indus clivilization. But about 3,600 years before the present, radiocarbon date, or about 1900 BC, calendar date, those fresh water lakes started to turn to salt. The cat-tails disappeared, halophytes appeared, salt started to deposit, and the lakes dried up entirely. The Indus civilization totally disappeared. The lakes were gone, the people were gone, the vegetation was gone and the sand dunes were once again migratory. For 600 years there were no occupants in the region. There is no dated site that lies in that 600-year period. After 600 years, the Aryans moved in. You may have read somewhere that the Aryans conquered the Indus civilization, but did you ever hear of a conquerer who waited 600 years to enjoy the fruits of conquest? They couldn't move in until 600 years later. Eventually the lakes started to accumulate sediment again about 2,000 years ago. You'll notice that the monsoon rainfall never did come back to what it had been before (Fig. 6). The last 2,000 years have been different: the climate has changed. This was a case of a period of expanded Arctic, when the climate changed in the Arctic and changed world-wide. The monsoons totally failed in India, and the evidence from tropical Africa shows that the monsoons failed there also. When the Arctic cools off, the monsoons tend to fail. Under some of the sand dunes of

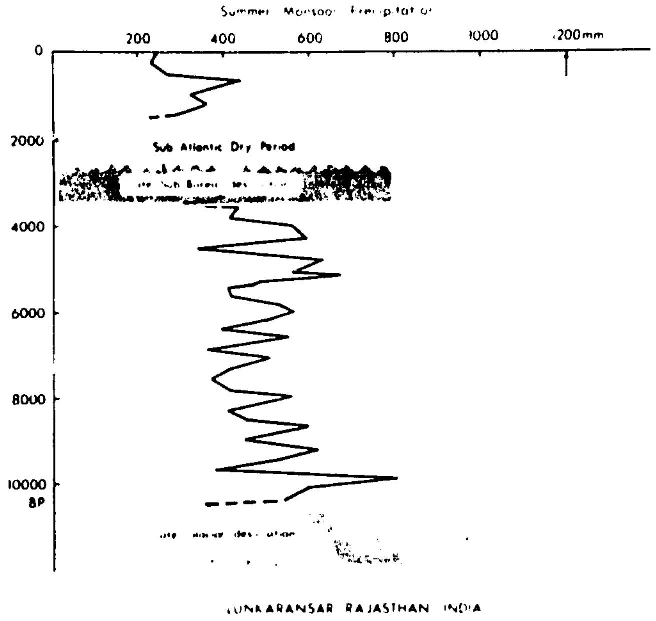

Fig. 6 - Tentative reconstruction of the summer monsoon rainfall in Rajasthan over the past 10,800 years, based on fossil pollen accumulated in a lake. The lake contained fresh water until shortly before it dried up about 3,500 years ago. BP = years before present. (5)

Rajasthan, you can find the remains of Indus culture cities. I was taken to a town in Rajasthan which my host said was a new town. (I didn't want to see a new town, I wanted to see nature and see what was going on in the real ecosystem.) As we approached this town, which didn't look so all-fired new to me, I said, "I thought you said this was a new town." "Oh, it is, it is." I said, "It looks old." "Well," he said, "it's a new town because every time you dig a hole you find the walls of the old town." So I said, "When was this town built?" "I don't know," said he. "Let's go to the temple around which the town was built and find out when it was built." The date was 500 BC. That was the Aryan influx that followed the time of total failure of the monsoon. The dunes had stabilized again, but they are becoming destabilized once again.

Now let's take a little shorter view: only 1,000 years. We don't have to rely on fossil soils to tell us about expansions of the Arctic during the last millenium because we can go to written records of the Vikings in Iceland. For 1,000 years, they wrote down the time at which drift ice reached their shores, how long the ice was there, and how far it extended. An Icelandic meteorologist by the name of Bergthorsson put all this together and correlated it with temperatures in recent years (6). He found that the correlation was very good and reconstructed the temperature of Iceland for 1,000 years from the Icelandic chronicles (Fig. 7). Iceland is far north and when the temperature goes down in Iceland you know that the Arctic has expanded. When the Vikings moved in, 1,000 years ago, Iceland was moderately warm. About 1,200 A.D., there was a sudden drop in temperature as the Arctic expanded a little bit. That drop in temperature lasted for a couple of hundred years. So there should have been some changes in other parts of the world as the circumpolar vortex expanded a bit.

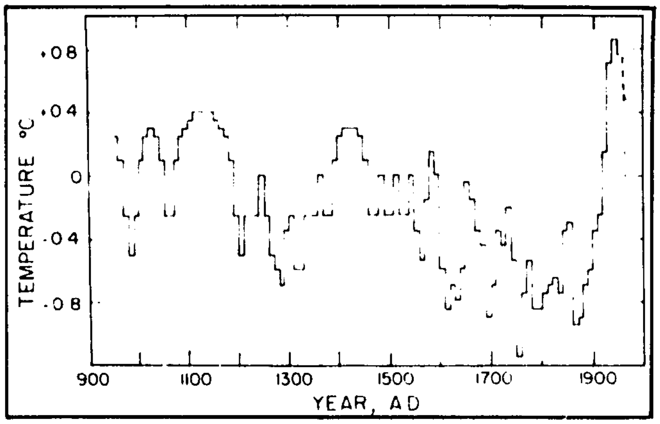

Fig. 7 - Bidecadal mean annual temperature in Iceland over the past millennium. The dashed line on the right indicated the rate of temperature decline in the 1961-71 period (based on additional data), and the dotted lines show the variation of mean temperature in the Northern Hemisphere plotted to the same relative scale. (6)

There is a dramatic example of this in the Chronicles of Iceland itself. They stated that prior to 1,200 A.D., the way to get from Iceland to Greenland was to sail west a distance of 2-1/2 days and there on the Greenland coast was a landmark, Black Mountain. Then one should go down the coast to the southwest side. After 1,200 A.D., the sailing directions read as follows: To get to the Greenland colony, sail 1-1/2 days west, watching out for the drift ice. In the distance, on the Greenland coast, you will see the landmark, White Mountain. It was now covered with ice and snow - dramatic evidence that there had been a change.

There was also an expansion of the Arctic in Canada. There is another paleosol on top of the first one in parts of Canada which dates from 1,200 A.D. When the forest retreated in Canada, the temperature had also dropped in

Iceland, and the ice had moved down around Greenland. There were also changes in Europe. The shifting southward of the westerlies carried moist Atlantic air into Europe. One of the important consequences was the increased frequency of an interesting disease known as St. Anthony's Fire. You probably all know more about the cause - the ergot blight - than I'll ever know.

St. Anthony was the patron saint of a group of monasteries set up to care for the thousands of people suffering from chronic ergotism, an evil disease. It doesn't take very much blighted grain in a loaf of bread to produce the disease. It causes gangrene of the extremities because it is a vasocontractor, therefore they turn black as though they were burnt. I've had gangrene in my hand, and it does feel like fire. That epidemic was brought about by an outbreak of ergot blight. I don't have to tell you the climatic conditions that bring about large expansion of this particular blight. It's climatic, isn't it? That outbreak was associated with the mild, continuously wet weather recorded in the history of England when the peasants in England said to Edward II, "Please don't collect the taxes this year, because as you know, it has been so continuously wet that we couldn't get into the fields at all." It shows up in abandonment of the heavy clay soils of Denmark and the Midlands of England before the Black Death hit.

There is an associated change in North America. When the westerlies shift south so that they bring continuously damp weather in Western Europe, there is continuously dry weather in the high plains of North America. Here, when the westerlies blow across the country they come down the east face of the Rockies as a dry airmass. About 1,200 A.D. there was such a shift. Figure 8 is our reconstruction, from modern data, of what happens to the rainfall with an expansion of the westerlies (7). This is then, a simulation of what happened in the year 1,200 A.D. You will notice in Figure 8, that in Nebraska, the Dakotas, Illinois, and Iowa, there is up to a 50% reduction of summer rainfall. Now, what does that do to open pollinated corn? It produces up to 75% reduction in yield. And the Indians at that time were growing open pollinated corn. Where? All the way across the Plains

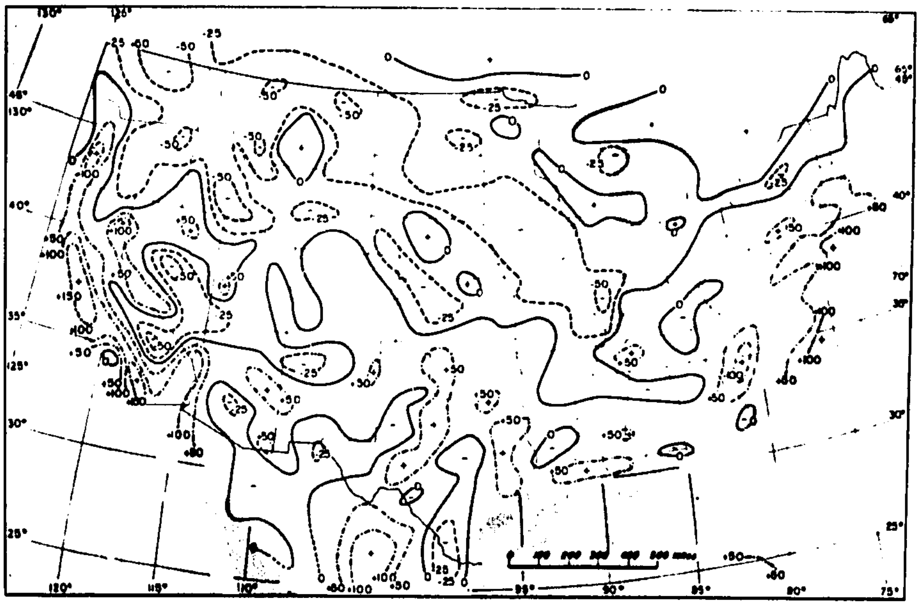

Fig. 8 - July precipitation changes, in per cent, to be expected with a southward shift of the westerlies, i.e. from weak westerlies over the 35-55 latitude band to stronger westerlies in that band. Based on 20 years of modern data. (7)

as far as the Rockies non-irrigated, rain-fed corn agriculture was practiced. This time is known to the archaeologists as the Small Village horizon.

Did this reduction of rainfall actually happen? Well, we dug a hole to find out. We found an Indian village in western Iowa that we thought might have been of about the right age and dug a hole through their trash pit. We looked at the plant remains and the animal remains to see what happened. Up to about 1,200 A.D. they had been living in tall grass prairie, growing corn and hunting deer. After 1,200 A.D., within fifteen years or so, the environment changed to steppe and their meat diet changed from 97% deer to 67% bison. This was a dramatic change in the environment. How long did that drought last? Two hundred years! Now look carefully at Figure 8 ladies and gentlemen, because that pattern looks like 1974. The United States once had a drought like 1974 that lasted 200 years. One exciting thing about natural history is that if we find that something did happen, it obviously is possible. It is possible to have a drought last 200 years in the corn belt. I don't think we could hack it!

There are other places where we have found evidence of the same thing, for example, around St. Louis. There is a place called Monk's Mound across the river from St. Louis that was a temple of the corn priests. When that drought came and the corn didn't yield, who was in trouble? The priests. About 1,200 A.D. they built the heavy defensive fortification around the temple of the corn priests - not around the city, to protect the city, but around the temple to protect the temple. There was a high concentration of arrow heads around that wall. The lesson of that is that civil unrest is not new in America!

There are some other interesting things that happened. There was a short respite from that drought period and then the "Little Ice Age" began. The glaciers actually started to expand in the Canadian Arctic and in the Alps, where they expanded dramatically. The North Atlantic turned cold, the Gulf Stream shifted southward. The very first map of the Gulf Stream, drawn in 1605, had it farther north than it has been in recent years. By the year 1,800, the

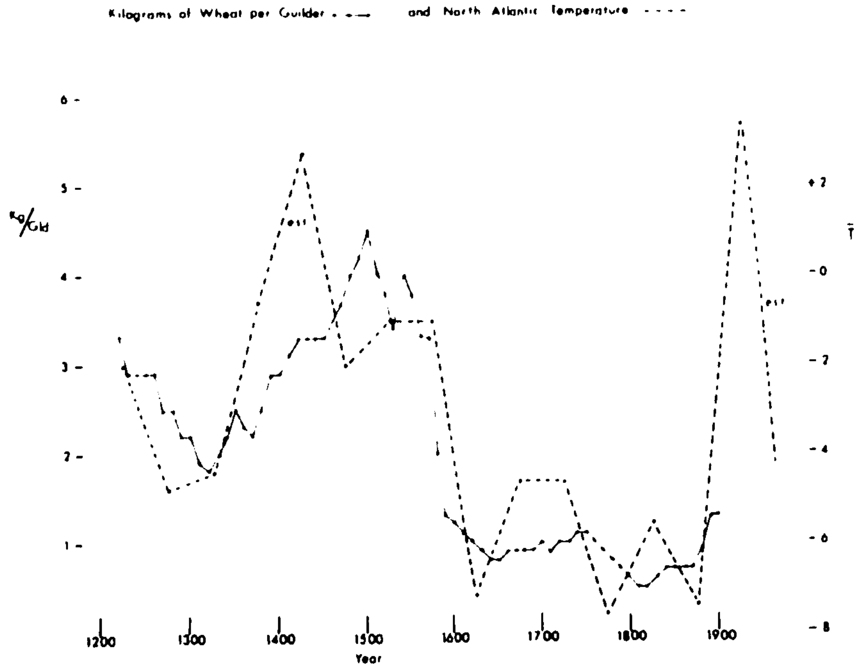

Fig. 9 - Decadal mean amount of wheat that could be purchased for one Dutch guilder (average of England and Holland) compared with estimated North Atlantic temperatures which are plotted to an arbitrary scale and are the fifty year means of Bergthorsson's Icelandic temperature series (7). This comparison was suggested by Leona Libby (pers. comm. 1974). The height of the temperature peak, 1400-1450, is questionable and the last 50 year period is incomplete.

Gulf Stream had shifted almost to a full glacial position and then came back. The "Little Ice Age" was like a tentative step into a glacial period. Consider what it did to the price of grain in Europe (Fig. 9). European grain agriculture is more temperature-limited than it is water-limited. When North America was warm (1,300-1,400 A.D.), one could buy a lot of wheat in Western Europe for a Dutch guilder. When the North Atlantic got cold, one couldn't buy much wheat in Western Europe for a Dutch guilder. In fact, an average man's wages weren't enough to feed a man and his family. Look at the history of that time. I didn't put the wheat prices for this century on the graph because you all know them. Could you buy a lot of wheat for a Dutch guilder or a buck or a nickel back in the 1930's when the North Atlantic was warm? Sure. In 1974 when the North Atlantic was cold, could you buy much wheat for a guilder? 1/10 of a bushel. So there you go. There are direct agricultural and economic implications of these fluctuations which have occurred even in the post-glacial climate. Now I want you to look at that righthand side of Figure 7. That right hand side is this century. If you call the weather bureau and say "Tell me the normal temperature for New York City or Lincoln, Nebraska or St. Paul, they will give you probably either the 1931-1960 average or the 1941-1970 average. Look at that figure, now. What they call normal is the most abnormal period in 1,000 years. That's logic - to call it normal! It is to that very unusual normal that you have adapted crops. Over the last fifty years, all the excellent work on adaptation of crops has been shooting at the target of what existed at that time - the most abnormal climate in 1,000 years It is during that same time that the population of the earth more than doubled. It is during that time that the national boundaries were frozen in the present position and mass migration became something of the past. And yet, that is the normal towards which adaptation has been shooting. As I said before, it's a moving target, and that was a very unusual position for the target.

When the earth is warm the monsoons are reliable; when the earth is cold, the monsoons are unreliable. Back at the turn of the century when the northern hemisphere was cold, drought came in northwestern India an average of once every four years (Fig. 10). When the earth warmed up, the monsoon became more reliable and the recurrence interval of drought became 18-20 years. From the time of Indian independence until the 60's, they never had it so good. And some said "See, once we got rid of the British there's no problem with agriculture in India." There was no problem because there was no bad weather. However, Figure 10 is weather facts. Now the frequency

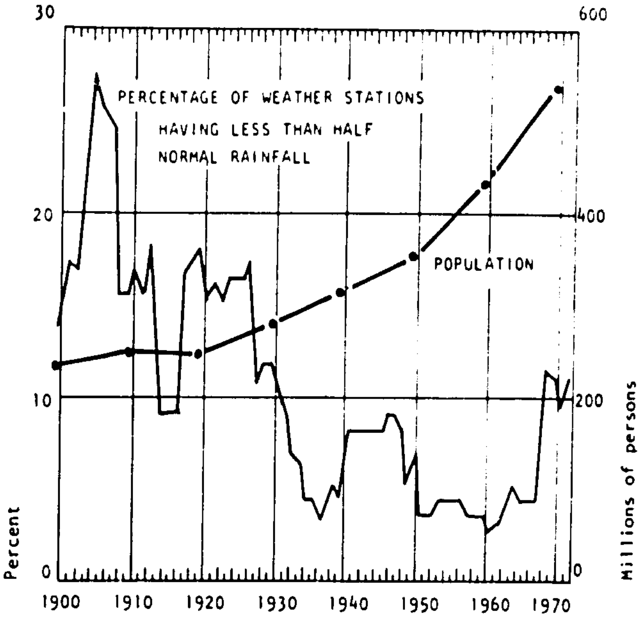

Fig. 10 - Trends in the percentage of weather stations in northwestern India reporting less than half of normal annual rainfall in a given year. Overlapping ten-years averages.

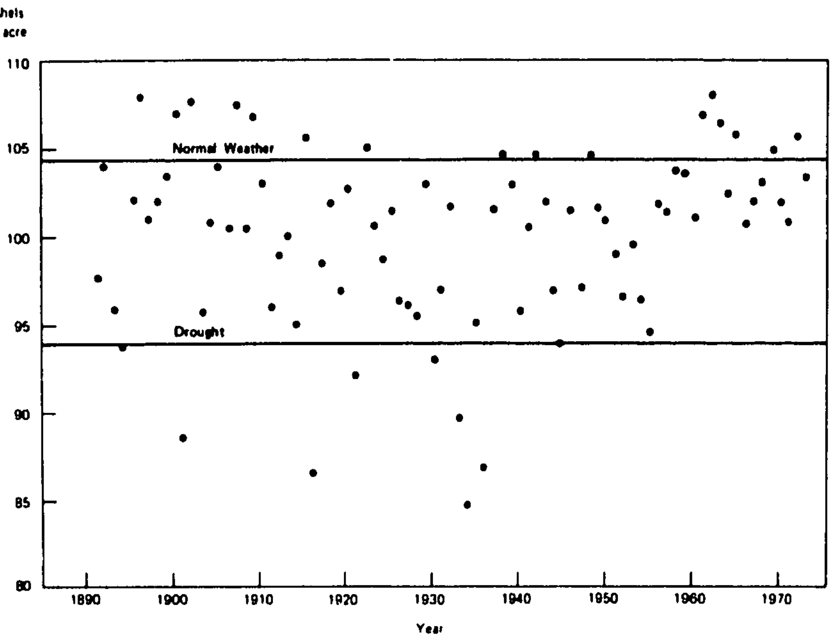

Fig. 11 - Simulated five-state weighted average corn yield using 1973 technology. The ordinate though labeled "bushels per acre" is actually estimated yield considering the climate of the year. It is thus really "quality of the corn-growing weather" and "drought" is really any combination that produces estimated 10% reduction in yield below that estimated for normal conditions. (8)

of drought has started to rise as the earth has been cooling off. But now they have 2.4 times as many people. They just topped 600 million, going up 15 million a year. What would happen if the frequency of drought returned to once every four years? What has happened is possible. It is also possible in North America.

Figure 11 is from Jim McQuigg's study, which many of you have seen (8). It is not actually a plot of corn yield, even though it is labeled yield. It is the yield calculated from the weather data alone, so it is really weather data. Look at the recent years when the corn yield was very steady. This plot was calculated as though each year for the last century had 1973 technology. Look at that spell of superb weather where the calculated yield goes along very high with just no bad years at all, just as the Indian weather went along with no bad years. Then something dramatic happened.

In this extremely non-linear system we call climate, something dramatic happened in the winter of 1971-72. The hemispheric ice and snow cover increased by 15% - 1/6 of the increase we had during the great Ice Age. In one winter, the ice and snow cover increased as the climate changed from that stable climate that gave us 15 years of superb corn yield. (The probability of getting 15 years like that in a row is around one in 10,000, by the way.) It changed to a much more unreliable climate. What's it going to do in the future? I don't know. That's one of the research imperatives - we *must find out* where the climate is going to if we're going to know where that target is at which we're shooting. We must know if we're going to optimize the allocation of what food we *can* produce - we must know if we're going to know which technology to use, and which stresses are the ones that we're going to have to deal with. This is a piece of research that *must* be done and must be done *soon*. In the meantime, we must use an actuarial approach. We may look back at the last 1,000 years and see what happened after a decline of temperatures such as the last 30 years (Fig. 12). At no time in the past millenium has such a decline lasted less than 40 years (9). Therefore, it is unlikely that the trend of the last 30 years terminated last year. (It is more likely that it will go on and level out - maybe continue

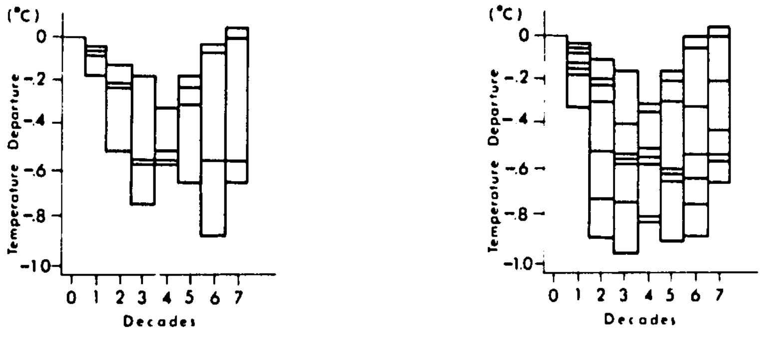

Fig. 12 - 'Superposed epoch analysis' made by plotting the temperature departure of each decade following a peak decade of temperature. The rate of decline varies and the total magnitude of the decline varies, as shown by the short horizontal segments representing individual decades. Sudden returns to the original value have not happened in the last millennium, however The left-hand figure (a) is based on the four most prominent times of decline, and the right-hand figure (b) on the seven most prominent. (9)

on down. The temperature has never returned to its original value in less than 70 years.) That takes us to the turn of the century. So are we shooting at a target that will be like the last five years? Knowing the last five years of crop reports, that's not very encouraging.

As long as there were reserves, few worried about the fact that a few years came along with less than enough production. But in recent years, the production has leveled off (Fig. 13). It has been erratic, with ups and downs, but it has generally leveled off and the reserves have been drawn down. Figure 13 shows that in December 1974 the best estimate

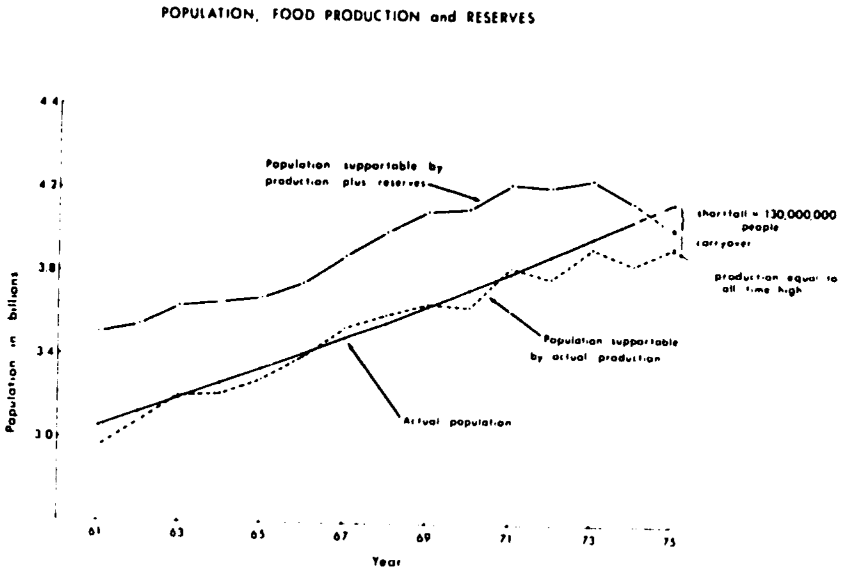

Fig. 13 - Population of thw world versus food grain production and reserves expressed as numbers of people supportable at actual consumption rates of the year in question. Production was estimated from the drawdown of reserves. Reserves were derived from several sources. Actual 1975 production appears to have been less than 1973, hence below the x at the righthand end of the production line.

of world grain reserves that one could get from FAO and other sources was about 8 days of normal consumption, if "pipeline" contents are included in the reserves. It shows that if 1975 production equalled that of 1973, the highest in history, and all the carryover were used, the 1975 supplies would fall short by the minimal food needs of 130,000,000 people. We now know that 1975 production was less than 1973 by a significant amount, even though the United States had a good year.

Your mission, and the mission of this Conference, is a noble mission, but it may be a "Mission Impossible." With reserves gone, significant climatic variations can produce catastrophes. Since desperate but powerful nations with nothing to lose are dangerous neighbors, climatically induced food production shortfalls are also a threat to peace. Let us hope we do not face a bloody dawn.

Let's "get with it."

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9. Courtesy of Professor John Kutzbach, University of Wisconsin, Madison.

NITROGEN INPUT

Submitted on behalf of the group by:
R.W.F. Hardy
P. Filner
R.H. Hageman

INTRODUCTORY STATEMENT

Crop productivity during the last quarter century is highly correlated with input of fertilizer nitrogen. For example, the yields of cereal grains in both more developed (MDC's) and less developed countries (LDC's) from 1950 to 1975 parallel the increasing application rates for fertilizer nitrogen (Fig. 1). Up to one-half of the credit for this 3% average annual increase in world cereal grain production is assigned to the exponential increase in the use of fertilizer nitrogen. In 1974 this fertilizer nitrogen supplement was 40 x 10^6 metric tons with a value of $8-$10 billion and projections indicate that demand for crop production will grow to about 160 x 10^6 tons by 2000 A.D. (16). A variety of factors including cost, utilization, and environment make it desirable but not essential to seek improved or alternate technologies for nitrogen input into crops (12, 16, 30, 35, 36, 37, 42). The desired technologies will possess one or more of the following characteristics:

1. Minimized energy and capital costs for nitrogen fertilizer production.
2. Nitrogen self-sufficiency.
3. Maximized efficiency of use of soil nitrogen and fertilizer nitrogen.
4. Improved nutritional characteristics of the product.

All are of international significance.

Our discussions on nitrogen input at this Conference were directed towards the identification of research imperatives that would have the greatest possibilities of producing these new generations of nitrogen input

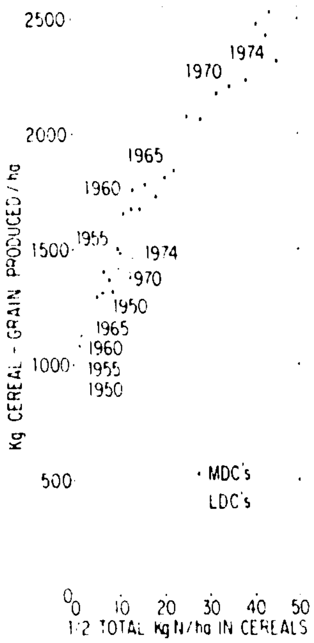

Fig. 1. Relationship between cereal grain yield and nitrogen fertilizer use rate for LDC's and MDC's during past 25 years. Note that one-half of total nitrogen fertilizer is included since this is the approximate amount used on cereal grains. From R.W.F. Hardy, Fertilizer research with emphasis on nitrogen fixation in Proceedings of 24th Annual Meeting of Agricultural Research Institute, National Academy of Sciences, Washington, D.C., 1975.

technology. We recognized that the technology for nitrogen input into crops is already up to its sixth generation, which number attests to the long recognition of the importance of nitrogen in crop production. Such technologies as green manures and recycling of nitrogen-containing wastes date back to biblical times, while mined nitrates as nitrogen fertilizers, inoculation of legumes with Rhizobia, synthetic nitrogen fertilizer manufactured by the Haber-Bosch process, and nitrogen-responsive corn, wheat, and rice are of more recent origin.

Our approach to the identification of the research imperatives and the establishment of priorities took the following path. The major world crops (8) - rice, wheat, corn, sorghum, soybeans, potatoes, sugarcane, sugar beet, cotton, and alfalfa - were selected for exclusive consideration. Nitrogen imput was considered comprehensively, including manufacture and use of fertilizer nitrogen, biological N_2 fixation, soil nitrogen transformations, recycling of nitrogen-containing wastes, and utilization of fixed nitrogen by plants up to and including harvest index for nitrogen, and protein synthesis, quality, and quantity. An interdisciplinarily diverse international group of experts on all phases of nitrogen input into crops, including at least one engineer, economist, chemist, biochemist, molecular biologist, physiologist, microbiologist, geneticist, ecologist, and plant breeder was identified. Advanced input on the present state of knowledge and problems requiring research were solicited from this group and these inputs provided the basis of the initial working paper and program design. Four technical working sessions were used to generate and evaluate research imperatives of both national and international significance. A modified Delphi Technique was used to provide guidance from the group for the establishment of priorities and an indication of timing of initial impact of the research on crop production. (pages 171-172) Only the two highest categories of priority are included in our imperatives - priority one is highest rating, priority two is higher rating, and priority three is high rating, but was not included. The timing for initial possible impact of the specific research imperatives on crop production is divided into short-term (0-10 years), mid-term (10-25 years), and long-term (25 or more years). Research emphasis in terms of percent to be placed on the major areas is given.

CURRENT STATUS AND STATE-OF-THE-ART

SOURCES AND AMOUNTS OF NITROGEN FOR CROPS

Industrial N_2 fixation and biological N_2 fixation* provide the major inputs of newly fixed nitrogen for crop production. In addition, mineralization of nitrogen in the soil and recycling of nitrogen-containing wastes make fixed nitrogen available for crop production. In 1974, 50 x 10^6 tons of N_2 were fixed industrially with 10 x 10^6 tons used for fibers, plastics, explosives, and animal feed (15).

The amount of nitrogen fixed biologically is difficult to estimate because of the heterogeneity of the environment in which they function, and the extremely limited data base. The most recent estimate of 175 x 10^6 tons of N_2 fixed per annum assigns 90 x 10^6 tons to the amount fixed in agricultural soil. Of this input, 35 x 10^6 tons is attributed to crop legumes, 9 x 10^6 tons to non-legume crops, and 45 x 10^6 tons to permanent meadows and grasslands (5).

In addition, natural abiological processes such as lightning, combustion, and ozonization are estimated to fix about 10, 20, and 15 x 10^6 tons of nitrogen, respectively, each year and a part of this is available for agricultural crops.

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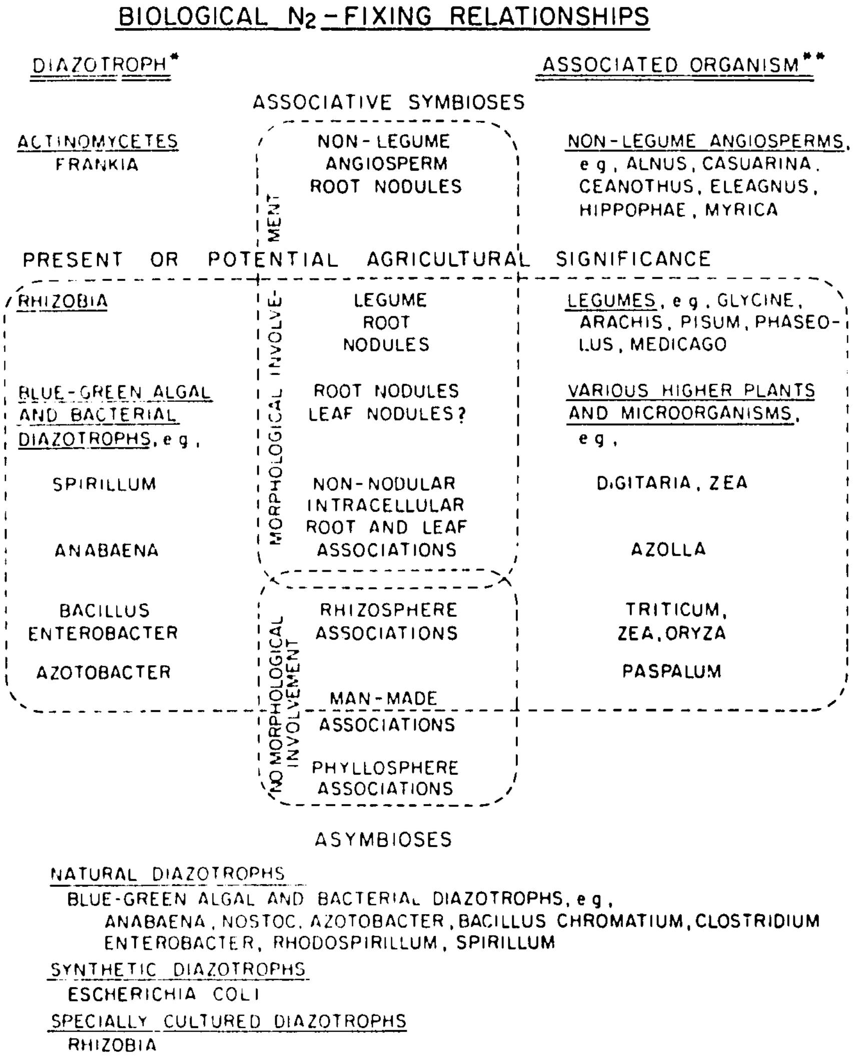
*Terminology, N_2 fixation is the conversion of molecular nitrogen (N_2 or dinitrogen as it is often labeled nowadays) to a fixed form in which nitrogen is combined with another atom. Examples of fixed forms of nitrogen include NO_3^-, NH_3, urea, N_2O, NO, NO_2, N_2H_2, N_2H_4, etc.

Fertilizer nitrogen is produced almost exclusively by a single-type of chemical plant. This industrially fixed nitrogen which is used now mainly as anhydrous ammonia, a gas, or urea, a solid provides over 90% of commercial fertilizer nitrogen with the remainder obtained from mined nitrates and fish and meat by-products (43). In contrast, there is a diversity of biological N_2-fixing organisms, and relationships (Fig. 2). They can be divided into the asymbioses in which N_2 is fixed independently by the microorganism and the associative symbioses in which a microorganism which provides the genetic information for N_2 fixation (diazotroph) is associated with a non-N_2-fixing organism such as a plant that provides the photosynthetic energy and/or favorable environment for N_2 fixation and is the recipient of at least some of the fixed nitrogen. Examples of diazotrophs include certain bacteria and blue-green algae while a synthetic diazotroph, *Escherichia coli*, has been constructed by genetic engineering. The agriculturally important rhizobia were previously believed to require association with a legume for N_2 fixation but have been shown to be diazotrophs under special culture conditions in the laboratory. Examples of associative symbioses extend from nodulated legumes to rhizosphere and phylloplane associations in grasses.

In general, those biological N_2-fixing relationships in which the site of N_2 fixation is located on or in the crop plant will permit direct and thereby efficient coupling of the fixed nitrogen to the plant in amounts that parallel the changing needs of the plant througout its complete growth cycle. Many of the associative symbioses such as nodulated legumes (41), rhizosphere associations (31), and possibly phylloplane associations in which the crop plant is one of the symbiotic partners would meet these requirements, as would crop plants containing the genetic information. Free-living bacteria and blue-green



*DIAZOTROPH- N_2-FIXING ORGANISM PROBABLY PROVIDES GENETIC INFORMATION FOR *nif* IN ASSOCIATIVE SYMBIOSES

**ASSOCIATED ORGANISMS- PROVIDES ENVIRONMENT, ENERGY, etc FOR DIAZOTROPH AND PROBABLY RECEIVES FIXED NITROGEN

Fig. 2 - Biological N_2-fixing relationships identifying those associative symbioses with present or potential agricultural significance. From Hardy as in Fig. 1.

algae do not meet the requirements and symbioses of bacteria or algae with non-crop plants do not meet the absolute requirements but may be of agricultural significance in special situations such as a rice paddy (32).

While the amount of nitrogen input for crop production contributed by biological N_2 fixation has not changed in recent times, that from fertilizer nitrogen has increased exponentially from 0.4 x 10^6 tons in 1905 to 3.5 x 10^6 tons in 1950 to 40 x 10^6 tons in 1974. The annual value of world fertilizer nitrogen is about $8-$10 billion, or double that for all pesticides. The projected demand for fertilizer uses may increase this amount to a total of 160 x 10^6 tons by 2000 A.D., with possibly an additional 40 x 10^6 tons for non-fertilizer uses. (13, 16).

The amounts of nitrogen fertilizer applied varies with region, crop, and time. For example, in 1970, the nitrogen fertilizer application rates in Kg N/ha were 66.6 in Europe, 32.5 in North America, 19.8 in USSR, 15.9 in Asia, 11.4 in Latin America, 3.9 in Africa, and 3.3 in Oceania. Nitrogen fertilizer use by individual crops on a world basis is not available but such figures are available for the United States (14) where corn received 40% of nitrogen fertilizer at an average application rate of 130 Kg N/ha. Wheat receives 9% of nitrogen fertilizer at an average rate of 52 Kg N/ha and cotton receives 4% at an average rate of 85 Kg N/ha, while soybeans receive only 0.8% at an average rate of 12 Kg N/ha. The rate of application during the last decade has doubled in the case of corn, increased by 70% for wheat, and is unchanged for cotton and soybeans. Improved crop prices such as occurred during the past two years have accelerated further the demand for fertilizer nitrogen. It is important that research imperatives to increase the efficiency of use of fertilizer nitrogen be focussed on those crops where the opportunity is the greatest.

The absolute nitrogen requirement for various crops also shows extreme variation. Protein contents of seeds range from 8% for rice to 42% for soybeans. Assuming a nitrogen harvest index of two-thirds, 20 Kg N are contained in the mature rice plant for each ton of seed it produces and 100 Kg N are contained in the soybean plant for each ton of seed it produces. In the case of a goal yield of 100 bushels of seed/A, 600 Kg N/ha is contained in the mature soybean plant, while only 120 Kg N/ha is contained in the mature rice plant. High yields of grasses as well as legumes will require 600 Kg N/ha (31, 44).

Nitrogen input technology for production of different crops is further complicated by the type of culture, e.g., paddy vs. upland, the timing of nitrogen need, e.g., high nitrogen requirement for growth and low nitrogen for ripening in sugar crops vs. low nitrogen for vegetative growth and high nitrogen for seed filling of grain crops, and capability of symbiotic N_2 fixation, e.g., legumes vs. nonlegumes.

FERTILIZER NITROGEN

Almost all fertilizer nitrogen is synthesized from N_2 and H_2 by the Haber-Bosch process which requires large energy and feedstock inputs. The process is highly engineered and occurs for the most part in large plants with rated capacities of 1000 to 1500 tons per day for each plant. These plants have substantial economic advantage over smaller ones (4, 13, 17). The additional nitrogen inputs required for increasing world crop productivity during the next quarter century could be provided by the construction and operation of about 500 additional large-scale ammonia synthesis plants at a capital cost approaching $50 billion and an annual cost to the world farmers of $30-$35 billion, both at 1975 prices.

However, there are many reasons that support the desirability of developing and applying improved technologies for nitrogen input (12, 16, 30, 35, 36, 37, 42). Fertilizer nitrogen is a high technology solution. It may be desirable to develop lower technology solutions for lower value crops such as forage crops and for LDC's.

An average threefold increase in the price of nitrogen fertilizers occurred during the last two years following the removal of controls in 1973 and the shortage of nitrogen fertilizer created by increased crop prices and the termination of acreage limitations in the United States (10). The extremes of nitrogen fertilizer prices are even more dramatic with prices of $50/ton in the late 1960's due to excess capacity and up to $400/ton during the period of shortage of 1974/75. Current prices are about $200/ton and prices projected to 1980 may be similar. Returning to the pre-1973 prices for any extended period of time would appear to be precluded by the high-energy consumption for fertilizer nitrogen manufacture and the escalated capital cost for new plant construction which is about $75 million per plant for ammonia manufacture and an additional $40 million for urea manufacture, both for a rated capacity of 1000 tons per day of nitrogen fertilizer. These economic costs are even far less tolerable in LDC's than in MDC's. Fertilizer cost in LDC's may take a very large part of the farmer's low per capita income and some suggest that fertilizer use in South America and Africa may be curtailed by current prices

Natural gas is the preferred energy source and feedstock for industrial ammonia synthesis and 35-40 thousand standard cubic feet (MSCF) (40×10^6 BTU's) are required to produce one ton of fertilizer nitrogen with 22 MSCF for H_2 production and 16 MSCF for heat. This consumption coverts to 380 Kcal/mole N_2 fixed.

Feedstocks suitable for synthesis gas preparation by steam reforming are dictated by economics and availability. Capital cost, construction schedule, energy consumption, labor requirement, land area and pollution control, favor steam reformable feedstocks, e.g., natural gas and naphtha. Natural gas is preferred over naphtha due to lower capital cost and lower energy consumption. Heavy liquid fuels may be used as feedstock from partial oxidation processes to prepare synthesis gas, if available long-term at attractive prices. Capital cost, land area, energy consumption, and labor required are 1.3-1.5 times the equivalent for reformable feedstocks and construction schedule is longer and pollution control more difficult. Synthesis gas from solid feedstocks, e.g., coal, oil shale, waste, etc., may be required in the long term, but all factors are more unfavorable.

About 2% of domestic natural gas consumption is used to manufacture fertilizer nitrogen and of the energy required to produce the three major fertilizer nutrients, 87% is consumed by ammonia synthesis (11,43). Furthermore, fertilizer nitrogen may represent 1/3 of the fossil-derived energy input for corn production (18, 29) However, the ratio of extra feed or food calories produced per added fossil-derived energy in the form of fertilizer nitrogen has been calculated as a favorable 5 to 8 for corn production in the U.S. Midwest (20). While natural gas contracts in established plants may be as low as $0.20/MSCF and represent only 10% of the cost of manufacture, new contracts may be up to $1.50/MSCF and constitute almost 50% of the cost of manufacture. The increasing limitations in natural gas supply and accelerating cost in the United States have arrested domestic construction of fertilizer nitrogen plants and may within a few years force the United States from a net export of 0.9MM ton in 1969 to a net import by 1980 at a cost of up to $1 billion.

In addition, fertilizer nitrogen has additional economic and energy costs associated with conversion to a solid form such as urea, and transportation, storage, and application.

Chemical systems that convert N_2 to hydrazine and ammonia under mild conditions have been discovered in recent years (42, 44). Some of these systems are based on the nitrogenase reaction while others are non-biologically based. Dinitrogen (N_2) ligating transition metals has been reduced to ammonia and/or hydrazine in up to stoichiometric yields. A terminal N_2 ligand of some molybdenum (zero) and tungsten (zero) complexes is protonated and rapidly reduced at room temperature, to ammonia, often with a little hydrazine. Some dinuclear complexes of titanium and zirconium (and possibly iron) have a bridging N_2 ligand which can be protonated and reduced to hydrazine. Aqueous solutions of vanadium (II) reduce N_2, in presence of catechol, to ammonia.

BIOLOGICAL N_2 FIXATION (5, 9, 12, 16, 26, 32, 34, 38, 41, 42, 44).

Biological N_2 fixation provides an input of fixed nitrogen that is agriculturally important in legumes and may become so in non-legumes. It is catalyzed by an enzyme called nitrogenase. Nitrogenases from different diazootrophs are sufficiently similar so that a unified description of characteristics and reaction is justified. The enzyme is composed of two proteins. The large one contains Mo and Fe, and is called the Mo-Fe protein, while the small one contains only Fe and is called the Fe protein. Both compoents are essential for nitrogenase activity with a ratio of one or two Fe proteins for each Mo-Fe protein. Both components are highly sensitive to O_2 and special reactions or structures protect them in aerobic organisms.

Nitrogenase is a reducing enzyme with electrons transferred from photosynthetically produced substrate via the electron-transferring proteins ferredoxin and/or flavodoxin. In addition, nitrogenase requires ATP provided by oxidative phosphorylation of photosynthetically produced substrate in aerobic organisms or other ATP-producing reactions in anaerobes. Fifteen molecules of ATP are converted to ADP and inorganic phosphate for each molecule of N_2 reduced, and the activity of nitrogenase is regulated by the ATP/ADP ratio. The ATP-equivalent cost of electrons and directly used ATP is 24 molecules per molecule of N_2 reduced, although the overall reaction of $3H_2 + N_2 \longrightarrow 2NH_3$ is theoretically energy-yielding. Obviously, the nitrogenase enzyme is highly wasteful of energy but possibly only about one-half as wasteful as the commercial Haber-Bosch process. The nitrogenase enzyme is also very slow with a turnover number for N_2 of only 200 per minute.

For nodulated legumes, the photosynthetically produced substrate is transported from the shoot. The developing vegetative and reproductive structures in the shoot may outcompete the root and nodule for this limited substrate. The biologically fixed nitrogen is transported back to the shoot as specific amides and amino acids which in the case of the soybean are mainly asparagine, aspartic acid, and glutamine. Measurements of the photosynthetic energy costs of the N_2 fixation system have been made in vegetative peas where the total requirement for nodule growth, nodule respiration, and export of fixed nitrogen was 9-10 Kg carbohydrate per Kg N_2 fixed. Since about 5 Kg of carbohydrate were contained in the exported product, 3.6 Kg were respired by the nodule, and 0.4 Kg was used for nodule growth, the actual charge to the N_2-fixing process was 4 Kg carbohydrate per Kg N_2 fixed. A similar value is obtained from calculations based on the <u>in vitro</u> ATP and electron requirements of nitrogenase. However, this cost should not be considered a disadvantage of N_2 fixation vs. utilization of nitrate since the calculated and measured energy costs are identical on a nitrogen basis. Increasing the photosynthetic energy available to the plant by a variety of means such as elevated CO_2/O_2 ratios around the canopy of soybean and pea plants increases the N_2-fixing activity of these plants severalfold (41, 42).

Nitrogenase action reduces N_2 to $2NH_3$ which is the normal reaction but it also reduced $2H^+$ to H_2 as well as a variety of artifical substrates including acetylene which is reduced to ethylene. The latter reaction provides a most useful assay for measurement of N_2 fixation and is facilitating research advances in genetics, agronomy, physiology, and ecology related to crop production.

The ammonia produced by nitrogenase is incorporated by glutamine synthetase and glutamine a-ketoglutarate aminotransferase to form glutamic acid in free-living diazotrophs. The route is undefined in associative symbioses. Additional reactions to convert the product of N_2 fixation to the amides or amino acids translocated to the shoot are not understood (9, 41, 42).

The techniques of molecular biology have begun to be applied in genetic studies of a free-living diazotroph whose genetic map is closely related to the much-studied but generally non-N_2-fixing Escherichia coli. The genes for nitrogenase have been transferred from this free-living diazotroph to E. coli and the location of nif relative to other genes has been determined. A plasmid containing nif has been constructed and some investigators hope to utilize plasmids to move nif and the associated processes necessary for N_2 fixation including protection against O_2 to crop plants although no confirmed example of the effective transfer of genes to higher plants has been achieved and this approach is not included as a research imperative. It is also noted that nif genes have been found only in prokaryotic cells. The practical significance of this distribution is unexplained as far as transfer possibilities (38, 42).

Recent genetic advances are providing molecular understanding of the system controlling nitrogenase synthesis (33, 38). Ammonia has been long recognized as an inhibitor or repressor of nitrogenase synthesis in at least all diazotrophs except possibly rhizobia. The regulatory effect of ammonia appears to function through glutamine synthetase which acts as a positive control agent on *nif*. Organisms that are constitutive for glutamine synthetase are constitutive for nitrogenase. Other controls may also be involved.

Most recently, N_2-fixing activity by various free-living rhizobia in both solid and liquid culture has been obtained (33,34). This system provides opportunities for genetic and physiological studies of N_2 fixation in this agriculturally important microorganism. These experiments also improve the feasibility of the very long-term proposition of extending the rhizobial based N_2-fixing system to nonlegume crops.

The amount of N_2 fixed by biological systems is inadequate for high yield agriculture even in the case of legumes where the average amount of 75 Kg N_2/ha for grain legumes such as soybeans and 150 Kg N_2/ha for forage legumes such as alfalfa (23, 34). However, specific examples suggest that substantially higher rates have been measured.

Biological N_2 fixation requires carbohydrate to provide electrons and ATP, and to remove NH_3 as organonitrogen compounds (31, 33, 41). The photosynthetic inefficiency of domesticated legumes and most cereals is a major limitation for biological N_2 fixation and probably utilization of fixed nitrogen.

There is ineffective coupling to the crop with free-living diazotrophs or associations not involving the plant.

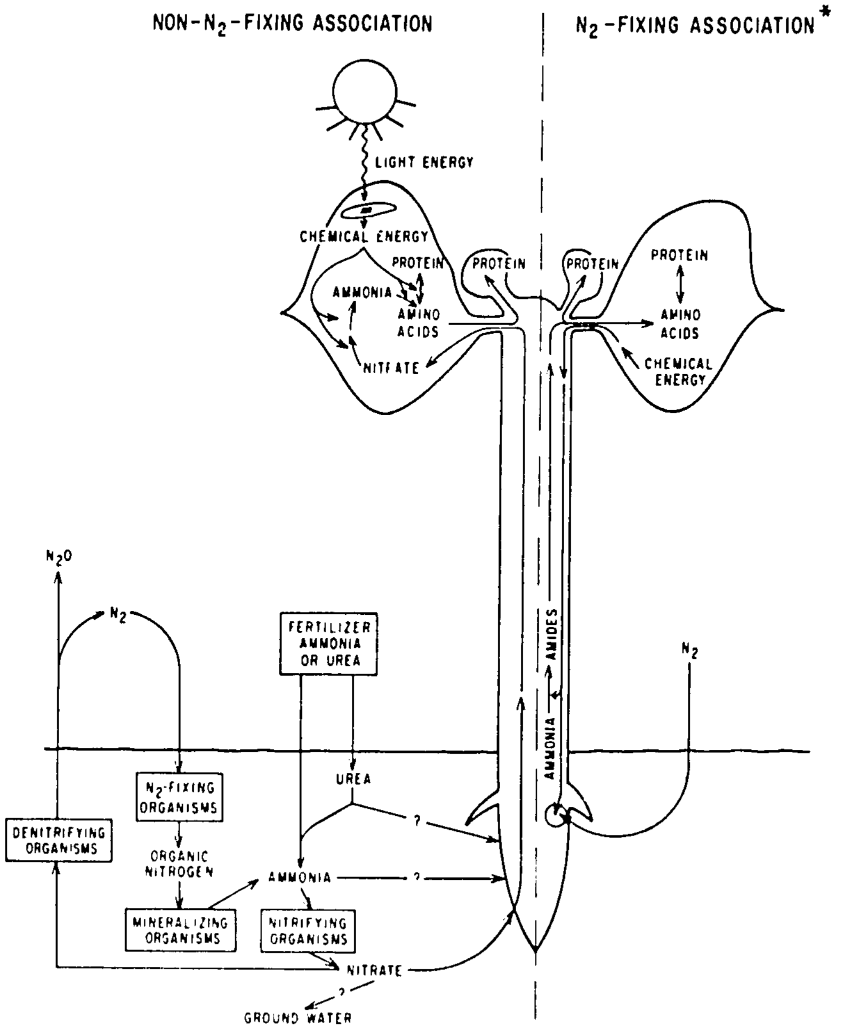
Fixed nitrogen at levels such as occur in high fertility soils inhibits N_2 fixation. For example, addition of fertilizer nitrogen to

N_2-fixing legumes decreases N_2 fixation and does not increase total nitrogen input.

There is a need for N_2-fixing organisms and/or strains dependent on crop, soil, climate, etc., while one form of fertilizer nitrogen is applicable in all cases. The problems of manufacture, storage, handling, and application of labile biological organisms are more complex than those for abiological material. Biological materials such as rhizobia inoculum need quality control to assure a standard level of activity. Competition occurs between applied and endogenous bacteria so that the preferred applied bacteria is not assured success in establishing the N_2-fixing relationship.

SOIL TRANSFORMATIONS OF FIXED NITROGEN (6, 39)

The chemical form nitrogen added to the soil as fertilizer is almost exculsively ammonia or urea, while the form provided by mineralization of immobilized soil nitrogen is ammonia (Fig. 3). Transformations by soil microorganisms convert the urea to ammonia utilizing the enzyme urease and the ammonia is converted relatively rapidly to nitrate by a process called nitrification. In unammended soils the nitrate may be taken up by the plant or leached from the root zone where it may contribute to the nitrate content of aquatic environments or undergo a transformation called denitrification in poorly aerated environments and thereby produce molecular nitrogen and nitrous oxide. This process can also cause high losses in some cultural practices used with paddy rice. The trend towards the exculsive use of ammonia-based vs. nitrate-based fertilizers is dictated by economics of manufacture. This change may provide opportunties for benefical control of soil transformations (27). Development of practices consistent with the new forms is needed. Slow release forms of fertilizer nitrogen such as sulfur-coated urea may have applications for specific crops,



*ADDITIONAL REACTIONS TO THOSE OF NON-N_2-FIXING ASSOCIATION

Fig. 3. Sources of nitrogen input for crop production including soil transformations and related plant conversions for crops that do and do not possess associative N_2-fixing systems.

while chemical regulators of soil transformations may also play significant roles. Inhibitors of urease are known but are somewhat toxic. At least ten nitrification inhibitors are described in the patent literature and commercial production of one is being initiated. It will be added directly to anhydrous ammonia at the distributor level and is suggested to produce an average 20% saving in nitrogen fertilizer.

Crops are inefficient in their uptake and use of fertilizer nitrogen with only 50% of applied fertilizer nitrogen taken up by non-legume crops such as corn and wheat and only 30-40% by paddy rice. Moreover, legumes such as soybeans show little yield response to applied fertilizer nitrogen. The nitrogen not used by the crop may contribute to environmental problems such as possible pollution of ground water and denitrification loss coupled with possible destructive effects of the nitrogen oxide denitrification products on stratospheric ozone (1, 24, 25). However, the scant data base precludes quantitative assessment of the significance of these possible problems.

UTILIZATION OF FIXED NITROGEN BY PLANT (2, 3, 7, 19, 21, 22, 28, 46)

Fixed nitrogen is actively taken up by plants. The rate for nitrate or ammonia uptake by corn is equivalent while information for amino acids and soluble organic nitrogen is unknown. Uptake is believed to be the limiting reaction for nitrogen utilization by the plant in the case of nitrate concentrations of normal soils with transport a possible limitation, while reduction is thought to respond to uptake and transport activities. The interaction of nitrate and ammonia on the uptake of each other is not defined. Ammonia at high concentrations is more detrimental to root growth than nitrate. Temperature influences uptake rate. Oxygen is required for nitrate uptake but the need for ammonia is unknown. Uptake is generally related to soil moisture. In most crop plants, the nitrate is transported to the leaves where it induces nitrate and nitrite reductases and is reduced to ammonia utilizing photosynthetic energy.

The ammonia is incorporated, probably by amination reactions to yield glutamine and glutamate with subsequent transaminations to produce the mixture of amino acids used for leaf protein synthesis. This step again utilizes photosynthetic energy. Subsequent proteolysis of leaf proteins during seed filling yields amino acids which are transported to the seed and resynthesized into the various seed proteins. Considerable proteolysis and resynthesis of enzymes may occur in the leaf and further add to the high demand of nitrogen metabolism for photosynthetic energy. About two-thirds of the plant nitrogen is harvested in the seed but this varies with varieties and, in general, has not been maximized. Factors controlling this partitioning are unknown as are also those controlling dry matter partitioning.

PROTEIN QUANTITY AND QUALITY

The amount and composition of the individual seed proteins and their relative proportion dictate the nutritional characteristics of the seed with respect to protein quantity and quality. Many crop plants are inadequate in protein quantity and/or quality for use by humans or monogastric animals. Quantity-deficient crops include rice and corn and, for some but not all uses, wheat. Although selections with higher protein content have usually been accompanied by lower yield, exceptions exist. Increased fertilizer nitrogen will increase protein content in some cases. Most crop plants are deficient in lysine, while soybeans and other pulses are deficient in methionine. Plant breeders have identified high lysine varieties of corn and sorghum which are nutritionally superior for humans and monogastric animals but are not yet widely accepted because of reduced yields and the absence of price premium. In fact, there may be a price penalty. Continuing work is attempting to overcome this severe limitation of reduced yield. In addition, simple, rapid and low-cost techniques are needed for measurement of protein quantity and quality so that farmers can be compensated (35).

GLOBAL NITROGEN CYCLE

Integration of N_2 fixation and related soil and aquatic transformations into the global N cycle has been achieved qualitatively but has only been approached quantitatively. For example, measurements of denitrification are extremely sparse because of the absence of adequate techniques and global nitrogen cycle values for denitrification are obtained by forced balance rather than measurement (Fig. 4).

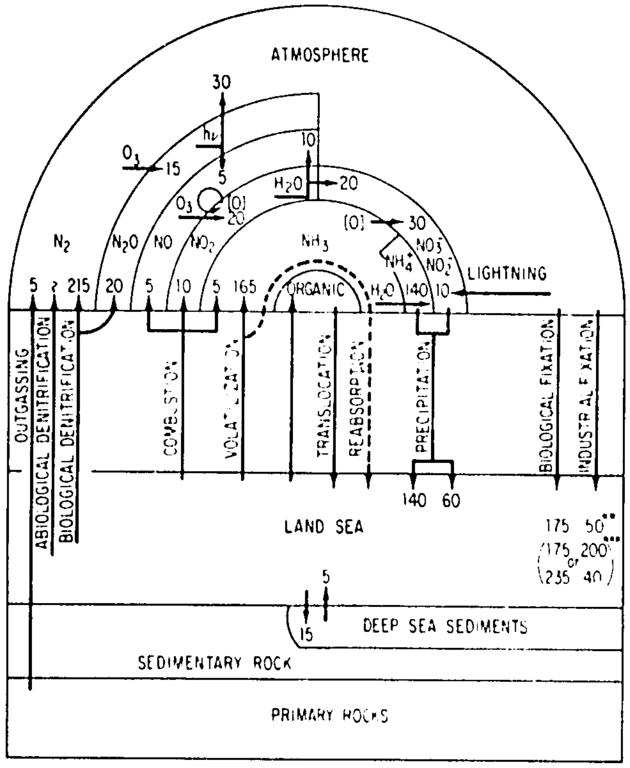
RESEARCH IMPERATIVES

I. MINIMIZE THE ENERGEY AND CAPITAL COSTS OF NITROGEN FERTILIZERS

The major limitation for fertilizer nitrogen manufacture are high energy cost and high capital cost which result in high economic costs for fertilizer nitrogen. This economic cost is a more severe deterrent in LDC's than in MDC's while the energy intensiveness may be a social deterrent in MDC's. In addition, the operational rate of nitrogen fertilizer factories in some of the LDC's is only about 60% of rated capacity vs. 80-90% for MDC's. The factors responsible for this inefficiency should be identified and procedures developed for corrective action. The proposed training in all aspects of nitrogen fertilizer production by the International Fertilizer Development Centre may be relevant.

One research imperative of priority 1 with

NITROGEN INTER-POOL TRANSFERS*



*EXPRESSED IN 10^6 OF METRIC TONS PER YEAR

**1974 RATE WITH 40 MM TONS USED AS FERTILIZER

***PROJECTED 2000 A D WITH RANGE OF COMBINATIONS OF BIOLOGICAL AND INDUSTRIAL ORIGIN

Fig. 4. Global nitrogen cycle. It is emphasized that the data base is limited and values for denitrification are forced to balance the cycle. From Hardy as in Fig. 1.

potential impact in the long term and two imperatives of priority 2 with impact in the short-term are recommended. Thirty percent of research emphasis on nitrogen input is allocated to these areas. A policy recommendation is also made.

A. DEVELOP CATALYSTS THAT WORK AT LOWER TEMPERATURES AND PRESSURES

A catalyst that fixed nitrogen at high rates under lower temperatures and pressures could reduce significantly the capital cost of nitrogen fertilizer plants and could also decrease the 40% of fossil fuel used as energy. Research is needed to identify possible routes to lower the temperature for catalyst operation from 400°C to 225°C and thereby achieve cost reduction.

Other research is needed to find new homogeneous or heterogeneous catalysts that fix N_2 under ambient conditions of temperature and pressure and in aqueous media as does nitrogenase and in a plant of minimal size. A catalyst that could function in an irrigation stream at field temperatures would eliminate transportation, storage, and applications costs In the long term even a fragment of nitrogenase that did not require ATP and was electrochemically reduced might be useful (42).

The development of a catalytic system to convert N_2 to ammonia under ambient conditions rests on the belief that N_2 is activated by ligating a transition metal. By inference, from knowledge of nitrogenase, the metal of choice is molybdenum although tungsten, iron, titanium, zirconium, and vanadium are currently under investigation. Little is known of the mechanism of the reduction of N_2 in its complexes or the active species in the solutions of vanadium. More research is required on these aspects and on the evolution of catalytic systems based on the reducible N_2 complexes.

Development of metal-complex catalysts relies also on the rather sparse knowledge of the metal content and function in N_2-fixing bacteria. More effort must be expended to increase this knowledge. Additional mechanistic studies of nitrogenase are needed. For example, knowledge of the structure of the active site for N_2 reduction and the definition of the role of Mo and Fe in this site and the changes in the valence of these metals during reduction would assist in catalyst design.

Biological N_2-fixing microorganismal factories utilizing agricultural wastes or solar energy in case of blue-green algae or photosynthetic bacteria may find application in the LDC's (38). Special mutants that are highly efficient in N_2 fixation and not inhibited by fixed nitrogen would be required. The practical feasibility of this approach should be evaluated.

B. IMPROVE PROCEDURES FOR ROTATIONAL-, INTER-, AND RELAY-CROPPING OF LEGUMES AND CEREALS

Intensive use of the limited arable land in both MDC's and LDC's has made the conventional rotational use of legumes as green manure crops impractical. It is recommended that plant breeding and cultural practices be investigated to establish systems of rotational-, inter-, and relay-cropping of legumes and non-legume crops that would minimize the need for fertilizer nitrogen and be consistent with high-yield agriculture. This technology should be implementable in the near-term. Some aspects such as inter-cropping may apply more to the labor-intensive low-cost, high-yield agriculture of LDC's than MDC's. Legumes that excrete fixed nitrogen for use by cereals or fix large amounts of N_2 in a short period may be useful.

C. DEVELOP BETTER RECYCLING PROCESSES TO RECOVER NITROGEN FROM WASTES

Research is recommended to develop low-cost methods of recycling wastes for agricultural use and to optimize the impacts of these wastes on crop production. Recycling of nitrogen-containing wastes in greater amounts would somewhat reduce the need for nitrogen fertilizers (40) but the positive environmental impact of recycling urban wastes would possibly be of greater importance. Although China is a most effective recycler of such wastes, it is noted that ten large nitrogen fertilizer plants are under construction there. This is the largest number under construction anywhere in the world.

D. POLICY FOR NATURAL GAS PRIORITY

It is recommended that high priority be assigned to the use of natural gas for nitrogen fertilizer production. Alternate energy and feedstocks are less efficient and require more costly plants (4, 17). Essential manufacturing processes such as nitrogen fertilizer production should be given priority over non-essential personal uses where substitutes may be used. The absence of a priority allocation of natural gas for fertilizer production may result in the operation of plants at low rates and the decreased productivity could lead to shortages of fertilizer nitrogen. In the long-term alternate feedstocks for nitrogen fertilizer manufacture utilizing coal technology or nuclear energy to supply power for electrolytic hydrogen production may replace natural gas, but in the near-term this technology is unavailable.

II. DEVELOP NITROGEN SELF-SUFFICIENCY IN CROPS

Some plants, notably legumes, have the capability to be at least partly nitrogen self-sufficient through symbiotic N_2 fixation. The prolific expansion of information on all phases of biological N_2 fixation during the last 15 years is providing a basis from which the degree of nitrogen self-sufficiency may be improved for legumes and expanded to include cereals and grasses (9, 12, 16, 30, 42). Exploratory research in its earliest stages suggests that N_2 fixation systems may exist or be developed for cereal grains and grasses (45). These possibilities will require continued in depth exploratory research on the catalytic mechanism, control, and efficiency of nitrogenase and associated reactions, genetics of regulation and transfer of *nif* genes, and physiological and agronomic studies of N_2-fixing microorganisms and their associated crop plants.

Experimentation with whole plants should emphasize the major feed and food crops and be performed under conditions of normal crop growth where possible vs. growth-room and greenhouse studies where the limitations may be different from the field. Different emphasis for developed vs. developing agriculture, temperate vs. tropical areas, and humid vs. arid areas is required with research priorities to be established on the basis of the major crops for each area. The desired sytems must support high-yield agriculture to be of major interest.

Three research imperatives are identified and a policy is recommended. Thirty percent of research emphasis on nitrogen input is allocated to these imperatives. All research imperatives are priority one with initial impacts on crop productivity ranging from the near-term to the long-term. Improved rhizobial technology will provide modest increases in the near-term while development of other associative symbioses for cereals and grasses and improved carbon input may provide major increases in the long-term.

A. DEVELOP OPTIMAL PLANT-MICROORGANISMAL COMBINATIONS

The legume-rhizobia N_2-fixing associations do not provide all of the nitrogen required by legumes and in the case of soybeans, provide an average of only 30% at a rate of 75 Kg N_2 fixed/ha·season (32, 34, 37, 41). The goal is to increase the amount of N_2 fixed to 600 Kg/ha·season. Major emphasis should be on soybeans as a grain legume, alfalfa as a forage legume, and various pulses used as foods in many LDC's. Legume and rhizobia genotypes should be matched for more effective N_2 fixation and yield. This matching should be done for the specific variables found in the area where the crop is to be grown. These variables include soil type, pH, and stresses of temperature and moisture.

Isolation and selection of new strains may be desirable. Since specific rhizobial strains are endogenous to various soils, the host variety might be matched with the endogenous strain. Inoculation technology is inadequate and practical methods need to be developed that would enable a superior applied rhizobial strain to outcompete inferior endogenous strains in the formation of N_2-fixing associations with the legume. Auxilliary requirements for formation and operation of the symbiosis such as mineral nutrition should be established.

High levels of fixed nitrogen such as occur in high fertility soils or following fertilizer nitrogen applications inhibit biological N_2 fixation. Genetic approaches should be used to develop strains of rhizobia that are not inhibited by fixed nitrogen. The recently discovered technique that enables rhizobia to fix N_2 in liquid culture in the absence of a legume host provides an experimental system for strain selection. The success in overcoming this inhibition in free-living N_2-fixing bacteria supports the achievability of this approach. (33, 38, 42).

Exploratory studies should identify the genetic and molecular determinants of rhizobial infection and development of the N_2-fixing symbiosis. Attempts should be made to increase the promiscuity of rhizobia with respect to host legumes. A single rhizobial strain which would form highly active N_2-fixing symbioses with all legumes would be advantageous. Additional examples of naturally occurring promiscuity such as the N_2-fixing *Trema-Rhizobia* association should be sought and used as tools to understand and expand promiscuity (42). In the long-term, the rhizobial association with legumes might be extended to non-legume crops.

Similar programs should be developed for non-rhizobial-based symbioses such as *Spirillum*-corn (45) when the evaluation of these systems justifies such studies.

POLICY

A center should be established in the U.S. to collect, assess, store, and distribute N_2-fixing organisms of current or potential application for crops (12). Initial emphasis would be exclusively on rhizobia with expansion to other N_2-fixing organisms when warranted. This centre should also have responsibility for quality control of commercial rhizobial inoculums. Quality criteria should be established with inputs from the public and private sector involved with rhizobia. Such control at the national level would guarantee a consistent high quality in inoculums. Such control has existed in Australia for some time. In addition, this centre should train technologists to work in the aspects of selection, production, testing, and distribution throughout the world. Consideration must be given to establishing systems for rhizobial manufacture and distribution in LDC's where the economics may not be attractive for commercial involvement without subsidy.

B. INCREASE PHOTOSYNTHETIC ENERGY FROM THE PLANT TO N_2-FIXING MICROORGANISMS ASSOCIATED WITH THE PLANT BY GENETIC AND CHEMICAL MEANS

Utilization of N_2 is costly to plants in terms of photosynthetic energy and establishes the necessity of cooperation between carbon input and nitrogen input research. The goal of this research is to increase the supply of photosynthetic energy that is available to the N_2-fixing organism so that the amount of N_2 fixed is increased and the yield of the crop is increased.

In the case of soybean and peas the provision of photosynthetic energy has been demonstrated to be a major factor limiting N_2 fixation. A variety of research approaches are recommended. Quantification of amount and time course of N_2 fixation and percent of total N from N_2 for important crop legumes, grasses, and cereals grown in the field where they are commercially grown under the various soil and climatic conditions is needed. The extent of photosynthate limitations for N_2 fixation by different types of soybeans, other grain legumes, and forage legumes should be determined. The production of seed requires an enormous drain on photosynthate supply. Legume cultivars need to be developed that are capable of providing photosynthate for both N_2 fixation and seed production. Improved morphology of leguminous plants may enhance the efficiency of photosynthesis. Genetic and chemical means to manipulate optimally the partition of photosynthate supply between seeds and nodules should be developed. The control of nodule sink activity should be identified. The efficiency of photosynthesis in leguminous plants and therefore N_2 fixation may be increased by selecting naturally occurring or man-made mutants with decreased photorespiration rates or by use of plant growth regulators. Photosynthetically efficient legumes may occur naturally in the tropics where the evolutionary pressures were probably the greatest. It is doubtful that practical methods can be found to increase the CO_2 supply to the canopy of legume plants.

Similar approaches will be needed in the case of the N_2-fixing associations in cereals and grasses. In fact, the key to the development of such associations with high rates of N_2 fixation may rest on the provision of high levels of photosynthetic energy in the proper chemical form. For example, Spirillum requires certain acids such as malate for optimal rates of N_2 fixation.

Studies of the nitrogenase reaction should seek opportunities for decreasing the energy demands which are probably the single greatest limitation of biological N_2 fixation. In theory, this reaction should be providing energy rather than consuming large amounts of ATP.

C. SEEK, EVALUATE, AND DEVELOP N_2-FIXING MICROORGANISMS FOR USE IN SUPPLYING NITROGEN TO CEREALS AND GRASSES

Recent observations in Brazil, France, the Phillipines, and the United States have established that diazotrophs may associate with various crops (31, 33, 42, 45). Some of these associations are of the rhizosphere type while one is intracellular. Most of the associated crops are of the C_4 photosynthetically efficient type, but some of the C_3 type have been found. These naturally occurring associations have been found with a limited amount of searching. It is recommended that organized searches in both the tropical and temperate areas of the world be made for additional examples. The existing and new associations should be evaluated. The evaluations should include measurements of N_2 fixation under in situ conditions and measurements of yield with appropriate statistical treatment. The current use of extended pre-incubations on excised roots or whole plants under reduced pO_2 may be misleading and must be replaced by in situ measurements before the significance of these associations in the field can be established. Development and application research should follow on the most attractive associations but may require novel inputs beyond direct inoculation.

III. MAXIMIZE EFFICIENCY OF USE OF SOIL NITROGEN AND FERTILIZER NITROGEN

The major goal of this work is to increase the efficiency of use of soil and fertilizer nitrogen from its average value of 50% for most cereal grains to greater than 75% (2, 3, 6, 7, 19, 21, 27, 36, 39, 46). The saving in economic cost and energy cost would obviously be great and of significance to both MDC's and LDC's. The goal may be achieved by genetic, chemical, and cultural practices which are compatible with $200/ton fertilizer nitrogen as opposed to earlier technologies that were developed on the basis of low-cost fertilizers. A smaller but economically viable goal is the development of technologies whereby legumes are made yield-responsive to fertilizer nitrogen. Legumes such as soybeans that were 50% efficient in use of fertilizer nitrogen would be economically attractive with a 4:1 ratio of value of additional yield to cost of nitrogen fertilizer. In addition, the harvest index for nitrogen in non-legumes and legumes should be maximized.

Soil nitrogen is constantly being depleted and replenished by natural processes (Fig. 3). Some soil nitrogen is readily available to plants but the majority of the nitrogen is unavailable. The concentration in soil of readily available nitrogen is usually insufficient to support high crop productivity. With the exception of the cultivation of legumes, nitrogen fertilizers are added to elevate the concentration of available nitrogen in soil. In theory, the same objective might be achieved with less fertilizer nitrogen by increasing the efficiency of uptake by crops, and/or by shifting more soil nitrogen into the available form while simultaneously increasing the rate of natural replenishment of soil nitrogen from atmospheric nitrogen. Such approaches are departures from the usual agronomic practice of adding fertilizer nitrogen when more nitrogen uptake is desired.

Another factor in over-all efficiency of use of nitrogen is the effective storage of crops after harvest. Although it is not a part of conventional crop production, it is noted, since much technological improvement is needed and possible in this area. Some crops have inherently poor stability, while others are exposed to fungi, insects, rodents, etc. It is inefficient to devise improvements in the chain from N_2 to harvested protein with a resultant gain in productivity and then throw away a sizable portion of the gain by storing the crop improperly. In the LDC's up to 30-50% of the harvested crop may be routinely lost by ineffective storage after harvest. Where an inherent storability problem exists, more research is needed to identify the problem and develop practical solutions. Where the problem is consumption of the stored crops by pests, better training of personnel to use existing pest management techniques and improvement of design of storage facilities may be useful solutions.

Three research imperatives are recommended. Thirty percent of research emphasis on nitrogen input is allocated to these imperatives. Two of these imperatives are priority one and the other priority two with impact occurring from near-term through long-term. In addition, extension activities are recommended whereby the available knowledge of efficient use of soil and fertilizer nitrogen which has immediate practical value is transferred to farmers and farm advisors. Application of this knowledge would have an immediate positive impact on food production and efficiency of nitrogen use.

A. IMPROVED UITILIZATION OF NITROGEN BY PLANTS THROUGH CHEMICAL, CULTURAL, AND GENETIC MEANS

Soil nitrogen occurs mainly as organic nitrogen, ammonia, or nitrate. Currently used fertilizers add either urea or ammonia (4, 6, 17). Nitrate uptake and utilization is considered to be the normal way that most land plants obtain nitrogen for making protein, nucleic acids, etc. However, conversion of the nitrogen in ammonia and urea to nitrate may not be necessary for its utilization by crop plants. The quantitative importance of direct utilization of urea and ammonia in the nitrogen nutrition of crop plants should be determined as should the influence of this parameter on crop productivity. There is a need to reexamine agronomic practices which were developed from studies of plants grown on nitrate now that ammonia and urea are the dominant chemical forms of nitrogen in fertilizer. Research on how plants obtain and use the nitrogen in urea and ammonia fertilizers is urgently needed. Optimal conditions for these processes in the field should be defined for the major crops.

An increase in the rate of uptake of nitrate (or urea or ammonia) without increasing the concentration of the compounds in the soil may be achieved by causing the plant to form and operate more uptake sites, or without changing the number of uptake sites, by causing the plant to make uptake sites with a higher affinity for the absorbable nitrogen in the soil water. The uptake of the main absorbable nitrogen forms should be further characterized. Root modification including deeper root systems may be useful. The regulation of these uptake processes and their genetic variability should be determined. Fast, simple, dependable uptake assays should be devised for use in screening for the desired genetic characteristics and seeking chemical effectors. Radioactive chlorate, which should be absorbed via the nitrate uptake site in chlorate-sensitive plants, should be explored as a possible means of rapidly assaying the activity of the nitrate uptake system. Cultural practices such as split applications or continuous addition in the irrigation stream or localized applications such as the mud-balling technique in LDC's should be developed to maximize the efficiency of use of nitrogen in a way that is compatible with labor cost.

A substantial portion of the nitrate taken up by a plant may be stored rather than utilized immediately. The physiological, developmental, and genetic factors governing the storage of nitrate should be determined with the objective of decreasing the stored proportion and increasing the total or protein yield.

The control point in the sequence of reactions between internal nitrate and protein is probably the reduction of nitrate to nitrite, catalyzed by the enzyme nitrate reductase. This enzyme is regulated in an elaborate and complex way. The role of the regulation of this enyzme in protein yield should be determined and exploited. The mechanisms which cause leaf protein to be degraded, the resultant amino acids to be translocated to the developing seed, and the developing seed to synthesize a given quantity of protein are not well understood. This information controlling the harvest index should be elucidated. It may be possible to modulate these processes by either genetic or chemical means.

B. MODULATE THE RATE OF SOIL NITROGEN TRANSFORMATIONS BY CHEMICAL OR CULTURAL MEANS

Soil nitrate can be lost by leaching, by conversion of N_2 and oxides of nitrogen which escape to the atmosphere, and by immobilization when it is converted to organic nitrogen by soil microorganisms. The availability of nitrate for movement from soil into plant could be improved by lowering the amounts of nitrate lost via these routes. Specific chemicals which decrease the activity of the soil microorganisms responsible for conversion of ammonia or urea to nitrate should be developed.

The pattern of nitrogen demand varies with the stage of development and the nature of the crop. Ideally the availability of nitrogen in the soil should match the pattern of demand. This could be achieved if chemical or cultural methods existed for stimulating and inhibiting the specific soil microorganisms responsible for the various nitrogen transformations which occur in soil. The first generation of such chemical regulators is beginning to be used in agriculture. Steps in microbial nitrogen transformations suitable for specific inhibition or stimulation should be identified.

A non-toxic inhibitor of soil urease activity might be useful. It would slow the conversion of urea to ammonia, hence slow the formation of nitrate and consequent loss of the nitrogen. Improved retardants of the ammonia to nitrate conversion might be equally valuable. Inhibitors of the denitrifying bacteria also might be of value for minimizing losses of nitrogen during flooding. Possible problems from these approaches might be lack of adequate selectivity or the inadvertent selection of resistant strains of the organism being controlled. Another approach is the use of slow-release fertilizers but problems of cost and manufacture for existing forms such as sulfur-coated urea limit broad-scale application. More economical forms are needed.

C. IMPROVES RATE DATE FOR EACH OF THE STEPS OF THE GLOBAL NITROGEN-CYCLE (1, 5)

Although the major components of the nitrogen cycle have long been known in a semi-quantitative way, quantitative data for the rates of movement of nitrogen through the various parts of the nitrogen cycle, the steady state concentrations of the components, and quantitative descriptions of responses to important types of perturbations of the nitrogen cycle are inadequate. Of the components of the nitrogen cycle, denitrification is most poorly understood with methodology inadequate, while additional measurement of N_2 fixation are needed. Quantitative information is needed for at least three levels of magnitude: the over-all global level, the local level for specific combinations of soil, crop, and agronomic practice, and the micro-environment level. The lack of such data is largely a reflection of inadequate analytical methodology. Monitors and analytical methods which can be used under field conditions need to be designed and developed.

The stable isotope, ^{15}N, and the short-lived, but in special cases usable radioisotope, ^{13}N, should be exploited to the utmost for determination of rates of interconversion of compounds in the nitrogen cycle. However, most of the experimentation will require the use of the somewhat expensive ^{15}N in large quantities under field conditions. This isotope expense is an unavoidable cost of obtaining the necessary data. Analytical centers at which scientists could have samples analyzed for ^{15}N content or could be trained in nitrogen isotope methodology should be established. The acetylene-ethylene assay will also be useful for measurements of N_2 fixation with greater sensitivity than ^{15}N-enrichment.

Novel approaches should be sought that would enable analysis and monitoring of the nitrogen cycle. Are there, for instance, physical or chemical properties of nitrogenous compounds or nitrogen-containing materials which allow one to estimate time since formation, e.g., properties analogous to those used by archeologists and geologists, but for a time scale of hours to months, rather than years to eons?

The quantitation of the processes of the nitrogen cycle and the factors which influence those processes will make possible the construction of more accurate models with greater predictive potential. Such predictive models are sorely needed to assess the impact of agricultural changes. For example, will the changing ratio of nitrate:ammonia:urea in soil produce undesired effects? The magnitude of the changes in the concentration of nitrogen oxides in the atmosphere from the projected quadrupling of production and use of fertilizer nitrogen should be determined as well as the significance on the concentration of ozone in the stratosphere. The impact on the flora and fauna of lakes, rivers, and seas should be assessed. The number of important questions which a well-based model of the nitrogen cycle could help to answer is very large. The answers to some of the questions could affect decisions pertaining to international and national policy, as well as to agronomic research, development, and practice.

IV. IMPROVE NUTRITIONAL CHARACTERISTS OF PRODUCT

Humans and monogastric animals cannot assimilate inorganic nitrogen to make protein, but rely absolutely on plants to incorporate the inorganic nitrogen into several essential amino acids. The nutritional value of diet staples is determined by the total quantity of amino acids in the food and the relative abundance of the essential ones. The nutritional value of many plant foodstuffs such as rice will be improved if the total protein content is increased while that of other plant foodstuffs such as corn or grain legumes will be improved if the content of the limiting essential amino acids (most commonly lysine and tryptophane in corn and methionine in grain legumes) is increased.

A. IMPROVED PROTEIN QUANTITY AND QUALITY IN CROPS BY GENETIC, CHEMICAL, AND CULTURAL MEANS

The amount of nitrogen a plant absorbs and uses to make amino acids and protein can be influenced by environmental, developmental, and genetic factors, but the mechanisms by which these factors express their effects are poorly understood and should be determined. The mechanism by which a plant is switched from making leaves to seeds should be identified to enable us to devise methods for slowing or accelerating the operation of this major developmental switch.

A plant which has switched from vegetative to reproductive growth draws on the leaves for nitrogen. The processes by which the leaves are depleted of nitrogen (and fixed carbon) and by which that nitrogen is transported into the developing seed to be used to make seed proteins are poorly understood. These phenomena are all of obvious importance in determining protein yield in seed crops. The magnitude of the importance of leaf senescence, seed development, seed protein synthesis, and differential expression of seed protein genes in the production of the major protein crops supports the need for additional exploration. Scientists skilled in study of protein synthesis and its regulation in microorganisms and animals should be encouraged to apply their skills and knowledge to these problems in the plant kingdom where there is a skilled manpower shortage.

The objective of improving protein quality in seeds seemed inherently very difficult from the genetic point of view, until it was shown that in maize, barley, and sorghum, genetically determined increases in the lysine percentage in the seed protein fraction resulted from changes in the proportions of the various proteins in the seeds. Thus, it appears that one key to changing the protein quality of seed protein is genetic variation in the regulation of the rates of accumulation of individual seed proteins. The regulatory system(s) for seed protein accumulation should be identified and means for selecting chemical regulators or regulatory mutations developed.

The discovery of genetic stocks of corn high in lysine has not solved the lysine problem. Research and development on implementation factors are necessary. How will a farmer be encouraged to grow high lysine corn or high protein rice? He must profit in some way. Ideally the price he receives for his crop would reflect the lysine or protein content. Simple, rapid, and cheap assays for lysine and other limiting amino acids as well as protein for use at grain elevators are needed. In addition, governmental regulation or some more subtle form of encouragement may be needed to assure production of cultivars with improved nutritional characteristics.

IMPLEMENTATION

A graduated and substantial expansion of research funding of exploratory activities in specific aspects of nitrogen input is needed to provide the opportunities for future development and application work. Most of this work should be done in the public sector while inadequate support in the past has forced the private sector to assume an unfair share of this work.

Developmental and application activities where the focus should be on seeking solutions rather than identifying new information should occur in both the private and public sector. Where the solution types are compatible with necessary objectives of the private sector in terms of economics and policy the work will be pursued by this section. Where the opportunity for protection by current policy is minimal such as non-hybrid genetic solutions, the work for the most part probably will occur in integrated public sector approaches. Alternatively, policy may need to be changed if it is desirable to obtain private sector participation. A large increase in funding will be required for this essential but more expensive developmental work where there has been negligible activity in the public sector in recent years. Current exploratory leads provide the basis for immediate work to develop solutions.

It is noted that crop productivity is an integrated function of all aspects of nitrogen input and other areas such as carbon input, stress, pests, soil and water relationships, and plant development and focussed interprocess approaches are not only desirable but essential. Changes may be needed to enable such interactions. These may include expanded team approaches at existing national and international centers of expertise or a new centralized group to which the necessary diverse skills would be assembled from centers of expertise for a period of time to solve specific problems, e.g., to seek, evaluate, and develop new N_2-fixing associations for cereal grains and grasses. The establishment of a permanent single national institute for research on nitrogen input into crops was not recommended unless adequate support was provided to assure the continuance of diverse approaches by other smaller but less focussed groups.

IMPLICATION

Since nitrogen is a common denominator for all crops and a limiting factor for their production, success in each of the four major research imperatives would have impact on all of the major food and feed crops in both the MDC's and LDC's. The huge current economic cost of \$8-\$10 billion for fertilizer nitrogen would be reduced or its rate of increase slowed.

A 50% improvement in the effiency of use of fertilizer nitrogen would shave the world bill for nitrogen fertilizer by \$3 billion. The figures become even more dramatic for the year 2000 A.D. where the saving would be about \$10 billion based on current prices. There is, of course, a proportionate saving in energy and a reduction in possible negative environmental effects of the products of inefficiently utilized fertilizer nitrogen. Alternatively, improved technologies for manufacture could achieve similar economic and energy benefits. Self-sufficiency in provision of nitrogen could also achieve similar or maybe even greater economic, energy, and environmental benefits. Another major area of benefit is the increased productivity made possible by technologies that will make available the greatly increased amounts of fixed nitrogen. Provision of ever-increasing quantities of fixed nitrogen to crops has been one of the most significant factors in increasing crop productivity and will continue be in the future.

In addition to improved crop productivity and decreased costs in terms of economics, energy, and possibly environment, success in the identified research imperatives would increase the nutritional quantity and quality of the product. However, a new era of human nutrition which has been relatively dormant in the post-vitamin and amino-acid era will be required to provide more definitive guidance to the crop scientist in terms of the specific needs for long-term health.

SUMMARY OF RESEARCH IMPERATIVES FOR INCREASING CROP PRODUCTIVITY THROUGH IMPROVED OR ALTERNATE TECHNOLOGIES FOR NITROGEN INPUT

I. Minimize the Energy and Capital Costs of Nitrogen Fertilizers (30%)

A. Develop catalysts that work at lower temperatures and pressures (Long-Term, Priority 1).

B. Improve procedures for rotational-, inter-, and relay-cropping of legumes and cereals (Short-Term, Priority 2).

C. Develop better recycling processes to recover nitrogen from wastes (Short-Term, Priority 2).

II. Develop Nitrogen Self-Sufficiency in Crops (30%)

A. Develop optimal conditions for plant-microorganism combinations (Short-to-Long-Term, Priority 1).

B. Increase photosynthetic energy from the plant to N_2-fixing microorganisms associated with plant by genetic and chemical means (Mid-Term, Priority 1).

C. Seek, evaluate, and develop N_2-fixing microorganisms for use in supplying nitrogen to cereals and grasses (Mid-to-Long-Term, Priority 1).

III. Maximize Efficiency of Use of Soil Nitrogen and Fertilizer Nitrogen (30%)

A. Improve utilization of nitrogen by plants through chemical, cultural, and genetic means (Mid-to-Long-Term, Priority 1).

B. Modulate the rate of soil nitrogen transformations by chemical or cultural means (Short-Term, Priority 1).

C. Improve rate data for each of the steps of the global nitrogen-cycle (Mid-Term, Priority 2).

IV. Improve Nutritional Characteristics of Product (10%)

A. Improve protein quantity and quality in crops by genetic, chemical, and cultural means (Mid-Term, Priority 1).

Policy Matters

Priority for allocation of natural gas for fertilizer production.

Technology center and quality control for N_2-fixing microorganisms.

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CARBON INPUT

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INTRODUCTION

The importance of carbon imputs in crop productivity is self-evident, since 95% of the dry weight of plants is derived from photosynthesis. The limitations of photochemistry, the biochemical events associated with the carboxylation reactions of photosynthesis, and subsequent events that lead to the synthesis of various products all contribute to the regulation of photosynthesis. Net photosynthesis is affected by the reactions occurring within the chloroplasts as well as by reactions taking place in other parts of cells and even in other organs far removed from the leaf.

Increasing net photosynthesis and realizing more efficient partitioning of the products of photosynthesis into food products of high nutritional value constitutes a logical strategy for increasing crop productivity. Accomplishment of these goals will require cooperative effort of scientists of diverse disciplines and backgrounds including biophysicists, biochemists, plant physiologists, crop physiologists, crop ecologists, geneticists, and plant breeders. The present knowledge and promising areas of research that might be exploited to increase the carbon input in crops, and hence yield, are set forth below.

I. BIOCHEMICAL CONTROL OF PHOTOSYNTHESIS

LIMITATIONS ON CO_2 ASSIMILATION BY THE CARBOXYLATION REACTION

Photosynthetic CO_2 uptake by leaves of many species is saturated at irradiances about one-fourth of full sunlight, indicating that the biochemistry of the carboxylation reaction or physical diffusion resistances limit the rate of photosynthesis[1] and that the photochemical reactions supply sufficient ATP and NADPH needed for CO_2 assimilation. With isolated spinach chlorophasts at atmospheric CO_2 concentrations, it appears that the potential for carboxylation, rather than the rate of photosynthetic electron transport, (13) limits CO_2 fixation, although at saturating CO_2 concentrations electron transport is limiting (14).

Evidence that the photochemical reactions are not limiting at high irradiation comes from the observation that increasing the CO_2 concentration from that normally found in air (320 ppm) to 600 to 1,000 ppm doubles the rate of CO_2 uptake in many C_3[2] species (15). Smaller increases are also observed with increasing CO_2 concentration even in species such as maize (16) which do not ordinarily show light-saturation. Thus increasing carboxylation efficiency should increase the potential for photosynthesis.

Net photosynthesis in some plants increases when grain (17,18) or tubers (17, 20), which serve as "sinks" for the products of photosynthesis, are formed. A decrease in

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[1] This document is a summary of the deliberations at the Crop Productivity Conference of the scientists listed hereafter. A few reviews (1-12) are listed at the conclusion of the text to which the reader can refer to find specific original sources.

[2] Three biochemical systems have been discovered for reducing carbon dioxide in higher plants. Two of these are symbolized by whether the first stable product of CO_2 fixation contains 3 carbon atoms (C_3) or four (C_4). The third system is called Crassulacean Acid Metabolism (CAM) because it was first studies in the plant family Crassulaceae.

photosynthesis is often observed when the "sink" is removed (21-23). This suggests that net photosynthesis may be controlled by a feedback signal from the fruits or other "sinks" to the carboxylation reaction sites. Changes in enzymatic carboxylation rates caused by the presence of low concentrations of certain phosphorylated carbohydrates have been demonstrated (24-26). It is not known whether such controls of the carboxylation rates occur in intact leaves. The pool sizes of such metabolites in leaves under different conditions have not been measured adequately.

The chloroplast is a simpler system than intact leaves for studying the enzymes of carboxylation and the other reactions of the photosynthetic carbon reduction cycle. Many investigations on regulation of CO_2 fixation have thus far been limited only to chloroplasts isolated from young pea and spinach leaves, where rapid rates of CO_2 fixation are obtained (27-29). Chloroplasts from other leaves have low activity, perhaps because of isolation difficulties. The mechanisms for regulating CO_2 fixation may vary among species, among cultivars within a species or at different stages of plant development. No information is available about these important questions. Chloroplasts capable of fixing CO_2 have been isolated from a C_4 species (maize) but the rate was low compared to those isolated from a C_3 species (30). However, the regulatory mechanisms were similar in the two kinds of plastids. Obtaining active chloroplasts from numerous plant species at various leaf ages could help in studying the regulation of photosynthesis.

LIMITATIONS ON CO_2 ASSIMILATION BY LIGHT REACTIONS

Although leaves of many species become light saturated at higher light intensities, many crop canopies show increasing photosynthesis with increasing light up to full sunlight (31). This occurs because most leaves in the canopy are shaded and are therefore not light-saturated. At low irradiance, the rate of photosynthesis is controlled by the maximum quantum yield (32). Thus, photochemical efficiency might be limiting in shaded leaves, although this would probably not be important in the overall carbon budget. Under drought, however, there is evidence that, in addition to the increased stomatal diffusive resistance, leaf water deficits also cause an inhibition of photosynthetic electron transport (33). It is possible that low temperature also affects photosynthetic electron transport adversely. Research needs to be done to determine the sensitivity of light reactions to non-optimal environmental conditions.

Reduced ferredoxin, an intermediate product of photosynthetic electron transport (34), is used in the reduction of sulfate, nitrite, and oxidized ferredoxin in desaturation of fatty acids. Thus the photochemical reactions may be important in providing products besides ATP and NADPH and may affect the nature of the products resulting from photosynthesis. For example, the ratio of ATP/NADPH may control the proportions of protein and starch produced. Thus, control of photosynthetic electron transport may have indirect effects in directing carbon into specific products.

PARTITIONING OF PHOTOSYNTHATE AND REGULATION OF PHOTOSYNTHESIS BY RATE OF TRANSPORT

It is not certain whether the carboxylation and reduction reaction rates are the only limitations to photosynthesis by chloroplasts. There is evidence that the chloroplast envelope membrane is permeable only to some metabolites. An inability to transport sucrose, for example, is characteristic of isolated spinach chloroplast envelope membranes. On the other hand, some metabolities which enhance or inhibit carbon assimilation enzymes in chloroplasts are transported across the envelope membrane with apparent ease (35-37). Thus the degree of permeability of the chloroplast to selected metabolites may control CO_2 assimilation. It is important to know whether chloroplast permeability in different cultivars and species is sufficiently different to account for differences in CO_2 assimilation. If so, it may be possible to alter the properties of the chloroplast envelope membranes. The transport of metabolites to and from other organelles such as mitochondria and peroxisomes may control carboxylation rates. Differences in transport properties between mesophyll and bundle sheath chloroplasts or other organelles in C_4 species may be related to the rapid fixation of CO_2 which occurs in these plants.

EFFECTS OF DEVELOPMENTAL STAGE ON REGULATION OF CARBON METABOLISM

The regulation of carbon input has been studied most often in plants grown under a single set of environmental conditions, with measurements made at one tissue age or during one development stage. Mechanisms of regulation may differ in tissues of different ages. Regulation of carbon metabolism may vary in tissues of plants grown under different environmental conditions. In fact, this regulation may be a part of the adaptive mechanism of plants to environment. Currently, there are limitations of techniques (isolation of organelles, for example) that prevent the pursuit of these problems.

ADVERSE EFFECTS OF OXYGEN ON PHOTOSYNTHETIC REACTIONS.

Oxygen has an inhibitory effect on net photosynthesis of C_3 species, partially because of its stimulation of photorespiration (1, 5, 6, 10, 12). At low light intensities, where the light-response curve for net photosynthesis is linear, and at 0.03% CO_2, increasing oxygen in the atmosphere from 1% to 21% inhibits photosynthesis about 35% (12). The inhibition is reversed within seconds by increases in CO_2 concentrations. Light-limited photosynthesis is believed by some investigators to be increased more than can be accounted for by reduced photorespiration when the O_2 level is lowered from 21% to 1% (38). This suggests that there is an inhibitory effect by O_2 on the light reaction. It is important to learn the nature of this inhibition and possibilities for its regulation.

The photosynthetic activity of isolated chloroplasts is rapidly lost in the light when CO_2 is depleted (39). It is known that O_2 can react with chloroplast components in the light to produce damaging hydrogen peroxide and the superoxide radical (40). Ascorbate and other natural substances protect isolated chloroplasts against the damaging photooxidative effects. Photorespiration may be a mechanism for reducing O_2 concentration in cells, thereby offering protection for chloroplasts. The role and regulation of anti-oxidants in green tissues requires further study.

II. DARK RESPIRATION AND PHOTORESPIRATION

Respiration is essential for many physiological processes, but the respiratory losses of carbon are large and it appears in some instances that these losses are wasteful (41). Decreasing respiration would result in increases in net photosynthesis (42). The elimination of wasteful respiration is a goal which should be pursued vigorously.

Dark respiration may consume 30 to 70% of the net carbon assimilated during photosynthesis (12). While much of this respiratory activity is undoubtedly tightly coupled to essential energy requiring metabolism, a large portion may be released by an alternate pathway of electron transport that only produces one-third as much ATP as the standard pathway (41). There is good experimental evidence that respiration by the alternate pathway (cyanide- and antimycininsensitive but sensitive to salicylhydroxamic acid) occurs to an appreciable extent in many plant tissues (43). This pathway, when dominant, diminishes growth in fungi, for example, in the so-called "poky" strains of *Neurospora* (44); it also may diminish growth rates in higher plants. It is important to learn how much of the respiration of leaves occurs by the alternate pathway, especially in C_4 species where photorespiration is already slow. The effect of removing the alternate pathway might be a more efficient coupling of respiration and energy-requiring processes. Carbon losses caused by dark respiration may be decreased by exporting photosynthetic products more rapidly from leaves. Studies are needed on the energy requirements for transport of photosynthetic products and possible respiratory sources of such energy.

Photorespiration of C_3 species in bright light is much faster than dark respiration at temperatures of 25° or higher (12, 45). There are numerous experiments showing that decreasing photorespiration will increase net photosynthesis in C_3 species by 20 to 50%. Although the regulation of photorespiration appears to be a promising means of obtaining large increases in carbon input, a number of important questions about the process of photorespiration and its control remain.

The ratio between photorespiration and net photosynthesis in C_3 species is reported by some workers to be constant (46, 47), while others claim that the ratio varies among plants (48) and during leaf development (49). These contrary results could be caused by uncertainties in the validity of the photorespiration assay employed. Cultivars of C_3 species might be obtained in which this ratio is different. It may be possible to develop biochemical inhibitors which will decrease photorespiration and increase net photosynthesis.

Glycolic acid is implicated as the primary substrate of photorespiration. It is synthesized rapidly in the chlorophasts of C_3 plants, but apparently only slowly in C_4 plant chloroplasts (1, 50). The manner by which glycolic acid is synthesized is a matter of controversy. Some workers believe that the ribulose diphosphate "oxygenase" reaction can explain all of the data in the literature relating to glycolic acid synthesis (51-53) while other argue that multiple biochemical reactions are involved in its biosynthesis (50, 54, 55). Decreasing the rate of glycolic acid synthesis is an obvious method for reducing photorespiration. The reactions by which the carbon atoms of glycolic acid are oxidized to CO_2 and the question of which organelles are involved in photorespiration is also controversial. A better understanding of the sites and mechanisms of photorespiration is required.

There may be some advantages to photorespiration, but its usefulness is not apparent. C_3 species which have rapid photorespiration, generally have lower temperature optimums for photosynthesis than do C_4 species (12). Is this correlation a valid one? Does photorespiration have some maintenance or protection function? Can C_3 species or cultivars be found that already have the characteristic of a slowed photorespiration? It appears that biochemical and genetic studies will be needed to answer such important questions.

Since the increased net photosynthesis of C_4 plants can be partially attributed to decreased rates of photorespiration, achieving slower photorespiration in C_3 species seems worthwhile. To determine if that is true also will require both biochemical and genetic investigations.

III. PLANT GROWTH REGULATORS AND CARBON INPUTS

Growth rate and morphology of plants are two important determinants of crop productivity. The relation to growth of the rapidity of plant establishment, the rate of leaf expansion, the orientation of the leaves to light, the ratio of newly expanding to senescing leaves, and the leaf-shoot ratio are but a few examples. Further, the anatomy of leaf photosynthetic tissue and of the vascular system are related to photosynthetic efficiency. For many crops, altering morphological characters or developing genotypes adapted to greater planting densities has potential for increasing the photosynthetic productivity of crop canopies. Many of the above characters are under hormonal as well as environmental control.

REGULATION OF PHOTOSYNTHESIS BY TRANSPORT AND PARTITIONING

Numerous studies have shown that the rate of photosynthesis may be affected by flowering, fruiting, or bud break (56, 57). The so-called "sink" effect has been demonstrated in numerous plants and the involvement of several hormones such as indoleacetic acid, cytokinins, and gibberellins in the sink effect is now well established (58-60). Often an increased capacity of the the sinks to accept photosynthate increases net photosynthesis and the activities of competing sinks may determine the partitioning of photsynthate among different plant organs. Partitioning can occur at several points in the transport path (61). Within the leaf, photosynthate is divided between storage and export. Once out of the leaf, photoythate is partitioned among all competing sinks. The mechanism of phloem unloading into the sink and how it is controlled is poorly understood (62). The effect of the sink appears to be more temperature sensitive than is photosynthesis; hence, the limitations of sink activity may slow the expansion of leaves in cool environments in early spring. Hormones may influence the rate of transport to the grains or affect loading and unloading of photosynthate in the phloem and thus indirectly affect photosynthesis. We need a better understanding of how sinks control transport and synthesis in plants and their relation to crop productivity.

In most crop plants sucrose is transported from the green cell to the sink; yet there is evidence that sucrose does not pass quickly through the chloroplast envelope membrane. In sugar beet and corn, sucrose is broken down to hexoses before entering the storage organ and resynthesized after entrance. Knowledge of the nature of metabolites moving from the chloroplasts to sinks and the necessary biochemical conversions in the transport pathway is important in determining limitations of transport on yield.

EFFECT OF LEAF SENESCENCE ON PHOTOSYNTHESIS

The senescence of leaves, especially since it often occurs while the food product is being produced, appears to limit yields in many crops. It is not known whether senescence occurs because of competition for assimilates and inorganic nutrients or because of a "death signal" controlled during development. Senescence may sometimes be delayed by supplying additional nitrogen to plants. Some examples are also known in which the application of hormones or other chemicals delays leaf senescence (63). However, we do not understand how to control senescence in crop plants in the field. Further research is needed to permit an extended duration of photosynthesis in different species grown in a diversity of environments. There is evidence that the synthesis of ribulose diphosphate carboxylase ceases in some species when leaf expansion is complete and this surely limits photosynthetic potential in these species. Is this a general constraint and can it be regulated?

Finally, it should be asked whether increasing photosynthesis will be even more beneficial in crop productivity when coupled to an increase in the number of seeds set in grain cereals. Can hormones prolong or enhance chloroplast activity? Would this help produce a greater number of seeds per plant? How does photosynthesis interact with hormones controlling sink size? What feedback signals from sinks affect photosynthesis and senescence? These important topics must be studied.

IV. GENETIC ASPECTS OF CARBON METABOLISM

VARIATIONS IN NET PHOTOSYNTHESIS AMONG GENOTYPES

Variations among genotypes within a species in the rate of net photosynthesis per unit leaf area or dry weight are often observed. Sometimes varieties with high net photosynthetic rates have superior yields. In wheat however, cultivated varieties have lower rates of leaf photosynthesis per unit leaf area than do wild species, but the leaf area per plant is much greater (64). Thus increasing the unit leaf rate of net photosynthesis alone may not always be beneficial; attention must be given to the capacity of the entire photosynthetic factory of the plant. Nevertheless, the rate per unit leaf area is one aspect of the plant's productive system which can be measured and selected for in a breeding program, and the role of photosynthetic rates of leaves in crop productivity needs evaluation.

Variations in rates of net photosynthesis per unit leaf area among genotypes have not generally been analyzed to determine whether the effects were caused by differences in such factors as stomatal diffusive resistance, respiration, carboxylation efficiency, or response to irradiation. We need to understand how genetic differences in leaf photosynthetic rates are achieved and to evaluate how leaf photosynthetic rates and leaf area interact in carbon inputs in yield. Can the size of the factory and the rate at which it operates be manipulated independently to develop higher yield potential?

If plants breeders were able to identify genotypes with greater net photosynthesis it seems probable that these genotypes would be superior parents to be used in crossing. Plants with a large capacity for photosynthesis are surely superior in yield potential to those which have low capacity. The chances of obtaining higher yielding cultivars would surely be more likely when the selection is aided by screening for characters which contribute to high yield potential than if selections are made for yield alone. There is a great need for assay techniques which could be used for this purpose.

Plant breeders can manipulate such factors as leaf angle (65, 66), leaf orientation (67), leaf anatomy, leaf stomatal frequency (68, 69) and the harvest index (70, 71).

The capture of photosynthetic radiation by the crop canopy, the distribution of radiation within the leaves of the canopy, and the response of individual leaves of environmental factors are important in affecting net crop photosynthesis. Yield may be increased by genetically changing these indirect factors.

USE OF TISSUE CULTURES TO INCREASE NET PHOTOSYNTHESIS

Recent advances in somatic cell genetics provide a new tool that may be useful for obtaining increased CO_2 assimilation (72, 73). It is possible to grow isolated tobacco cells photoautotrophically (74). This provides an opportunity to select cells directly that have superior photosynthesis if, for example, they can tolerate higher than normal levels of oxygen in the atmosphere. One limitation in the use of tissue cultures at present is working out methods of selecting superior mutants, and accomplishing regeneration of intact plants in cells of important crop species. A major difficulty in devising selection systems in cell cultures arises from inadequate knowledge about important biochemical pathways in higher plants and their regulation. This knowledge is badly needed.

The opportunity may also exist in the future to introduce foreign genetic information into plants by transfer of organelles (chloroplasts or mitochondria). No information is available concerning the potential of these untried genetic tools.

V. ENVIRONMENTAL CONTROL OF PHOTOSYNTHESIS

Of the environmental factors which limit photosynthesis, it is obvious that temperature extremes, water stress and mineral nutrition are major limiting environmental parameters; no consideration of carbon metabolism can ignore their effects.

DIFFUSIVE RESISTANCE CONCEPT

The effects of various environmental factors on net carbon exchange by leaves have been analyzed successfully, in some instances, by use of diffusion theory. For plant leaves, the main port of entry and egress of gases is through stomatal pores. Many factors have their major effect on photosynthesis by regulating stomatal opening. These effects have been analyzed by considering the flow of gases in the leaf-atmosphere system to be analogous to current flow in dc circuits, where the gas concentration gradients are analogous to potential gradients and the barriers to diffusion (diffusive resistances) are analogous to electrical resistors (75, 76). The leaf-air system can then be described by an equation analogous to Ohm's law. Several forms of such equations are in the literature but all divide the system into a series of resistances which represent portions of the diffusion pathway on which measurements can be taken. In general,

$$P = \frac{(\Delta CO_2)}{r_a + r_s + r_m}$$

where P = the net exchange of carbon dioxide;

ΔCO_2 = the gradient of CO_2 from the bulk atmoshere to the reactive sites inside the leaves; and

r_a, r_s and r_m = the apparent diffusive resistances of: the air layer near the leaf; stomata; and a residual quantity called "mesophyll resistance".

Analyses using this system have shown the controlling role of stomata over the photosynthetic process as affected by such factors as water stress, light intensity, CO_2 concentration, temperature, mineral nutrients, certain chemicals and some endogenous growth regulators. Many of these factors have striking effects on the "mesophyll resistance" also, indicating they affect the enzymatic processes inside the leaf.

The mesophyll resistance is composed of many factors including physical diffusive resistances in the mesophyll cells as well as the chloroplast, limitations of photochemistry and enzymatic carboxylation, and even respiration. The contribution of each of these components of mesophyll resistance under different environments and their possible regulation needs extensive study.

EFFECTS OF ADVERSE ENVIRONMENTS ON CARBON INPUT

A major problem with increasing crop productivity under limited water availability is caused by the paucity of research relating physiological behavior to crop yield. We have mentioned earlier that water deficits appear to damage the light reactions of photosynthesis. Under some conditions the translocation mechanism apparently is adversely affected.

In nature, there are certainly wide differences in the ability of plants to use water efficiently.

In some enviornments, C_4 species require one-half as much water per unit of dry matter produced as do C_3 species (77). Understanding of the differences in water use efficiencies of plants will become increasingly important as water becomes more limited.

We can select plants for chilling insensitivity. One effect of chilling temperatures on plant growth may be due to subsequent failure of leaf stomata to open. A chilling-insensitive ecotype may be able to produce a greater yield in cold temperature environments. Much can be gained by better matching genetic varieties to their environment.

High temperatures may cause deposition of callose in phloem and thus slow translocation. Ecotypes can be chosen that are more heat tolerant.

The physiological basis for adverse environmental effects on carbon metabolism should be amenable to genetic regulation. Genotypes can be selected that are superior in given environments and the potential is much greater than has yet been realized. Better understanding of the physiological basis for the adaptation of plants will provide a basis for great advances in this area.

Modern computer technology offers hope that plant response to the bewildering arrays of environmental factors which they experience in the field can be summarized in realistic models (78-81). In modeling the effects of environment on carbon inputs to yield, an attempt is made to describe mathematically our best understanding of how each environmental factor affects growth. The successful models will be those which model at one level of organization and summarize at a higher level, for example, model biochemical reactions to summarize leaf growth or model plant organs' response (leaves, stems, etc.) to summarize crop canopy growth.

If the inputs are adequate and the assumptions made by the modeler are sound, the value of models is great in showing where our understanding of how plants grow is inadequate. However, more widespread access to benefits of the better models needs to be provided. Interpretive structural modeling can be used to organize our understanding of complex systems even when dynamic modeling is not yet possible.

Empirical models of systems offer little promise of aiding our understanding of carbon inputs to crop yield. Under this category come such things as describing crop canopy carbon inputs as a function of time within the growing season or other simplified descriptions of crop yield factors. Models, if they are to be useful, must deal realistically with the complexities of the environment in which plants grow.

VI. RESEARCH IMPERATIVES

As an international group of scientists representing several disciplines related to crop productivity, we recognize the seriousness of the world food problem and the urgency with which we must face the responsibility of markedly increasing food production. We note that our understanding of the regulation of carbon input is incomplete, and that this information is essential to increase in crop production through genetic and chemical modification of plant growth.

In many parts of the world crop yields have increased sharply in recent years; for example, national average per acre corn yields in the United States have approximately doubled since 1950. Such progress may lull us into believing that a doubling of crop productivity in the next 25 years offers no particular challenge to the plant scientist. We must analyze carefully, however, where the food will come from to meet the needs of the earth's rapidly expanding population.

The scientists discussing the topic of carbon inputs to crop productivity recognized two facets to the awesome task ahead. Perhaps crop productivity in the Developing Nations can be increased markedly by utilization of technology and knowledge that even now is available. The group was not able to deal quantitatively with that possibility. However, it is unlikely that the entire solution to the world food problem lies in the Developing Nations. Crop yields in all countries must increase sharply.

To see more clearly the task ahead it is well to consider that the per acre yield increases in many crops such as corn have been accomplished by developing varieties in which the ratio of food to crop residue is high and which respond well to dense plantings and high fertility. When diseases and insects are controlled and the fields are kept weed-free, only small yield gains can be expected from further progress in these aspects of crop productivity. In contrast, little of the increased yield has come from enhanced capacity or efficiency of the plant's photosynthetic factory. Therefore, further marked gains in crop yielding ability must be obtained largely from changes in the intrinsic ability of plants to produce food.

We, therefore, recommend that research be expanded in the following areas:

I. Identify the aspects of photosynthesis which limit CO_2 input in natural environments.

a. Interception and Utilization of Light: Crop photosynthetic productivity is strongly influenced by growth rates of leaves, leaf angle, leaf lifetime, and photosynthetic capacity. Research is needed to determine how these factors interact and the degree to which they can be exploited to increase photosynthetic productivity per unit field area.

b. CO_2 Absorption: The opportunities must be explored to increase the rate of CO_2 fixation in plants by altering leaf stomatal characteristics, cell size and shape and components of the transport system of plants.

c. Biochemical Processes of Carbon Metabolism: Emphasis should be placed on characterizing the properties of the enzymes of CO_2 fixation and subsequent metabolism. How are these enzymes controlled, and what are the limits within which they can be altered? The limitations imposed by electron transport processes should be determined. The role of photorespiration and its relation to photosynthesis and plant growth must be evaluated. The range of enzyme variation in natural ecosystems should be determined with particular emphasis on the different biochemical systems for photosynthesis in the C_3, C_4, CAM type plants.

The roles of respiratory processes in carbon input in plant productivity should be examined. The environmental responses of rate-limiting steps in carbon metabolism should be studied. Genetic basis of these processes and chemicals to modify them need to be identified.

II. Relationship of plant development to photosynthesis: We need to know how photosynthesis influences plant growth and which developmental stages of crop plants are limited by the availability of products of photosynthesis.

a. Translocation and Partitioning: Studies are needed on the transport process in crop plants and on the partitioning of photosynthetic products among the sites of utilization such as fruits or other storage organs or sites of nitrogen fixation. We need to know the mechanisms and controls that determine whether photosynthate remains in the leaf cell or moves into the phloem and on to sites of storage or utilization.

b. Hormonal and Chemical Regulation in Crop Plants: Both basic and applied research on plant growth regulators is needed. What plant hormone systems are involved? What are the signals between cells and plant organs? Which signals control plant productivity and how can the signals be altered? Synthetic growth regulators and genetic means should be developed to modify beneficially the production, internal partitioning, and storage of carbon compounds in plants.

III. Provide Plant Breeders with New Screening Procedures: Research is needed to provide plant breeders with rapid screening procedures which would aid in identifying and incorporating yield-enhancing carbon input characteristics into crops.

IMPLEMENTATION

The need for a vastly increased capacity to product food within one or two decades dictates three strategies to exploit the potential for increasing photosynthetic productivity through the research areas outlined above.

STRATEGY 1: In order to set in motion the full potential of the research community, we recommend that sufficient funding be provided to national granting agencies so that all meritorious proposals for research on photosynthesis and associated metabolic processes related to crop productivity can be supported.

STRATEGY 2: Long term funding must be made available so that individual or team efforts may be pursued to a logical conclusion utilizing sound ideas for research on carbon inputs to crop production. This program should include significant increases in funds for new and ongoing photosynthetic research projects, but also should include career development awards, postdoctoral and graduate fellowships.

STRATEGY 3: Funding also must be made available to develop strong research teams whose efforts are devoted to commodity-specific, site-specific, mission-oriented goals of developing superior crop varieties. These teams will work not only with carbon input but also may well include nitrogen input, stress and pest research and deal in general with the ecology of crop plants in specific environments.

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WATER, SOIL

AND

MINERAL INPUT

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The total area of potentially arable land on earth, estimated (1, 2) at 3.2 billion hectares (ha), is more than twice the area cultivated at some time during the last few decades. About 44% of this area is cultivated at some time, possibly 30% is harvested in any given year. About half of the potentially arable land, over 1.6 billion ha, lies in the tropics - divided roughly equally among the humid, subhumid and (semi) arid tropics (Tables I and II).

The bulk of the arable land not yet developed is not located where the major concentrations of population are found (Table III). Thus, though the potentially available land is not now limiting, its distribution relative to population presents major problems. While the potential for increasing net cultivated area in Europe and Asia is small, availability of water is more likely to prove the limiting factor than the availability of suitable soil in developing adequate areas of land for agricultural production near areas of high population density.

An intensive study in 1967 (1) found that, "of the total potentially arable land in the world, about 850 million acres (345 billion ha) or 11 percent of the total required irrigation for even one crop. In the remaining nearly 7 billion acres (2.85 billion ha), at least one crop could be grown without irrigation, and over a considerable region, multiple-cropping is possible. Without irrigation,

Table I. World land area in different soil groups

[In billions of hectares]

Soil group	Potentially arable		Grazing		Nonarable		Total	
	Hectares	Percent	Hectares	Percent	Hectares	Percent	Hectares	Percent
1. Tundra	0	0	0	0	.52	3.9	0.52	3.9
2. Desert	0.43	3.3	0.91	7.0	.78	5.9	2.13	16.2
3. Chernozem and brunizem	0.50	3.5	0.28	2.2	0.07	.5	0.82	6.2
4. Noncalcic brown	0.11	.8	0.14	1.1	0.04	.3	.29	2.2
5. Podzol	0.32	2.4	0.50	3.8	1.14	8.7	1.96	14.9
6. Red-yellow podzolic	0.13	1.0	0.20	1.5	0.06	.5	0.39	3.0
7. Latosol	1.06	8.1	0.71	5.4	.73	5.5	2.50	19.0
8. Grumusol, terra rossa	0.17	1.3	0.11	.8	0.04	.3	.33	2.5
9. Brown forest, rendzina	0.02	.2	0.05	.4	0.02	.2	0.10	.8
10. Ando	0.01	.1	0.01	.1	0.01	.1	0.02	.2
11. Lithosol	0.08	.6	0.41	3.1	2.23	17.0	2.72	20.7
12. Regosol	0.06	.5	0.15	1.1	0.56	4.3	.77	5.8
13. Alluvial	0.32	2.4	0.17	1.3	0.10	.8	0.60	4.5
Total	3.18	24.2	3.65	27.8	6.31	48.0	13.16	100.0

Source: Reference 1

Table II. World land area in different climatic zones excluding ice-covered areas

[In billions of hectares]

Climatic zone	Potentially arable		Grazing		Nonarable		Total	
	Hectares	Percent	Hectares	Percent	Hectares	Percent	Hectares	Percent
I Polar and subpolar	0	0	0	0	0.56	4.2	0.56	4.2
II Cold-temperate boreal	0.05	.4	0.19	1.4	1.73	13.2	1.97	15.0
III Cool-temperate	0.91	6.9	1.00	7.6	1.00	7.6	2.91	22.1
IV Warm-temperate subtropical	0.55	4.2	0.84	6.4	1.37	10.3	2.77	21.0
V Tropical	1.67	12.7	1.63	12.3	1.65	12.7	4.95	37.7
Total	3.18	24.2	3.65	27.8	6.31	48.0	13.16	100.0

Source: Reference 1

Table III. Present population and cultivated[1] land on each continent, compared with potentially arable land

Continent	Population in 1965 (millions of persons)	Area in billions of hectares: Total	Poten-tially arable	Culti-vated[1]	Hectares of cultivated[1] land per person	Ratio of culti-vated[1] to potentially arable land (percent)
Africa	310	3.02	0.73	0.16	0.52	22
Asia	1,855	2.74	0.63	0.52	0.28	83
Australia and New Zealand	14	0.82	0.15	0.02	1.43	2
Europe	445	0.48	0.17	0.15	0.34	88
North America	255	2.11	0.46	0.24	0.94	51
South America	197	1.75	0.68	0.08	0.41	11
U.S.S.R.	234	2.23	0.36	0.23	0.98	64
Total	3,310	13.6	3.13	1.39	0.42	44

[1] Our cultivated area is called by FAO "Arable land and land under permanent crops." It includes land under crops, temporary fallow, temporary meadows, for mowing or pasture market and kitchen gardens, fruit trees, vines, shrubs, and rubber plantations. Within this definition there are said to be wide variations among reporting countries. The land actually harvested during any particular year is about one-half to two thirds of the total cultivated land.

Source: Reference 1

multiple-cropping could increase the gross cropped-area (the cultivated area times the number of crops) to 9.8 billion acres (4.0 billion ha) annually, about 2 billion acres (0.8 billion) more than the total arable land and about 3 times the presently "cultivated" land. The gross cropped-area could be increased an additional 6.5 billion acres (2.6 billion ha) if irrigation water could be made available for double- or triple-cropping. The maximum gross cropped-area on the earth is about 16.3 billion acres."

Thus, within clear restraints, the potenttial is there for significant expansion of the land and water resource devoted to food production. Realization of this potential would require huge capital investment (an estimate made in 1967 was $80 billion for water development on the Indian subcontinent and Southeast Asia), but also extensive adaptation of existing and development of new technology. The potential for increasing production by better utilization of land and water resources on land currently in cultivation is likely as great if not greater than the potential of new development (1).

As we approach an economy based on current energy flux and recycled resources, the key to progress - and for some, survival - lies in finding creative approaches towards optimal and conservative use of our natural resource heritage, with minimal consumptive use of fossil energy resources, and with due regard for maintaining or enhancing environmental quality.

Economic optimization, in the western sense of maximum return on the investment, no longer suffices; the more so, because energy costs will have to be taken as actual, rather than being valued at exploitation costs only. As one approach, we may attempt to optimize food production in terms of energy conversion.

The dilemma, however, is more basic. We may illustrate it by pointing to what appears to be conflicts among four societal goals currently advocated in the U.S.: food production, energy conservation, environmental quality enhancement and full employment. It is mandatory that, in the U.S. and elsewhere, we choose options that make these and similar goals compatible. The manner in which we develop and use our soil and water resources is crucial to success of accomplishing such a goal on a broader, social scale.

A. WATER RESOURCE UTILIZATION IN RAINFED AREAS

The manner in which water use impacts all aspects of society creates the need for careful integration of water resource development and utilization in agriculture, industry and municipalities.

Rainfed regions range from those with an abundance of water to those where water is scarce. Even in areas of abundance, the time distribution of precipitation generally results in periods of excess and of deficit. Particularly where soils have limited storage capacity - such as sands and shallow soils - temporary deficits can be extremely serious. Water problems are not restricted to quantity; they are highly dependent on quality. In the U.S.A., the pressure on limited water resources has created critical demands for water quality improvement, with as yet partly unclear consequences for agriculture. Proper planning hopefully will take into account water quality as well as quantity as development takes place in less fully developed areas around the globe. Water quality changes often take place very slowly. Long time constants mandate caution in drawing conclusions from observations extending over only a few years; they also mean that decades may be required for corrective action to show dividends.

1. WATER MANAGEMENT THROUGH IRRIGATION AND DRAINAGE

Two of the oldest and most obvious ways to manage water in crop production are removal of excess through drainage and alleviation of deficits by irrigation. Conventionally, these two practices have been considered separately as independent in purpose and technique. Ideally, however, the soil water reservoir should be managed in such a way that the optimum condition for plant growth is maintained at all times.

The concept of total water management is relatively new. Current research suggests that, under conditions such as are found in the Coastal Plains of the southeastern United States, it is indeed feasible to control the soil water content in the root zone to continuously provide both adequate water and aeration. Neither the technology nor the economics has been fully resolved, but clearly there are opportunities for improved total water management systems that approach the ideal. Land clearing and grading, for example, may result in more economical farming units, provide surface drainage and permit other water management measures to minimize stresses from water excess or deficiency.

Rice, one of the most important food crops grown, requires unique water management, especially when grown in the wet-dry tropics. Water management becomes primarily a controlled drainage activity to maintain a desired depth of water in the paddy. Appropriate means are required to convey water to and from the flooded area with provision for stability against flood flows.

a. SUPPLEMENTAL IRRIGATION TECHNOLOGY

In a number of areas of the world, water shortages resulting from either inadequate rainfall or poor rainfall distribution are corrected by means of supplemental irrigation.

For example, in much of the southeastern United States, total annual rainfall is more than adequate for full crop production, but its distribution is often poor. Yet the favorable water balance often makes water readily available and the benefits of stabilizing production at high levels by conventional irrigation methods have been demonstrated for a number of crops through research and adaptation by farmers. The optimization of water management, however, still requires substantial research, and there are opportunities for innovations and adaptations of more conventional methods.

A case in point is the use of drainage systems to function as subirrigation. Water table control can greatly increase sugarcane production on fine-textured soils in Louisiana and subsurface irrigation has been shown to give benefits on grain and vegetable crops in the North Carolina Coastal Plain.

Thus a number of engineering and technological questions need better resolution and/or adaptation. At least as important is the adaptation of the theory of water flow through soils to field situations and the development of a better understanding of the dynamic interaction between root, soil and water. There seems to be a need for additional evaluation of the availability, the technical feasibility and the economics of water supply development for agriculture in areas of apparently ample supplies of ground water.

Water may be applied for reasons other than satisfying evaporative demand. Stress reduction through environmental modification is common, including frost protection and crop cooling. Water is also applied for seed germination and for delaying tree budding.

b. DRAINAGE TECHNOLOGY

Drainage enhances the environment in which roots of most important crop species grow.

It also modifies the mechanical properties of soil to improve the timeliness of farming operations.

The importance of drainage ranges from the extreme where no agriculture is possible - or human habitation advocated - without water removal, as in coastal lands below sea level, to situations where drainage simply reduces the cost of agricultural operations. Whereas the function of drainage is always to remove excess water, its purpose varies. In humid areas, the primary objective is to improve soil aeration and trafficability; in irrigated areas it is removal of excess salts.

The installation of a drainage system involves a substantial capital investment and the life of a properly designed and installed subsurface system is measured in terms of many decades. Thus errors in design can be costly. Both the theory of drainage and drainage technology have made rapid advances in recent times. There are still a number of unsolved problems, the solution of which would have substantial impact on the cost and effectiveness of drainage installations, and thus on food production. These problems, however, are not necessarily the same, or of equal weight, in developed and less developed countries. In the U.S., for example, current emphasis is on further mechanization and automation of subsurface drain installation with minimum labor requirement and reduced materials handling cost. Also, in the U.S. trafficability - or soil bearing strength - is important to facilitate the use of large farm machinery. Where labor is relatively more available than equipment, the emphasis should be different. Use of alternative materials to reduce cost and dependence on importation would be more crucial than labor savings; and maintaining optimum soil water and aeration status more important than trafficability.

Whatever the local emphasis, drainage problems in humid areas can be grouped in four classes.

First is the quantitative establishment of drainage criteria. To illustrate, the simplest drainage criterion, in concept, is a relationship between the minimum permissible water table depth and average rainfall intensity. Whatever the actual criterion used, its function is to describe, in terms useful for the design engineer, the requirement the system must meet to satisfy the needs of crops to be grown. Establishment of such criteria requires a thorough knowledge of the response of the crop to its environment as affected by drainage, and antecedent and consequent conditions.

Second is the technology needed to measure, on a field scale, those properties of the soil that control the functioning of a drainage system, the rainfall characteristics and the system boundary conditions. Especially in the area of soil physical properties, there is still a gap between theoretical understanding and laboratory techniques on the one hand, and field methods for establishing pertinent properties *in extenso* on the other hand. Drainage design continues to be hampered by the lack of suitable techniques for field investigation that are inexpensive and easily accomplished.

Third is the need for translating existing theory and field evaluation into reliable, routine design procedures. Further development of theory probably will have minimal effect on drainage practice, but a wedding of existing theory and practical decision making is long overdue.

Fourth is the development of materials and methods of installation. Tremendous changes have taken place in the last 20 years, in Western Europe and in the U.S.A., in drainage technology. Corrugated plastic tubing, requiring a low labor input for both manufacturing and installation, has virtually replaced clay or concrete tile. Laser controlled plow-in equipment has been introduced to replace the use of excavating equipment such as trenchers. These developments substitute petroleum-derived products for local resources, and substitute high capital investment by the contractor for similar capital requirements in industry. The optimum methodology would depend greatly on local circumstances and should be carefully evaluated.

Finally, there are a number of specialized problems and opportunities. These problems include establishing the need for envelope materials and the evaluation of available materials for the purpose; predicting, circumventing or correcting the fouling of drainage systems by the precipitation of mineral deposits, such as iron and manganese oxides; and possibly the design of drainage systems to enhance the reduction of nitrates to improve the quality of the effluent. The drainage of "heavy" clay soils (vertisols) remains an unsolved problem.

Drainage problems frequently are extremely site-specific and may best be solved by applying intensive general knowledge to creative solutions adapted to local circumstances. In the Red River Valley of North Dakota, it was found that salinization of nonirrigated and potentially highly productive land could be prevented and reversed by use of widely spaced, low volume drainage pumps that relieved the hydrostatic pressure at some considerable depth; this reversed the direction of the hydraulic gradient and thus permitted a downward flux of water derived from precipitation. In the lower Rio Grande Valley, a network of small, plastic well points was manifolded to a small pump; this lowered the water table below the interface between the fine-textured surface soil and the underlying sand aquifer. Upward seepage of highly saline groundwater was thereby eliminated at minimal cost.

In summary, drainage is a practice that has been demonstrated to be highly beneficial in extensive areas with quite variable properties. Need for drainage can only be evaluated by detailed local surveys and the optimum solution in a particular instance must always be diagnosed in situ.

2. WATER SUPPLY MODULATION

Many an act of man affects the hydrologic cycle. Some of the resulting changes may be extremely minor, other substantial; some are intended and beneficial, others inadvertent or even unknown. The science of hydrology deals with a description of such changes, and the relationships that enable one to make predictions in terms of evapotranspiration and soil-water storage, infiltration and return flow, surface runoff, stream-flow, or groundwater accretion - in other words, to predict and interpret the partitioning in time and space of the components of the water balance.

Agriculture on the one hand has a significant impact on hydrology - because of its large areal extent - and, on the other hand, is impacted by hydrologic events - because of its need for adequate and timely water supplies. Yet agricultural hydrology cannot be separated from the broader societal needs; both needs and impacts interact with municipal and industrial water interests.

An awareness of hydrologic processes and practical use thereof is hardly new. Water harvesting systems were built in the Negev Desert some 3000 years ago; their recent restoration and adaptation permitted effective food production in this otherwise barren desert. And Plato, in his Critias (3), remarked about mismanagement:

"But in the primitive state of the country (Attica), its mountains were high hills covered with soil, and the plains, as they are termed by us, of Phelleus were full of rich earth, and there was abundance of wood in the mountains. Of this last the traces still remain for although some of the mountains now only afford sustenance to bees, not so very long ago there were still to be seen roofs of timber cut from trees growing there, which were of a size sufficient to cover the largest houses; and there were many other high trees, cultivated by man and bearing abundance of food for cattle. Moreover, the land reaped the benefit of the annual rainfall, not as now losing the water which flows off the bare earth into the sea, but having an abundant supply in all places, and receiving it into herself and treasuring it up in the close clay soil, it let off into the hollows the streams which it absorbed from the heights, providing everywhere abundant fountains and rivers, of which there may still be observed sacred memorials in places where fountains once existed; and this proves the truth of what I am saying."

In the past 30 years, however, substantial progress has been made in man's ability to quantitatively describe and predict the effect of land management on water utilization and runoff, thus improving his ability to prescribe a combination of management and engineering measures that tend to optimize water utilization and minimize damages. More recently models have been developed for sediment, nutrient, salt and pesticide concentrations. Notwithstanding these advances in hydrology, most models depend heavily on empirical or statistical correlations and lack reliability when applied to areas other than the one for which they were developed. Furthermore, no model is useful without access to appropriate input data.

Information from past research is used extensively in implementing land and water resource programs in agriculture and forestry;

but serious knowledge gaps still exist and there is still much uncertainty, speculation and controversy regarding the effects of given watershed management practices upon quantity and quality of water supply, its timeliness, and floods.

The need is for a more reliable mathematical description for predicting the response of watershed systems to changes in management practices and to hydrologic sequences; to find, test and model techniques to manipulate vegetation, to increase runoff and to manage snow melt so as to extend the runoff period; and to improve methodology for evaluating alternative combinations of options in watershed development and protection programs. In addition, better basic data are needed. This requires an expansion of the weather and gaging station network with emphasis on the key climatological and hydrologic parameters.

The purpose is to modulate water supply - be it in soil storage, in streams or in reservoirs and minimize its fluctuations. It is also important to be able to predict extreme events, both droughts and floods. Maximum flow prediction, aside from its obvious application to flood forecasting and damage estimates, is crucial in the economic design of watershed structures such as culverts, channels, chutes and flumes.

3. WATER CONSERVATION IN DRY-LAND AGRICULTURE

A substantial part of the world's arable land suffers from an insufficiency of precipitation to meet the demand for potential evapotranspiration. Although the unit production in rain-short areas is generally less than in humid areas, their large areal extent makes them extremely important to agriculture. For example, in the Great Plains of the U.S., cultivated crops were grown on 72 million hectares in 1964, and 134 million hectares were devoted to grassland. This compares with

152 million hectares of cropland in the U.S. that same year. Water is the major limiting factor for production in the Great Plains, and in the climatologically similar areas elsewhere in the world.

Effective and conservative utilization of land resources in areas of limited precipitation depends on a comprehensive program of integrated soil and water conservation practices and agronomic management. Improper management can have devastating results, as evidenced by the 36 million hectares of brush land in the State of Texas, the 120 duststorms reported at Dodge City, Kansas in the 1936-37 season, and the famine, starvation, and decimation of cattle in the Sahael in the early 1970's. Wind erosion is closely related to water conservation. On the opposite side of the coin, the practice of summer fallow, while effective and even mandatory under the proper circumstances of winter precipitation, can result in excessive deep percolation; such accretion to the water table seems to be the cause of the rapidly expanding problems of saline seeps that are continuing to take land out of production in Montana, North Dakota, and parts of Australia.

In semi-arid tropical regions, rainfall may exceed potential evapotranspiration for limited periods during the warmer seasons of the year, but effective moisture conservation measures are needed to tide over the frequently occurring drought stress periods within the limited growing season and for extending the crop growing seasons on soils with better moisture holding capacity.

Based on past research, present technology reflects considerable progress in ways to improve storage, conservation and use of soil water; and in controlling wind erosion. Many conservation practices are now in use, such as stubble mulching, bench terracing, pitting, and skip-row farming; strip-cropping, use of shelter belts, emergency tillage and controlled grazing. In tropical latitudes, contour ridges and furrows and tied ridges are among the techniques which have been used.

Yet present technology is insufficient to obtain full utilization of the land resources, or to prescribe appropriate packages of methodology in areas to be developed. Wind erosion in the U.S. has been reduced substantially below the levels prevalent a generation ago, but it is still excessive and continues to remove valuable topsoil, to damage seedlings by abrasion, and to pose a hazard to human health.

Some innovative concepts have been developed and tested under limited conditions. For example, in western Minnesota, it was found that intercropping of soybeans and corn modified the microclimate such that total grain yield was increased by some 25%; in Montana a few rows of tall wheatgrass spaced across a grainfield increased snow catch for better water storage; land shaping to collect runoff from small cropped watersheds and spreading this runoff on lower, graded fields has increased available water and subsequent grain yield in eastern Colorado; and forming micro-watersheds, or shaping and treating the soil surface so that precipitation infiltrates only in the furrows of row cropped fields has reduced evaporation losses and thus enhanced available water supplies.

Such innovations indicate that there are opportunities for improving water use efficiency and thus crop production. The problems, however, are complicated, and variable weather conditions make it difficult to extrapolate short-term experimental results in terms of long-term benefits. Thus there continues to be a need for fundamental research to better understand the flows of water and heat through soils, the flow of water into and through plants, the control of gas and energy exchanges of leaves by stomata and the fluxes of water vapor, heat and CO_2 through and above crop canopies. Coupled with research on management practices, plant varieties and environmental requirements, such better understanding can lead to an assessment of the potential of specific practices in reducing the risk of crop failure, increasing the water use efficiency and enhancing sustained crop yields. Such specific practices would be directed at reducing evaporation loss from soils, increasing water infiltration and storage in soils, reducing or controlling runoff, and stabilizing soils against wind and water erosion. Also required is management of soil fertility to properly integrate water and plant nutrient availability as a function of stage of growth.

It should be evident that, having obtained the knowledge to permit evaluation of packages of practices in terms of effective utilization of natural resources, the actual selection must be strongly influenced by local conditions that may go beyond optimization of food production. For example, the inconvenience with multirow planting and harvesting equipment of planting alternately 2 rows of corn and 16 rows of soybeans would be a factor in Minnesota, but may not be a factor in East Africa.

4. EROSION AND SEDIMENT CONTROL

History teaches us a crucial lesson: Failure to properly manage soil and water resources to control erosion and sedimentation leads to disastrous consequences (4). Today, erosion is once again a major problem in many parts of the world, including India, Brazil, Poland and Yugoslavia. On the U.S. mainland, erosion by water is the dominant conservation problem on 72 million hectares of cropland and about 13 million hectares of non-Federal pasture and rangeland.

Erosion results in drastic losses to a precious natural resource - the land - and reduces crop yields and efficiency of farm operations. It results in tremendous losses of plant nutrients and frequently reduces the efficiency of water utilization. Erosion is the source of sediment which degrades the quality of the water resources in which it is entrained and frequently degrades the location where it is deposited. Sediment fills water storage reservoirs, lakes and ponds, clogs stream channels, destroys aquatic habitats, detracts from recreational water use, and increases water treatment costs.

Thus erosion adversely affects agricultural production, and also causes severe off-site damages. Substantial erosion occurs on agricultural land, but other sediment sources include construction sites, highways and stream banks. Surface mined lands are often left in erodible states, unfit for productive use, and thus reduce the resource base available for food production.

Methods for reducing erosion and sedimentation are known and being applied to a degree for most source areas and causes; however, there remains much to be done before the level of control can be achieved that is compatible with maximum land utilization and minimum damage. In many cases, the limited application of erosion control practices is associated with an apparent disparity between the beneficiary and the investor in control measures; another common complication is found in property boundaries that do not lend themselves to cost-effective control on land controlled by a single owner or tenant.

Control of erosion at the source is the most direct and, generally, the most effective approach to dealing with erosion and sediment problems. Agronomic and range management practices, together with mechanical and structural measures are used to contain erosion within reasonable limits. Changing from row crops to small grain may reduce rill and sheet erosion by 60 to 90%; the use of graded terraces often reduces sediment yield by more than 80%. Grassed backslope terraces with subsurface outlets not only eliminate essentially all soil removal from the field, but also improve water utilization and facilitate farming operations by reducing the effective degree of land slope. The (inappropriately named) universal soil loss equation (5) permits reasonably reliable estimates of soil loss as a function of soil properties, rainfall characteristics, land slopes and cropping and management practices, as long as its application is restricted to the geographic area for which it was developed. Nothwithstanding these advances, there is a need for additional research, especially if accelerated erosion is to be avoided as a result of pressures to increase food production.

A primary research need is to develop a fuller understanding of the dynamic mechanisms of soil detachment and transport. The "universal" soil loss equation was based on good intuitive judgement, careful observation and detailed statistical analysis of extensive experimental data. Thus it cannot be extrapolated with confidence beyond the limits of the data upon which it is based. Since its development, substantial additional progress has been made, but the current state of knowledge is still deficient in a number of aspects. An understanding of the dynamics of erosion will depend, in part, on the evaluation of control of infiltration by soil crusting and of the role of seepage forces in detachment.

Improve control practices are needed that can be integrated into total farm management systems compatible with the agricultural production practices suited for a given socioeconomic system. In the U.S., this may well require modification of currently recommended practices to accommodate larger machinery, requiring larger fields and longer rows than in the past. In other cases, it may demand adaptation to small fields, smaller machines, or use of draft animals.

Predictive equations are needed to evaluate the effectiveness of control practices on cropping systems that differ from those for which experimental data are available.

Techniques are needed for assuring the stability of natural and man-made channels, and for predicting stability problems in advance of construction.

The dynamics of gully formation must be understood to avoid the initiation of new gullies and to find effective ways for stabilizing existing head cuts.

The effect of conversion of tropical forests into cultivated land must be evaluated, in terms of hydrology, soil stability and cultivated soil fertility.

The erosivity of rainfall must be determined, possibly in a manner parallel to the rainfall-erosion index developed for the eastern U.S., but applicable elsewhere as well.

B. WATER RESOURCE UTILIZATION IN ARID AREAS

In terms of potential--both for improving water use efficiency and for expanding the world base for food production--irrigated agriculture demands high priority. Irrigation offers opportunities for high unit production and for a wide variety of crops, adding to the variety in diet that aids good nutrition.

Relative to other uses, irrigation is a very heavy water user. It is estimated that in the U.S.A., 90% of all water actually consumed from that withdrawn from streams and ground-water storage for use, is consumed in irrigation agriculture.

Irrigation efficiency, salinity management and ground-water management are closely intertwined. Separate discussion of these topics of necessity will lead to some overlap and repetition. All three of them have in common that good water management is mandatory if irrigation agriculture is to thrive, or even survive, in view of the tremendous pressures on available water resources, combined with the energy demand for irrigated agriculture. Unfortunately, exporting the extensive and economically often successful irrigation methods practiced in the U.S.A. could have drastic adverse consequences abroad. In the highly developed agricultural industry of the Western U.S.A., the average farm water use efficiency is still only around 40%. (In many instances, the water lost by runoff or deep percolation is recovered for later use. Its quality may be maintained or degraded in the process.) Little consideration has been given to the energy efficiency of this enterprise and the adverse effects on water quality only recently have begun to obtain the attention they deserve.

Conceptually, we should be able to draw on the U.S. experience to develop a framework for restructuring or developing a management strategy that enhances the utilization of the water resources in a manner compatible with energy conservation, environmental quality maintenance (or enhancement, as the case may be), effective labor utilization and food production. This is our challenge. Enough is known to plot the course; too many gaps still exist in our knowledge to draw detailed blueprints.

1. IRRIGATION EFFICIENCY

Irrigation alone obviously cannot prevent the spread of famine or near famine that exists in various parts of the world, but it can play a key role in feeding an expanding population.

The objective of irrigation can be simply stated: to minimize water stress as a factor in reducing crop yield. Reaching this objective effectively is less straightforward. It requires a thorough understanding of the response of plants to the soil water regime, optimization of all of the management practices that together affect crop growth, adequate ability to measure those factors that determine water demands, and the controls needed to satisfy these demands.

As indicated by the literature (e.g. 6), substantial progress has been made in understanding the relationship between water application in irrigation and crop response; U.S. farmers have learned to apply this knowledge reasonably well to maximize their economic return, within the socio-economic framework in which they operate. Such maximization does not necessarily optimize the use of natural resources for food production, and export of the associated technology could well be counterproductive abroad. As pointed out by Clark (7), irrigation schemes are often designed with political objectives in mind that do not necessarily result in rational water pricing. Even more important, Schumacher (8) stresses the fallacies of economic optimization without recognizing that consumption of natural resources is equivalent to living off capital rather than yields, and reminds us that optimization of the return to the investor may not optimize return to society.

Food production is the first demand one must place on the use of the soil and water resources, and irrigation plays a major role in this regard. Optimization, however, should be towards maximum food production while protecting the environment: minimum use of nonrenewable resources, minimum degradation of environmental quality (if not enhancement), and minimum adverse impact on societal values. Achieving or approaching such a goal will require the application of present technology and development of new technology; as important, however, may be a redirection of the criteria for success used by scientists in their research and by all in implementation.

a. GRAVITY IRRIGATION

Historically, irrigation was first practiced by more or less controlled diversion of flood waters. Ingenious systems for tapping artesian sources and for conveying mountain waters to land to be farmed were developed very early in various parts of the world. Over time, the primary method for large-scale irrigation has come to depend on the conveyance of waters from streams by means of canals, with or without the construction of storage reservoirs, and the distribution of water to the land by means of gravity. Pressurized irrigation and irrigation from pumped wells, dependent on mechanical power, are of relatively recent origin, as is the use of pumping plants to lift water to proper elevations for gravity flow along most of its route.

The typical gravity irrigation system uses water rather inefficiently, in terms of the fraction of water transpired by the crop. Many factors contribute to this situation. Soils are seldom uniform: they have variable intake rates and storage capacities. Their intake rate may be too low or too high for efficient irrigation management. Water volumes and flow rates are difficult to measure accurately and often are not measured at all. The timing of irrigations is often influenced by the need to schedule other farm operations. Water may be applied for reasons other than satisfying evaporative demand, such as frost protection, leaching of salt, germination or delaying tree budding. An important cause of inefficient water use often is the price of water relative to the cost of labor and other farm inputs.

Other factors affecting water use are seepage and evaporation losses in conveyance and limitations of the conveyance system to deliver the desired quantities on demand. Besides water loss, seepage can cause serious water logging and salinity problems. Conveyance system limitations may be illustrated by the situation in Pakistan where water delivery tends to be determined by the hydraulic characteristics of the canal system rather than by the need of the individual irrigated fields.

The efficiency of gravity irrigation on existing systems can be increased substantially above the level generally encountered by appropriate application of existing knowledge. A promising, fairly recent development (9) is the introduction of scheduling services that utilize specialists to combine field observations and computerized calculations based on soil, crop and climatological data for developing specific field-by-field recommendations. Other advances are possible by reducing seepage losses, introducing tailwater pump-back systems and a variety of other system improvements. Several bottlenecks exist, however. They include lack of economic incentive, limitations of devices for measuring flow rates and quantities, and inherent problems in design and operation of water delivery systems. Probably impossible of solution is the non-uniformity of soil properties in individual fields.

b. HIGH FREQUENCY IRRIGATION

Far greater control over irrigation water can be obtained with pressurized irrigation systems than with gravity systems (10). Such control enables the frequent and uniform application of small, metered quantities of water.

For most crops, keeping plant water potential high results in maximum production per unit area and also, per unit of water used. Thus keeping the soil root zone relatively wet by frequent application of small amounts of irrigation water will optimize water use. For crops where dry matter is not the ultimate aim, programmed periods of water stress are needed to initiate differentiation or maturation. There are a number of related potential advantages to frequent irrigations. A low rate of application will result in uniform infiltration, independent of soil variability, because the soil's infiltrability will not be exceeded. The requirement of high soil water potential can be met while maintaining a small rate of drainage. (In contrast, with low-frequency irrigation one tends to overcompensate for the periodic low water potentials, resulting in large rates of drainage immediately following an irrigation.) Losses of nutrients (natural or applied) by leaching will be minimized. Soil storage capacity should be increased, thus increasing the effective utilization of natural rainfall where it occurs. Soil water stored below the root zone can be utilized more effectively where the soil near the surface is kept moist.

The obvious way to accomplish frequent, light irrigation is by means of pressurized irrigation systems. Pivot sprinklers, lateral-move sprinklers and trickle irrigation systems are logical candidates; solid set sprinkler systems may be considered, with due consideration of non-uniformity of application. In orchards, small basins that are flooded daily, either from a pressurized system or by hand, will serve the same purpose. In some cases, gravity systems can also be adopted to frequent irrigation.

Potential advantages visualized include substantial reductions in amount of water delivered, with associated reductions in fossil energy used for pumping; reduction in fertilizer requirements; simpler control of irrigation amounts and timing; reduction in drainage rates; better utilization of water from soil profile storage and of rainfall. The significance of energy saving is illustrated by the estimate that 55% of the energy required to grow an irrigated grain crop is used to deliver the water to the farm (11). Possible disadvantages include the capital cost of conversion of existing gravity systems and the cost (in energy) of pressurization. However, Rawlins and Raats (10) calculated that the savings in fertilizers frequently will more than offser the energy consumed in pressurization.

Continuous irrigation, which may be regarded as the ultimate in high frequency irrigation, is practiced to maintain standing water for paddy rice in arid climates. This practice allows rice production in arid lands such as the Central Valley of California, USA; or in dry seasons in areas such as the Phillipines where there is production of rain watered rice during a wet season, and irrigation during the dry season can provide a second annual crop. Efficient use of water for irrigated rice require soils of very low intake rate and systems in which tailwater is reused or eliminated.

c. RESEARCH NEEDS

There is need for research to develop improved commercial systems that lend themselves to reliable and effective frequent irrigation. Pest control and farm management systems may be different than with more conventional irrigation management, and development of simple feedback systems is needed that enable control of the irrigation system with a minimum of specialized technical knowledge.

The establishment of a data base to enable accurate forecasting of crop needs, for either frequent or infrequent irrigation, is of high priority. Improvement in automation of gravity irrigation systems could lead to wider adoption of automated systems and substantial water savings. Refinements, utilizing remote monitoring and control and possibly automation, in scheduling water flow in open channel delivery systems are necessary to permit more precise water delivery on demand to farm fields.

Where salinity is not a major factor, capillary rise from the water table to the roots may, in specialized circumstances, greatly reduce irrigation and drainage requirements. In areas of limited water supply, selective irrigation of larger areas with less than a "full" water quota may increase total crop yield, as demonstrated for sorghum irrigation in Texas. Waste water from nonagricultural sources - such as secondary sewage effluent, cannery waste and power plant cooling water - can often be used effectively for irrgation. Such use, however, requires detailed knowledge of the impurities, evaluation or special study of the consequences of such impurities and, sometimes, the solution of difficult problems of matching supplies and demand.

Other concepts have been advanced that seem to have less potential, warrant less urgent attention. It has been proposed that increasing stomatal resistance by means of antitranspirants offered the potential of reducing transpiration relative to photosynthesis. Recent theoretical studies (12) and field observations (13) have demonstrated that increasing stomatal resistance greatly decreases water use efficiency. The possible future availability of water from desalting plants and geothermal wells has led to the suggestion of studies on the utilization of extremely high quality water and water of elevated temperatures. Neither question seems to create problems or opportunities of sufficiently widespread interest to warrant accelerated studies with the goal of adding to the world food supply.

2. MANAGEMENT FOR SALINITY AND SODICITY

In many dry parts of the world, salinity is the primary problem faced in agriculture. A 1960 survey indicated that nearly 30% of the irrigated land in the U.S. was sufficiently salt-affected to adversely affect crop growth and that excess soil salinity was a potential hazard on at least half the irrigated area. Szabolcs (14) reported 20 million ha of solonetz soils in Europe, out of a total of possibly 30 million ha of salt-affected soils. The plight of the Indus Plain is well known and many other examples could be given.

Although not wholly, salinity problems are generally restricted to arid and semi-arid regions. By no means, however, are they limited to irrigated agriculture. For dryland agriculture, managing saline or sodic soils, or preventing their spread, is a matter of agronomic and soil management. For example, the recent spread of saline seeps in Montana and North Dakota, as well as in Australia, seems to be caused by a combination of the cropping patterns in the watershed above the seep area and a cycle of years with somewhat higher precipitation. Whereas recent work has led to effective methods for predicting sites of incipient seeps, their proposed prevention by changes in crop rotations is still speculative.

a. MANAGING IRRIGATION FOR SALINITY CONTROL

The greatest potential for combating salt problems - prevention or reclamation - is associated with irrigation where water is available for leaching. Since all irrigation water contains minerals, a permanent irrigation agriculture must have adequate drainage. As the plant roots take up water and leave the salt behind, the soil solution increases in concentration. These salts must be removed by drainage. In some areas, ground water containing salts - reportedly up to 120 g/l - must be prevented from rising into the root zone. Whatever the source of salt, good management requires the maintenance of net downward flux of water sufficient to prevent excessive accumulation of soluble salts in or near the root zone. With respect to salinity, plants respond primarily to the osmotic stress in the soil solution. Secondarily, they respond to the concentrations of specific ions, especially Na, Cl and B. Large differences in salt tolerance occur among species and varieties, and at different stages of growth. The relative tolerance of many plant varieties has been approximately established but the data are far from complete. Soils also react to salinity in the sense that the soil hydraulic conductivity is highly dependent on electrolyte concentration, and soil structure is adversely affected by a preponderance of monovalent ions on the exchange complex.

Good irrigation water management is predicated on the provision of adequate drainage and on the application of sufficient water to satisfy the evaportranspiration demand plus the leaching requirement - or the amount of leaching (drainage) water needed to maintain a favorable level of soluble salts in the root zone.

Recent research (15) has indicated that the leaching requirement as just defined is substantially lower than that normally advocated. These findings suggest that, provided part of the root system has access to more freely available water, roots are able to absorb water from the soil solution until this solution reaches some relatively high osmotic stress threshold. This threshold level should correspond to that concentration, if uniform throughout the root zone, at which crop yield is depressed 100%. From a chemical point of view, the consequence of a reduced leaching fraction is that mineral dissolution will be reduced and that the less soluble salt species will tend to precipitate. From an engineering viewpoint, a lower leaching fraction reduces the amount of drainage required and results in a smaller mass of salt which needs to be disposed.

Adoption of a lower leaching fraction as a management tool requires a high areal uniformity in irrigation water distribution. To minimize osmotic stress, such management also calls for frequent irrigation. Thus, the foregoing discussion on irrigation efficiency has an important corollary in salinity management; salinity effects increase the benefits from frequent, low-rate irrigation.

Full utilization of the minimum leaching concept requires additional research to better establish the salt tolerance of a range of economic plants, and especially of the hypothesis sketched above. It also requires field scale verification on a broader scale than has been possible to date, with incorporation of all of the associated irrigation and farm management practices. It would be enhanced by improvements in feedback control systems that enable semi-automatic day-to-day irrigation management decisions.

Other important questions need further research, whether irrigation is frequent or infrequent. How do plant roots integrate salinity stress, over depth and time, as salinity and water stress change? How important, relative to mass flow, are the processes of diffusion and dispersion in salt distribution and disposal, and how does one describe the total flow system quantitatively? How does one establish meaningful water quality guidelines, both for managing existing irrigation and for prediction prior to initiating new projects? Under what conditions can supplementing irrigation water with plant nutrients alleviate salt stress, e.g. to balance excess of Na^+ by an addition of K^+? What are the mechanisms through which salt stress - either osmotic or specific ionic stress - affects plant metabolism?

As discussed more fully in a subsequent section, efforts to date have stressed adaptation of the environment to the plant. With reference to salinity, the possibility has not been explored of tailoring the plant to the environment A great opportunity exists in breeding food plants for tolerance to far higher levels of salinity in the soil solution than can be utilized effectively at present.

b. RECLAMATION

The only known method for reclaiming saline soils is leaching. Where rainfall is adequate, providing proper drainage or removing artesian pressure may suffice. Otherwise, leaching water must be applied. Experiments with sprinkling, intermittent flooding and continuous flooding have not always been fully consistent, but it is well enough established that leaching is more efficient when unsaturated flow prevails. An adequate rule of thumb seems to be that two pore volumes displacement are required to remove about 80% of the soluble salts (16).

Reclamation of sodic soils or soils high in boron is more complicated. For sodic soils, reclamation requires replacement of part of the exchangeable Na with Ca. Unless the soil has ample Ca, amendments must be added, such as gypsum or, in the presence of carbonates, acid or acid-forming sulfur compounds. Taking advantage of the higher hydraulic conductivity (k) of sodic soils for water with high electrolyte content, reclamation has been speeded up dramatically by means of concentrated $CaCl_2$ solutions diluted in successive steps. Unfortunately, this method is quite expensive, and wasteful in terms of the efficiency of use of applied Ca.

Less expensive and yet effective reclamation procedures may be possible by using a combination of a limited quantity of $CaCl_2$ to maintain a high k with a less costly gypsum application to complete the replacement process. An appropriate methodology would depend, however, on a better understanding of the relationship between k and electrolyte concentration, especially in terms of the time sequence of electrolytes. Another possible compromise may be the reclamation of narrow strips of soil to some reasonable depth (1 m?) using quick acting amendments, and planting a crop on these strips. Diffusion, lateral flow and organic matter decomposition would aid in reclaiming the remaining soil over time, especially if gypsum were applied.

As new lands with sodic soils are brought under irrigation - for example in California, Hungary and the USSR - the question of effective yet not extremely costly reclamation will become more central. Furthermore, the prospect of extensive strip mining for coal, not uncommonly resulting in exposure of soil material high in Na, places urgency on development of effective alternative methods for restoring such soils to productive use.

3. GROUND WATER MANAGEMENT

About a quarter of the water used at present in the U.S. for domestic, industrial and agricultural purposes comes from ground water and grown water consumption continues to increase. Irrigation is the greatest single user. Similar dependence on ground water is no doubt prevalent elsewhere in the world.

In some regions, ground water supplies appear ample; in others, serious overdrafts occur. Water shortages tend to be regional in nature and vary drastically with time. Aquifers provide extensive, conservative and cheap storage facilities that often can be used to modulate water supply.

A major consideration in ground water management is water quality. Both natural and artificial recharge may add impurities to the ground water body; some recharge schemes are specifically designed for disposal of wastes.

Notwithstanding substantial progress, our knowledge in the area is woefully insufficient for optimizing utilization of this resource. Especially with increased emphasis on water quality, associated with fuller development, there is a need for fuller understanding of water transport and water chemistry processes and for better technology for inventorying appropriate geohydrologic properties.

Induced recharge of rainfall runoff water, in the proper setting, offers the potential of substantially alleviating water shortage. Evaporative loss of rainfall in the area of Texas underlain by the Ogallala formation has been estimated to be of the same order of magnitude as the overdraft from ground water pumping. Unless local water supplies can be conserved or additional water imported, the use rate in the area must be drastically reduced, with a concurrent reduction in irrigated agriculture. In other cases, recharge of surface water supplies in excess of immediate need can store water for later use at the same point or elsewhere in the basin. Spring runoff in the Kings River, if stored underground, can supplement the water supply for Fresno, California, municipal use.

Each ground water basin, with its own hydrology, geology and economic environment, has a unique character calling for a particular set of solutions. The quality of the water recharged must not affect the aquifer or the recharge facility adversely. A means must be found for inducing the water to infiltrate at rates high enough to minimize evaporative loss and surface storage need.

A variety of designs of recharge wells, surface ponds and combinations of the two have been used effectively in some cases; or failed in others. Good progress has been made in identifying the pertinent soil and aquifer characteristics needed for prediction of success. Progress has also been made in developing and evaluating methods of water clarification prior to recharge. But many problems remain.

An important limiting factor in effective ground water management is the dedication of specific sites to recharge based on soil properties. Such dedication, which should be part of land use and zoning policies, requires better technology to delineate those areas particularly suited for recharge.

In some instances, it may be possible to use agricultural crop land for recharge by purposeful overirrigation. Such a scheme might enable dual land use, obviating the need for setting aside recharge areas. It would require additional research on crop response to excessive irrigation, in relation to crops, crop quality, soil properties and management practices.

An entirely different set of opportunities and problems is associated with recharge of waste waters for eventual reuse. Either cannery effluent or secondary sewage effluent may thus be reclaimed taking advantage of the clarifying and purifying potential of soils and vegetation. A large scale test project is underway near Muskegan, Michigan, and, in the Salt River District near Phoenix, Arizona, several years' research have led to initiation of a pilot project. In both cases, secondary sewage water is used. Substantial progress has been made in determining the effect of wetting and drying cycles on effective recharge rate and on nitrogen and phosphorous disposition, and in other aspects of management. At Phoenix, up to 125 meters per year of water have been successfully recharged. Besides waste water renovation, effluent can also be used - in conjunction with recharge - for the production of food crops. Most effective total utilization of the resources available requires integrated planning, evaluation of many site specific parameters, and further research to more adequately determine the appropriate relationships between crops, crop quality, soils and water quality.

4. RUNOFF HARVESTING AND UTILIZATION

Under arid conditions precipitation is often intense though infrequent. Collection of runoff can furnish water for domestic use, animals, kitchen gardens or larger scale cropping. Runoff may be collected from undisturbed natural areas or from areas subject to a variety of treatments ranging from minor clearing to complete soil surface sealing. Storage of collected runoff may be in closed or open tanks, containers or reservoirs or, in situations where runoff is to be used for plant growth, storage may be in the soil profile of the cropped area.

Runoff area and planted area may be intimately interspersed, for example between-row areas might be treated to enhance runoff to in-row areas, or runoff areas may be entirely discrete from planted areas. Studies in southern Arizona, including both theoretical analyses and field plantings have shown that under conditions of an average annual growing season rainfall of 125 mm a 5-ha untreated native desert runoff area may be expected to support 0.4 ha of grain sorghum. There is much opportunity to relate climate, soil, topography, native vegetation, water harvesting method, water storage method and water-use through plants, animals or humans for application throughout the world.

C. SOIL MANAGEMENT

Increasing world crop productivity will involve increasing efficiency of production from more intensive use of soils already under cultivation as well as bringing additional soils into production; but the immediate emphasis should be on soils already under cultivation because that is where the people are concentrated and that is where an infrastructure already exists.

Soils differ in their management requirements. The transfer of soil management technology among widely dispersed regions can be done only for soils that behave alike. Not widely done today, the transfer of relevant technology should be fostered.

For optimal plant growth rates, the soil must contain, or management practices must supply a reservoir of each essential element in a readily absorbed form in amounts sufficient to sustain the plants throughout their entire period of growth. In addition, the diffusive and convective transport properties of the soil must be such that the concentration of each element is maintained at the root surfaces and intercellular spaces at a level and form permitting effective operation of the root cell absorption mechanism. The storage, transport and functional characteristics of all the soil-derived essential elements must be synchronized so that they do not impose undue restraints on each other. Thus, the amounts and proportions of each element maintained at root surfaces should be such that the absorption of one of them is not excessively hindered.

Current knowledge of soil management and fertilization should permit sizeable increases in crop production on currently cultivated lands and should facilitate the development of new lands.

To sustain a high level of production, it is necessary to maintain an intensive program of examination of the chemical, physical and biological attributes of soils, the way they moderate each other and are modified by the plants growing on them.

1. SOILS UNDER CULTIVATION

The soils currently under cultivation vary enormously in their chemical, physical and biological characteristics. In many of these areas, soil surveys have been or are being conducted. They must be used when decisions are made about the best use of land in a given locality.

Within the limits imposed by the aerial environment and present germplasm, current chemical, physical and biological techniques are suitable for identifying many, but not all, of the major restraints on productivity of most major problem soils. The techniques involve measurements of bulk soil properties, (e.g. phosphorus fixation, bulk density, nitrification rates). Areas of excessive salinity, high soil acidity, low supplies of the major and trace elements, excessive heavy metals, and poor soil structure are fairly readily diagnosed by trained people. In many instances, one or more remedies for removing the major restraints are fairly well known.

Present knowledge of most of the currently cultivated soils permits reasonable estimates to be made for their nutrient supplying capabilities, for their reactivity with various fertilizer materials and for their resistance to erosion. Failure to apply present information, not the lack of concepts or principles imposes the present soil management limitation on crop productivity of currently cultivated soils. Increased application of the present knowledge involves (a) integration of present soils information with all other appropriate information in making more precise fertilization and management predictions, followed by the testing of these predictions under appropriate field conditions, and (b) increasing the use of present and developing knowledge by farmers.

2. POTENTIALLY ARABLE SOILS

The majority of the available soils of the world not yet in agricultural use are the Oxisols and Ultisols of the tropical jungles and savannas (17, 18). Many of these are highly leached, low in bases, and relatively acid with high contents of exchangable aluminum. They are commonly deficient in phosphorus and other essential elements and they generally are strong immobilizers of added phosphorus. It has already been demonstrated that many of these problems can be corrected and good productivity obtained but much adaptive research is necessary before we are ready to farm these soils. Such adaptive research, combined with good soil surveys should permit delineating the areas most suitable for farming. Provided the economic situation and social customs are favorable, a pronounced increase in the production of food could result from bringing these soils under cultivation. Special problems are associated with the high rainfall in at least certain periods of the year and the chemical characteristics of these soils (17). Excessive leaching of some nutrients and rapid immobilization of others, together with their high cost, dictates that the applied materials be utilized with utmost efficiency.

Three major constraints exist for bringing these areas into efficient production. (a) Transportation facilities for inputs of fertilizers and export of marketable products are extremely limited. (b) Initial investments are very high; it is not currently possible to obtain reasonable production without first clearing and then making appropriate applications of lime and phosphate and, in many instances, various trace elements needed to be supplied. (c) Agronomic management is technically very exacting; the local competence to manage the fertilizer, pesticide and other management inputs is very limited. Frontier hardships are such that high rewards must be evident to induce technically capable people to go to these regions. The continued expansion into new areas through colonization projects without any good information on the soils or their management presents a real danger of great environmental damage. There is immediate need for research in these undeveloped areas before irreparable damage is done.

Until such time as the severe non-agronomic restrictions can be removed, we are left with developing agricultural systems which operate with minimal inputs. Some plant species are able to grow reasonably well in these nutrient-poor environments. An intensive effort is needed to determine how they have adapted their nutrient absorption and growth characteristics to these conditions. This information, coupled with an understanding of how these attributes can be incorporated into existing crop species, should permit a sizeable increase in productivity until more intensive production practices are economically and sociologically feasible. In studies of adapted species, care must be taken to not overgeneralize from behavior of the more thoroughly studied common crop species.

3. EFFICIENCY IN SOIL AND FERTILIZER USE

Increasing the efficiency of fertilizer use also has become of urgent importance with currently cultivated lands. Low recovery may result from immobilization, particularly of phosphorus from volatilization or leaching, particularly of nitrogen, and from inefficient distribution relative to root activity. The magnitude of each of these effects varies widely. There is promise that nitrogen fixation capability can be increased substantially in non-legume crops by promoting associative symbioses and free-living nitrogen-fixing organisms in the rhizosphere. More efficient use of legumes may provide some relief. Nevertheless, the demand for fertilizer nitrogen, derived from non-renewable resources, is expected to remain high for many years to produce the desired food crops throughout the world. Its efficient utilization is of utmost importance.

One important resource which could reduce the demand for fertilizers is organic waste, including crop residues and animal waste, waste from agricultural processing plants, municipal sludge and, more generally, human waste. Waste disposal has become a major problem, in terms of dollar costs, energy consumption and environmental pollution. Recently, renewed emphasis has been given to the potential of waste utilization as opposed to waste disposal. In view of the quantities involved, total utilization would substantially affect the demand for fertilizer nutrients. Wastes used as an amendment also offer the potential of reclaiming denuded and otherwise impoverished land resources.

Recycling agricultural and human waste has been practiced for centuries. Extensive experience with composting, together with proper crop rotations and other management practices, has shown that high quality products can be grown commercially at comparable yields to conventional practice without use of artificial fertilizers (19).

Utilizing farm wastes as a nutrient source tends to make the farm enterprise less dependent on external market forces, and increases stability through creating more nearly a closed system of production. Making constructive use of industrial and municipal wastes turns a problem into an asset. Both aspects offer sufficiently attractive benefits for food production and for society to warrant far more intensive study in the scientific community than has been afforded to date. Composting, the recycling of wastes, can be used much more effectively to provide nitrogen inputs than is currently the practice in the more advanced countries.

Although sizeable phosphorus and postassium reserves exist (1), it is imperative that all fertilizers be used much more efficiently. Various efforts are already underway to increase efficiency of fertilizer use. These involve use of compounds of low solubility, coating fertilizer materials to give slow but sustained release to the soil solution, addition of chemicals to alter microbial transformations, varying the timing and placement of fertilizers, altering fertilizer formulations, and adding substances which moderate chemical immobilization (20). Significant advances can be expected from these approaches, each of which requires sustained adaptive research to delineate its suitability for specific soils, crops and aerial environments. This research must focus on supplying the mineral elements in optimal quantities at all stages of plant growth. For example, increasing evidence suggests that slow growth initially may set a pattern which may never be regained during the remainder of the growing season. Efforts should also focus on the possibility of altering the chemical composition of grain and oil seeds. Some modification in the amino acid composition of proteins may be possible by a combination of genetic manipulations and soil fertility practices.

Greater efforts to increase production efficiency per unit of land surface are required in those regions where expansion to potentially arable land is limited and population pressures are large. These efforts include the development of varieties with physiological and morphological attributes adapted to specific soils and environmental conditions which may result in substantially greater yield and quality potentials. We need to know more specifically the maximal yields that can be achieved on the various soil groups, and what combinations of soil management and fertilization practices are required to achieve them. There are few studies in which all chemical, physical and soil biology restraints to productivity have been removed in order to determine experimentally yield maxima with present cultivars.

Intensive multiple cropping and intercropping practices are required to maintain productive crops on the land for the maximal possible time. Incompatability of certain crops may be expected under these intensive cropping practices. We need to find out which crops are compatible and which are not. Soil pathogens may be expected to proliferate, and allelopathic effects magnified. Herbicide incompatibility among crops will have to be overcome. On the other hand, positive interaction among crops may occur and perhaps can be utilized much more effectively than is currently done. Minimum tillage practices tend to conserve the use of energy in production practices, to reduce erosion, and to increase water use efficiency. But these practices induce a complex series of changes in soil structure and soil biological activity which can modify root development, and the impact of these effects on crop production over extended periods without tillage needs to be evaluated.

Associated with intensive production practices will be expanded use of the soil for disposal of wastes, and the soils will be receiving a steadily increasing burden of chemical pollutants. Moreover, the soils must be managed such that there is minimal contribution of undesirable added materials to the runoff or ground waters, or to the food chain. Managing soils under these conditions requires sophisticated information about soil characteristics and about the manner in which nutrient supplies are controlled. The amount of nutrient supplied by the soil, and the amount supplied from the applied fertilizer, must be integrated with the nutrient requirement of each crop throughout the growing season. The methodology used for nitrogen fertilization of corn illustrates such an approach (21). Finally, intensive efforts must be made for applying all information about each component of the soil-air-plant system in predicting site productivity. Development of this interpretive technology should result in more definitive resolution of the appropriate soil management manipulations than is possible by the more commonly employed soil fertility experiments.

A primary requirement, in evaluating land utilization schemes and in developing agronomic and soil management systems, is the careful study of existing practices in the framework of the prevailing socio-economic system. Frequently, generations of experience have led to land utilization schemes that effectively produce substantial food in a manner compatible with the local social system, even if the methodology is inefficient by western standards. Too often, introducing new technology or transferring technology developed elsewhere, results in new agronomic, socio-economic, or political problems. As an example of intensive utilization, Hekstra (22) describes the extremely intensive and effective mixed farming system - field, truck and tree crops, with livestock - on Mid-Java. It is doubtful that introducing western concepts would materially increase the total production per land unit now obtained by the better farmers; yet population pressures, which have reduced the average holding to about 0.5 ha, have led to serious problems. The minimum area to sustain a family of 6 is about 1 ha with current practices.

4. TRANSFER OF SOIL MANAGEMENT TECHNOLOGY

"Soil surveys are essential for the full use of the results of research and of experience related to soil management. For orderly use in technical assistance, these results need to be reported and summarized by specific kinds of soils. No one has yet found a reasonable alternative for assembling knowledge about soils for application to specific land tracts where it applies." (17)

At last we do have a world-wide soil classification system (23). The soils where soil management research has been done, or successful farmers' experiences recorded, need to be classified according to this sytem and the relevant information catalogued. As this system is multi-category in structure, the lower (more detailed) the category used, the more specific the technology transfer can be. Then, in areas where we want to increase production or bring new land into cultivation, the soils in those areas must be classifed and the catalogue searched for information on the soils found there. The chances are favorable indeed that technology learned and practiced on a given kind of soil in one region will be relevant and practical on the same kind of soil in other regions.

Development of a suitable catalog system and devising a system of ready accessibility is a demanding task. Learning to use the system will require adaptive research in addition to experience.

5. GRAZING AND NONARABLE SOILS

In Table 1, 3 billion hectares or 28% of the world land area is classifed as grazing land and 6 billion hectares or 48% of the world land area is classified as nonarable. It may be expected that a substantial portion of the nonarable grouping is also used in some degree for grazing. Use of land strictly for grazing as compared to cultivation is dictated by some combination of factors of soil, climate, fertility, topography, location and local culture. Grazing, range or pasture lands occur in a wide variety of environments from hot and desert, where cultivation is prohibited by lack of water for irrigation, to tundra where climate and permafrost prohibit cultivation. In other cases steepness, rockiness, or shallowness of soil may be the controlling factor in prohibiting cultivation.

Grazing by animals offers the only potential for converting the natural plant crop of these lands to food useful to man. Worldwide, grazing of pasture and range lands tends to overuse, stressing the plants beyond the ability of the site to replace vegetation. Over-grazing continues to become increasingly severe.

Typically, animal numbers rise to range carrying capacity during years when weather results in maximum production of range vegetation. During less favorable weather, animal numbers are not decreased. The grazed area is denuded and erosion destroys the productivity of the soil. A virtually irreversible trend of land resource deterioration results. Techniques of range seeding, reseeding and fertilization are available and biologically effective but frequently not economically effective in the short run.

Use of range land must be planned with a view toward long-term equilibrium between natural forage production and forage harvest by animals. Excess forage produced in good years must be left to carry animals through poorer years. Animal numbers may be adjusted from season to season (virtually impossible in some cultures) or animal numbers must be maintained at the carrying capacity available in somewhat poorer than average years.

Distribution of grazing pressure uniformly over a range area is a key management principle if optimum range production is to be achieved. Development of well distributed water sources is an effective range management tool whether animals are grazed free choice, herded or fenced.

Range management principles are reasonably well established, but their introduction, especially in view of frequent social and institutional restraints, requires a major effort.

D. MINERAL NUTRITION

The discussion so far has dealt with the soil and the water and mineral reservoirs upon which crops have to draw if they are to thrive. Roots are the plant organs evolved in response to the need for the transfer of these inputs into the plant. Just as much is known about the soil and its properties, so a great deal has been learned about roots and their mineral and water absorbing capabilities. Yet there is an urgent need, almost entirely unmet so far, to study the actual interface between the root and the soil - a complex system. It involves the root and its exudates and excretions, the bacteria and fungi more or less intimately associated with the root and their metabolic activities (including absorption and excretion of substances), the moisture in this micro-region and its solutes, and finally, the gaseous micro-environment - all of these components of the "rhizosphere" being in a constant, ever-changing state of activity and flux. It is this micro-region in which the process of primary water and nutrient ion uptake by the root takes place; it is this complex chemistry, physics and biology that the root actually experiences and responds to.

Our ignorance of this vital zone is nothing short of appalling - and for obvious reasons. The system we are discussing is inaccessible, and the processes of gaining access to it tend to alter it severely, at the very least, and usually, to destroy it. At the same time, it is this region where the plant nutritional action takes place - it is here that almost all the chemical elements that are abstracted from the non-living surroundings are initially introduced into the terrestrial biosphere, first plants, and eventually, their animal and human consumers.

1. GENETIC VARIATIONS AND MINERAL NUTRITION

The success in bestowing disease resistance and other useful features on plants implies that plant pathologists and other specialists in crop science joined forces with plant breeders, and that this combination of expertise has proven successful. But those interested in mineral plant nutrition and the salt relations of plants have failed to take that route, with the result that geneticists and plant breeders have not been called in to make their contribution to the field represented by this group of crop scientists.

More often than not, the problems that the plant nutritionist encounters are deficiences of some essential nutrient or nutrients and excesses of others. So far we have dealt with them almost exclusively by applying mineral fertilizers and soil ammendments. Fertilizers were plentiful and relatively cheap, and it paid off to put them on the land. If the soil was not entirely suited to the crop, because of a deficiency or toxicity of some nutrient element, we suited the soil to the crop by supplying that element or immobilizing it. Little thought was given to the alternative strategy, namely, suiting the crop to the soil by purposeful selection and breeding for efficiency of nutrient uptake and utilization. In fact, far from breeding crops for these traits, we often have in effect selected and bred crops against efficiency of mineral nutrition, by selecting those strains that thrived and yielded best under nutritionally luxuriant conditions of fertilization. Fertilizers are no longer in liberal supply, and their cost, in terms of both dollars and energy, is great. It is therefore important, more so than ever before, that we learn all we can about the processes of mineral nutrition in order to maximize their efficiency. And it is equally important that we turn our attention to the genetic aspects of mineral nutrition and collaborate with geneticists and plant breeders in order to develop varieties of crops that are highly efficient in the uptake and utilization of mineral nutrients. Moreover, there is an increasing concern with the possible environmental impacts of applying fertilizers liberally: with pollution, eutrophication, matters of water quality, and other such aspects of fertilizer use. For this reason, too, the genetic approach toward maximizing efficiency of nutrient utilization must be pushed.

Large differences among plants occur in their adaptation to high soil acidity or alkalinity, to saline conditions, and to regions of high heavy metal concentrations (24). Apparently, genetic selection has occurred permitting certain ecotypes to exist, and frequently to thrive, under rather extreme nutritional regimes. Large differences have frequently been observed in nutrient contents of plants, and in responses to applied nutrients, with different cultivars of a given crop species. Transport from root systems of a given species can also vary greatly. The implication is that transport exclusion mechanisms are under genetic control, offering the expectation that appropriate genetic manipulations may permit the development of strains with specific, desirable transport properties. These may involve more efficient absorption mechanisms or effective exclusion mechanisms. The promise of this approach has substantial support from studies involving the differential tolerance to aluminum. This tolerance has been shown to vary greatly among cultivars of a number of food crops (25). In some species the inheritance of tolerance has been worked out (26). With intensive efforts, development of cultivars adapted to acid soils in specific climatic environments seems highly possible. Absorption by plants of toxic heavy metals is also a matter of concern. Breeding for tolerance to such conditions must be explored. Evidence exists for genotypic control of such traits.

Salt impairs or inhibits the growth of crops on an immense world-wide scale. Not only sea water, but much of the water available in the arid and semi-arid regions of the world is in some measure saline. Even moderate salinity, say roughly 3000 mg NaCl per liter, is injurious to many valuable crops. Such salinity is frequently encountered in the soil solutions and irrigation waters of the arid and semi-arid regions of the earth. Yet these are precisely the regions much favored for crop production for many reasons: their unleached soils are inherently fertile, growing seasons are long and light intensity is high, temperatures are high but the humidity is low.

Virtually all economic food crop plants are sensitive to salt. This does not, however, imply that plant life is incompatible with high concentrations of salt in the medium. Witness the phytoplankton of the oceans, the halophilic bacteria, and the salt tolerant land plants - those indigenous to the sea shores, salt water marshes, and saline desert soils. Although there presently exist virtually no plants combining high value as food crops with a high degree of tolerance to salt, recent evidence indicates that salt tolerance can be bred into at least some important crops. Strains of barley and tomato have been shown to be able to grow in media salinized to very respectable fractions of the salinity of sea water. It even seems feasible to think of systems of sea water hydroponics or brackish water hydroponics. Such systems would make the enormous wealth of water of the sea and of the plant nutrients dissolved in it available for crop production. These resources are now useless for this purpose, and in some situations even represent threats to existing agriculture. If these resources could instead be used for the production of crops the benefits would be large indeed.

The expectation for substantial advances to be made also is enhanced by the identification of many specific transport mutants in microorganisms (27) and a few have been observed in higher plants (24). Specific ion-binding proteins have been characterized in microorganisms, and the data suggest that these in fact serve directly in the membrane transport process. Further evidence is afforded by the fact that substrate induction has been observed for absorption of some mineral elements in higher plant tissues or cells, and that protein synthesis may be necessary for the induction to occur (28). Transport of ions across root cells with deposition in the xylem is especially sensitive to presence of protein synthesis inhibitors and hormonal regulation is becoming increasingly evident in this process. The isolation and characterization of specific transport proteins from higher plants now seems to be a reasonable possibility, as does the genetic manipulation of transport characteristics to provide crop plants with enhanced efficiency in responding to their nutrient environment.

2. ALTERATIONS IN THE RHIZOSPHERE

The chemical, physical, and biological state of the soil region immediately adjacent to plant roots is exceedingly complex and highly dynamic. Differences among many individual components exist along the length of roots; marked changes over short periods of time, and pronounced differences among soils and plant species, are common (29). Among the factors which contribute to the complexity of the root systems are (a) the soil is compressed as roots move through it, (b) the CO_2 and O_2 concentrations differ markedly as a result of the respiratory activities of roots and microbes, (c) removal of elements by the roots may be greater or less than their convective transport to the root surfaces in the transpirational water stream leading to depletion or accumulation of elements and to marked differences in the proportions of elements at the surface relative to the bulk soil, (d) acidity may be distinctly altered depending upon the relative absorption of cations and anions and the corresponding net excretion of hydrogen or hydroxyl ions by roots and microbes, (e) the mucilagenous outer layer and the excretion of a variety of soluble organic materials provide a rich microbial substrate and, together with the acidity changes, result in differences in chemical form, oxidation states, and mobility of the mineral elements, (f) microbial populations near or within roots respond to the altered chemical and physical environment resulting in large qualitative and quantitative differences between the root surface and the bulk soil, (g) the associated microorganisms may serve either as diversionary sumps or as efficient scavengers for the mineral elements and they may secrete substances, in some cases host specific, which result in altered root development or altered nutrient absorption and translocating functions. All of these events ebb and flow with time, and distinct modifications occur in different regions of the root and during different growth periods.

There are a number of benefits which accrue from the microbe-root associations in addition to the development of symbiotic nitrogen fixation relationships. Non-symbiotic nitrogen fixing associations have been found in the rhizosphere of some tropical graminaceous species and pronounced differences in cultivars occur (30). Expansion of this capability to major food crops would have enormous benefits (see the report of the Nitrogen Input Working Group).

Very large increases in uptake of phosphate and other poorly mobile ions, e.g. zinc, result from infection of agricultural, horticultural and forestry species with endomycorrhizae. This occurs from extensive fungal growth permeating the soil (at low energy cost), absorption of ions by the fungi, and translocation of them to the root. In monoculture this increased efficiency in uptake is important and it has a further importance in mixed cropping, viz. it enables species with low rooting intensity to compete effectively for nutrients with species with high rooting intensities. Definition of potential responses in many soils with highly selected fungal strains is needed. Application of inoculum, in labor intensive systems could be feasible within the near future but application to extensive areas with low labor input will require much more study (31, 32).

Noninfecting microorganisms in the rhizosphere can assist nutrient uptake by effects on root morphology, e.g. proteoid roots (33). Reports of small to large increases in yield by inoculation of planting material with various bacteria and actinomycetes are occurring in increasing numbers from Europe, Australia and the U.S.A. This subject has been little studied in the past and results are often variable from experiment to experiment. Despite this, it is a field deserving considerably more study and is likely to lead to substantial economic benefit.

The selection of highly stimulative rhizobia, mycorrhizal fungi and rhizosphere microorganisms is of little value unless they can be established in competition with the soil microflora and naturally occurring strains of lower efficiency. In the same way as some soils are suppressive of certain plant disease, some are inhibitory to certain rhizobia and mycorrhizal fungi (34). Establishment of beneficial organisms is likely to have great economic and production consequences in many areas. It is essential that the dynamics of microbial growth in the rhizosphere be studied in order to successfully introduce selective beneficial microorganisms.

Other examples of the importance of the rhizosphere region in effective nutrient utilization exist. Enhanced manganese absorption occurs in response to a compound formed in the presence of rhizosphere microorganisms and iron absorption is strongly dependent upon the secretion of a reductant from root tissues. Substantial quantities of material may be exuded from plant roots. Some of these may enter other species and alter their growth, their ability to compete for nutrients and light, or their rhizosphere microflora. Although the nature of these allelopathic effects is not fully understood, membrane permeability can be distinctly altered by phenolic acids, one of the allelochemicals. It is likely that plant species differ greatly in their response to these chemicals. The allelopathic effects, and the probably associated characteristics of mutual avoidance by adjacent root systems may well be involved in the suitability of intensive intercropping systems. It should also be noted that degradation products of soil organic matter can be absorbed by roots and alter their functions (35, 36); they may provide benefits when inorganic nutrition is not properly balanced or when other stress conditions occur (35). Increases in plant growth following fumigation sometimes cannot be accounted for by control of known pathogens or pests. Presence of subclinical pathogens is implicated and the magnitude of their effects must be evaluated.

It is thus apparent that the root-microbe associations, and the complex events occurring in the rhizosphere region, can result in very distinct advantages as well as disadvantages to plants. Because species differ enormously in their root excretion characteristics and in their associated microflora, because the excretion process varies considerably with plant age, and because sizeable quantities of material may be excreted (37), it seems reasonable to suggest that the rhizosphere populations and activity may be altered beneficially by developing genetic material or cultural practices so that excretion of a suitable combination of materials occurs for the preferential growth of desired microbes. Although the complexity of the work is great, the potential for large benefits is also great. Enhancing the capabilities for non-symbiotic nitrogen fixing associations and for more thorough soil exploitation of essential elements both offer the possibilities of substantial impact on food production.

3. EXPLOITATION OF THE SOIL BY ROOT SYSTEMS

In the field a prolific, much-branched and slender root system can be of great advantage to a plant particularly where soil, water and nutrients are in restricted supply. Many factors, however, can operate against the establishment of such a pattern of development amongst the more common of which are soil compaction, anaerobic conditions, toxic elements, salinity and low temperature. The morphology of a root system can be profoundly modified by any of these influences even though the functions of nutrient and water uptake may not be as greatly affected. This extreme plasticity of response of root morphology should be clearly understood if attempts are to be made to improve root characteristics by plant breeding. It is imperative that selection and breeding of root systems that may combat certain intractable soil conditions should be conducted in the particular situation where the plant is to be grown.

This plasticity in root development can be manipulated, however, to advantage in certain circumstances. Since it is known that localized concentration of nutrients, e.g. phosphate, nitrate- and ammonium-nitrogen, can stimulate intensive proliferation of a limited portion of the root systems, there is an opportunity to place fertilizers at depth in the soil so as to discourage superficial rooting and the consequent dessication hazard. There is also evidence that where the major source of a nutrient is available to only a limited part of the root system there is, in addition to root proliferation, enhancement of absorption in that zone. By continuing these responses the root system may partly, but rarely completely, compensate for a deficiency of nutrients elsewhere in the rooting zone.

A subject which merits urgent attention concerns the patterns of root branching which develop in mixed stands of crop plants. While techniques are available for this work, little has been done. Without some knowledge of how roots of different species are distributed in the soil relative to one another, it is difficult to forecast whether competition for nutrients and water will occur and impossible to follow a rational approach to the placement of fertilizers.

The size of the total root system is fixed largely by the supply of carbohydrate received from the shoot, but the use to which it is put in the initiation and growth of new meristems is flexible and depends, as indicated above, on soil conditions. It follows, therefore, that unless the total photosynthate production by the plant can be increased, any increase in size of the root system can only occur at the expense of the shoot.

Environmental and nutritional stress conditions can exert marked influences on the growth rates of roots relative to shoots. Under constant optimal growing conditions, however, the distribution of dry matter between roots and shoots remains relatively constant during a given growth stage. Altering this more stable characteristic of total dry matter distribution between shoots and roots likely will be more difficult than altering the pattern of growth within the root system itself. Nevertheless, the undertaking is worthwhile because the advantages may be great in some circumstances.

A second consideration having to do with the development of root systems is the abrupt change which usually occurs after the onset of reproductive growth. This more effective sink seriously retards the downward flow of photosynthate; and the functioning of the root system as an expanding, metabolizing, and transporting unit is greatly curtailed. Oddly enough, there is little direct evidence to say whether this massive diversion of materials away from the root system results in a significant detrimental influence on reproductive growth.

Equally lacking are data to say whether these more limited root functions, together with redistribution of materials from other plant tissues to the reproductive tissues, are sufficient to sustain the system at its maximal capacity. It is essential to have more definitive information on this aspect of root functions.

4. ADAPTATIONS IN TRANSPORT PROCESSES

The kinetics of ion transport into plant cells has been described intensively and the mechanisms involved are currently subject to detailed investigation. The state of the art can be considered fairly advanced (38). There are, however, a number of aspects in which information is relatively meager, and which are especially important for plants growing under natural conditions. Most detailed studies have been conducted with root tissue of a relatively few species, usually employing low-salt, high-carbohydrate roots grown under highly standardized conditions in solution culture in which only inadvertent microbial contamination occurs. Roots of plants in the field are not usually in a low-salt, high carbohydrate status. Roots growing in soils differ morphologically from those grown in solution, and they are exposed to an extremely heterogeneous microbial population. Sterile roots do not necessarily behave identically with non-sterile roots, and there is reason to believe that microbes secrete substances which not only influence root development but which also have specific effects on the absorption of individual ions. Moreover, a number of the essential heavy metals, and very likely many of the toxic ones, exist in the soil solution largely as soluble organic complexes (39). If they are transported into cells as the complexes, the process obviously differs from that of the uncomplexed ions, and it is the absorption of the latter which is commonly investigated. Many ions appear to be absorbed by and translocated from root cells along much of their length but differences among elements and among species are evident (40). Because current models of soil:plant systems usually express absorption per unit length of root, this conclusion needs to be thoroughly examined with many species, and with each essential element. Unequal absorption of inorganic ions leads to changes in the organic acids of root tissue. The extent to which these changes in turn modify the functional activities of roots is not well understood.

Once mineral elements negotiate the plasmalemma of root cells, they may be transported across the tonoplast and deposited in cell vacuoles, accumulated by subcellular organelles, complexed with endogenous organic molecules, subject to incorporation into low molecular weight compounds or into macromolecules, or translocated centripetally inward to the xylem via intercellular connections (the plasmadesmata). Forces regulating these relative fates remain enigmatic. Roots also synthesize growth regulators and transport them to the shoots (41) and thereby serve as metabolic units with functions additional to those of an accumulation and transport station for inorganic ions.

Upward movement in the xylem can occur as a result of an osmotic water-flow induced by the accumulation of salts therein, but the dominant force is the transpirational water flow. This implies diurnal variations in the amount and proportions of ions reaching the shoots. Ions are readily removed from the xylem by the surrounding tissue and many enter the phloem for redirected movement. Accumulation by leaf cells from the xylem occurs by plasmalemma transport processes apparently similar to those of root cells. Directed movement from specific regions of the roots to specific regions in the shoots has been observed but the extent of this preferential distribution for particular nutrients and its importance in growth and development are unknown. Many elements in older leaves, under a given stimulus, may be deposited in the phloem and reexported to other, younger leaves, to reproductive tissue, or back to the roots. Some elements (Ca, S, B and Fe) are only very feebly redistributed. The phloem loading process and the rate of movement in the phloem elements is but little understood for mineral elements.

Even in the case of so-called "mobile elements", there is some reason to suspect that the mobilization and redistribution of these reserves from their original points of deposition to functional sites for new growth may not be effective enough to sustain growth rates at their maximum under conditions when the external supply has been depleted (42). The principal regulatory factors controlling overall ion distributions throughout intact plants thus remain very poorly defined. Present methodologies should permit more precise experimentation and such studies should reveal information of value in attempts to utilize mineral elements with the greatest efficiency.

Reciprocal movement of potassium between guard cells and their neighboring mesophyll cells (43) provides an excellent example of regulation of vital plant processes imposed by intercellular transport of mineral elements. The consequences of this process on carbon dioxide fixation, water economy and crop yields are obvious. At the subcellular level, movements of ions into and out of chloroplasts and mitochondria appear to be closely related to their functions, although the appropriate in vivo concentrations and proportions of mineral elements required at specific subcellular and macromolecular locations largely remain unknown. This information, and the manner in which essential elements regulate metabolic processes in vivo during ontogeny must be known for optimal efficiency in the use of the mineral elements. Perhaps what is most important, however, is to determine whether the wealth of information already in hand about nutrient transport and function can be more effectively utilized in predicting the consequences of varied soil and environmental conditions on site productivity and in modifying plant attributes in order to maximize yield potentials.

E. INTEGRATION

Kellogg and Orvedal (17) stated:

"The most important single principle for guiding improved farming and agricultural development is the principle of interactions: Each practice or each program within a system affects all other components of the system, so that a proper combination gives a far greater result than the sum of the several components considered singly. The principle of interactions has been cryptically defined as a peculiar kind of mathematics from which the whole is much greater than the sum of its parts."

The obvious counterpart of this statement suggests that an improper combination gives a result less than the sum of the parts. Too often, changing one link in the complex systems of soil and water management results, presently or ultimately, in severe weaknesses elsewhere. Introduction of insectides may reduce the bee population and inhibit pollination. Reducing the labor requirements in forest clearing by mechanization may also reduce soil fertility, compared to burning. Much has been written in recent years about systems analysis and its formal tools of mathematical manipulations. Valuable as these techniques are they are no substitute for sound judgment based on thorough understanding.

Of particular importance in considering fuller utilization of the world's soil and water resources is the constant realization that the purpose is optimization of productive use of a limited resource base within the frame-framework of our established social system. Many changes may often be needed in infrastructure, marketing facilities, education, etc., before technological innovations can be gainfully introduced. But unless such changes are constructively absorbed in a total socio-economic system, they may do more harm than good.

RESEARCH IMPERATIVES

The first priority for increasing world crop production is to develop the mechanism for, and implement, an effective transfer and adaptation of technology to utilize currently available water, soil and crop management principles and practices on potentially productive soils in the proximity of needy populations.

WATER RESOURCE UTILIZATION

1. Devise systems of combined water, soil and crop management for maximum crop return per unit of available water and maximum conservation of soil water.

> Water, in shortage or excess, is the most common limiting factor in production. Areas of ample annual precipitation often suffer from critical drought periods, as well as periods of excess water. Irrigation water use efficiency is highly management dependent. Where total supplies of water are short relative to available land, maximum production may result from limited irrigation of extended areas. Precipitation on recently irrigated, wet or shallow soils cannot be stored for future use. The need is to add or remove water to optimize total utilization, preferably through total water management. Research should lead to:
>
> a) systematized rational design criteria for drainage,

b) efficient maintenance of high soil water contents for maximum plant production,

c) methods of forecasting crop water requirements and timing of irrigations,

d) methods of controlled drainage for subirrigation and ponding,

e) techniques for environmental modification including frost protection, delayed tree budding and modifications of rooting patterns,

2. Transfer available technology and develop new technology for erosion control to prevent the irreversible loss of agricultural land, especially marginal land coming under intensified production.

> Erosion is a potentially critical problem on land with steep slopes, long slopes, high rainfall, and/or fragile soils being brought into intensive crop production. Since soil is essentially a nonrenewable resource, effective control methods must be developed and related to different crop management practices for many soils and climates where current information is inadequate, suitable for adoption in the local socioeconomic environment.

3. Investigate the extend to which whole plant and cell water relations affect crop productivity and the degree to which they can be modified to suit particular field environments, and search for naturally adapted genotypes.

> The natural ecosystem is controlled by many interacting factors impossible to control or evaluate in one encompassing field experiment. Identification of the limiting process(es) in a reasonable time frame requires special, interdisciplinary

approaches. Modeling enables effective communication and integration of inputs from various scientists to speed up identification of those plant processes that limit crop yields most. Selection and breeding can relax or eliminate these bottlenecks.

4. Devise soil and water management systems to prevent deterioration of productivity through inadequate drainage and salinization.

Annually more land is taken out of production by salinization than added to the productive base through irrigation. Yet new irrigation is currently planned on well over 30 million ha. One of the most effective ways to maintain or increase our food production base is to avoid such salinization. Sophisticated and often untested techniques are needed to this end, if water is to be used effectively.

5. Devise systems of crop production which will enable agriculture to proceed in harmony with the total community.

Irrigation is by far the greatest consumer of diverted waters. This use is competitive with all other uses. Drainage water from irrigated lands always contains increased mineral salts, and often other farm wastes as well. Rainfall runoff of drainage water also may contain sediment and farm-derived nutrients or chemicals. Agricultural water management must use the water effectively for crop production, using no more than needed. Runoff and drainage waters should be managed to enhance their quality, or keep their deterioration to a minimum, and controlled to enable beneficial use while avoiding flooding. Whereas food production is of highest priority, management systems on the farm should enhance, where possible, the quality of community life.

Investigative techniques and evaluation systems are needed to provide a basis for quantifying the interactions between crop production practices, off-farm water supply and quality, and the many off-farm water uses.

SOIL MANAGEMENT

1. Design strategy for worldwide technology transfer through application of transfer principles inherent in the new Soil Taxonomy.

Much soil management information, obtained from research and farmers' experiences, exists; but it is widely dispersed and used only locally. Until today no sound basis has existed for the transfer of such information to widely separated areas with reasonable assurance that the transferred technology would be applicable. The new Soil Taxonomy makes reliable transfer promising. This taxonomy enables the transfer of in-information among soils similarly classified regardless of how widely separated physically they may be.

2. Tailor soil management practices for poor, subsistence farmers in developing countries.

The world food problem is largely a problem of the small farm in the tropical developing countries. The farmer's moods, needs, and aspirations are often different from those of the farmer in developed countries. The technology for increasing crop production must be designed to fit the culture of the recipient of the new technology.

3. Develop soil technology for making possible sustained food production on problem soils (mainly Oxisols, Ultisols, Alfisols, and acid sulphate Inceptisols) of the tropics.

> Vast areas of the tropics have soils which possess one or more characteristics seriously unfavorable for sustained crop production. Important among these are aluminum toxicity, phosphate fixation, low fertility, and high content of sulfides. For soils with such problems, technology and experience from developed countries do not apply. Many, perhaps most, of the problems are correctible but only at prohibitively high costs. Practical and economical corrective measures simple enough for farmers to apply have yet to be developed and tested on farms.

4. Quantify soil-related plant stresses for the purpose of coordinating soil research with, for example, genetic control of mineral nutrition and mycorrhizal proliferation.

> Soil-related stresses which limit crop porduction can be eliminated or decreased by soil management and/or plant genetics. A combination of soil management and plant selection is probably the best approach to overcome stresses. These stresses must be quantified to enable selection of resistant plants.

5. Develop better soil management practices that improve soil physical and chemical characteristics (e.g., soil structure) for the purpose of increasing seed germination, root activity and H_2O infiltration and decreasing soil evaporation from both mono-crop and multiple crop systems.

Many farmers in developing countries

practice multiple cropping, whereas in developed countries mono-culture is almost universal. These systems represent different cultures and require technologies appropriate to each. There is a need, and a potential, for soil management improvements in both cultures.

6. Identify locally avalable and inexpensive sources of soil amendments and plant nutrients including wastes and crop residues, and develop means to increase efficient use of these and conventional fertilizer.

Low farm incomes and high cost of purchased inputs prevent the small farmer from applying soil amendments, including fertilizers, to increase crop production. Identification of products which can be processed locally and handled by farmers will insure greater use of practices which will increase food production.

MINERAL NUTRITION

1. Select and breed purposefully for efficient plant use of soil resources and fertilizer, thus devdloping genotypes specifically for problem soils (e.g. saline, acid, or with some ion-toxicity) and for highly fertile soils.

Adverse nutritional features of soils range the gamut from deficiencies of essential plant nutrients to excessive concentrations of harmful components such as salinity and toxic ions. Rather than the conventional approach of modifying the water-soil system to suit the plant, we propose another: the strategy of genetically tailoring the plant to the substrate. Incontrovertible evidence indicates the feasibility of this novel departure. It requires the application of tried-and-true methods of genetics and plant breeding to a new task: that of creating strains of crop specifically suited to particular soil conditions. Collaboration between plant nutritionists and plant breeders, heretofore lacking, must be generated to implement this objective.

2. Stimulate plant growth by establishing beneficial root-microorganism associations through:
  a) selecting highly efficient mycorrhizal fungi for particular soils and plants, and developing methods for their introduction and manintenance,
  b) testing stimulative rhizosphere bacteria, and,
  c) learning to control biological antagonism to mycorrhizal fungi and rhizobia.

Endomycorrhizal fungi occurring on most agricultural and horticultural plants have given spectacular plant growth increases in soils of low and medium fertility both in glasshouse studies and in limited field atudies. Marked differences occur between selected mycorrhizal fungi, and many naturally occurring ones often have no effect. Methods of production of appropriate inoculum at present are potentially a relatively short step from implementation in labor intensive systems. Application to large area-low manpower systems will require more effort but is feasible. Supportive basic research should study principles of microbial growth around roots to overcome shortfall to response to mycorrhizal fungi, rhizobium and stimulative rhizosphers bacteria due to microbial competition from naturally occurring organisms.

3. Quantify nutrients and water absorption from the soil by the component species of multiple-

cropping systems and the distribution of roots of the different species in order to devise suitable fertilizer practices that ensure maximal utilization of all soil resources; and precisely characterize the environmental and endogenous control of root proliferation as essetntial basic support for these studies.

At present most of our limited knowledge of root development has been obtained from crop plants grown in monoculture and in uniform deeply cultivated soils. While there remains much to be learnt about the control of root growth in these circumstances, there is more pressing need for detailed observations to be made on the root distributions and absorptive characteristics of two or more crop species growing together. This is necessary before we can predict how, or whether, these plants will compete with one another for soil resources. This system of mixed cropping is very widely practiced in small farms of developing countries and the direct transfer of existing fertilizer practices, developed generally for monoculture, may not be possible. The research proposed is essential for devising new and efficient soil management practices.

4. Quantify the chemical, physical and biological properties of the root soil interface and its role in mineral nutrition and water uptake.

The interface of root and soil (the rhizosphere) is markedly different from that of bulk soil and determines the concentration of ions present for uptake, for the growth of symbiotic and disease organisms, and for root function. Many of the bases of genetic susceptibility to, or tolerance of, adverse nutrient conditions may reside in this small but important zone. Its understanding is basic to concepts of nutrient uptake from soil. The present poor understanding of this extremely crucial region has been due largely to the absence of suitable techniques. However, sophisticated equipment now available and innovative approaches should allow the urgently needed progress to be made in understanding the complex nature of the rhizosphere.

5. Elucidate the mechanisms of selective ion absorption (single ions or complexes), exclusion or extrusion of extraneous and potentially toxic ions, and distribution and redistribution of ions at the cellular and organ levels during various stages of the growth cycle.

Mineral nutrients initially in the soil play their evenutal essential metabolic functions in the cells of plants. This statement implies the paramount importance of ion transport, beginning with transmembrane active transport in root cells. There follows a progressive partitioning of the ions in the plant, its organs, tissues, cells and subcellular organelles. This process is accomplished through agencies ranging from transport proteins to mass flow in complex ducting systems connecting the remotest rootlet in the soil with the topmost leaf of the plant. The study of the metabolic control and integration of ion transport is important, rendered all the more exciting and promising by the breakthroughs that are now in the offing as a result of new research techniques. The involvement of hormones in ion transport holds promise for deliberate intervention in the process with a view to its optimization for maximal crop productivity.

IMPLEMENTATION

1. Utilization of existing knowledge can in the short run accomplish a great deal more than expanding basic knowledge.

The immediate problem is increasing food production by poor, subsistence farmers in regions of high population density. The welath of information already available about crop productivity must be got to, and utilized by these farmers immediately. What is not required in those countries most affected is the early development of large basic research oriented science capability. This information (for the short run) is already in hand or is emerging from the laboratories and fields of the more developed countries. What is required is a group of scientists and agriculturists able to, and devoted to, providing information of such nature and in such form that it can be utilized by the farmers.

2. Creation of additional International Research Centers with clearly defined missions should be an effective tool towards increasing food production.

The past successes of several of the International Research Centers suggest that much can be accomplished by assembling groups of competent, dedicated scientists of various descriptions to work towards clearly defined missions in close cooperation with national or local research units in appropriate countries. Whereas such centers could be located on University campuses, the need for continuity and single-minded dedication requires they be separate organizational units

3. Improved continuity of communications among all those involved in research applied to food production is necessary.

Most of the scientists and agriculturists devoted to putting current knowledge directly into practice must work at locations remote from their colleges. They must keep abreast of current research and its implications. Thus special attention must be given to development of newsletter networks and frequent opportunity for periods of intensive library study and direct involvement in active research at International Centers and Universities having vigorous specific research programs on crop productivity.

The need for another kind of continuity must also be recognized. It is well to remember that the success of U.S. Colleges of Agriculture resulted in part at least from the opportunity for transfer of information and ideas in small discrete steps from chemistry and physics to biological control mechanisms to behavior under natural conditions to production practices to explaining to producers how to increase production. What is crucial is that the gaps in comprehension between those communicating must be small. For example, the optimal communication sequence is not: biochemist → plant breeder; it is: biochemist → cell physiologist → plant physiologist → plant breeder.

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PLANT PROTECTION FROM PESTS

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INTRODUCTORY STATEMENT OF THE PROBLEM

One of the major factors in preventing crop production systems from delivering harvests near their full potential is the activity of pests. Pest organisms occur among all forms of life, including viruses, bacteria, fungi, weeds, nematodes, arthropods, molluscs, birds and mammals. The number of species which are known to reduce yields is legion and includes 8,000 species of fungi, 10,000 species of insects and about 2,000 species of weeds. Roughly 10 percent of these species are perennially important.

As an example of the necessity of protection against pests, it has been estimated that pests in the United States (1) and the world (10) destroy one-third of the potential harvest. For grain crops this loss exceeds quantity available for export. It was concluded in 1972 that crop losses caused by insects and diseases in the U.S.A. (9) have increased both absolutely and as a percentage of crop value since the 1940's, but that the opposite may be true for losses caused by weeds. In the case of weeds, the growing availability of improved herbicides is largely responsible for important gains in agricultural productivity.

Progress in reducing losses from insects and plant pathogens has been impeded by various changes in production practices which may favor these pests such as the shift to virtual monoculture of important crops, the increased use of irrigation and inorganic fertilizers, the introduction of multiple cropping and longer production seasons, the widespread use of genetically uniform varieties, and the trend toward reduced tillage. In addition, pest species of foreign origin continue to penetrate quarantine barriers and occupy extensive areas.

Although the main stress in this report is laid on pest arthropods, weeds and pathogenic microorganisms, it must be remembered that great damage to crops may be caused by nematodes (29), by rodents, birds and other vertebrates (20), and even by molluscs. In many situations the post-harvest losses due to pests can exceed the loss they have imposed before the harvest. The two problems are more severe in the tropics where the majority of the less developed countries are located, the first being largely due to lack of storage space and the second due to the more rapid developmental rates at the higher temperatures.

Crop protection has two important objectives, firstly to reduce the losses in potential production which are caused by pests, and secondly to reduce the adverse environmental effects due not only to the pests but also to the methods of combating them.

Aggravating the difficulty being experienced in reducing pest losses, there is the additional problem that crop protection technology in agricultural practice becomes obsolete at an alarming rate. For example in only 3-10 years many resistant crop varieties became obsolete because the pests developed new strains and biotypes that overcome the plant resistance mechanisms.

The very substantial losses that occur after harvest were recognized but are not covered by any research imperative. However, it is an alarming fact that the fumigants needed for coping with this problem are likely to become less available. Meanwhile this situation is further deteriorating due to the increasing resistance of stored-product pests to pesticides.

On the understanding that the critical period for crop productivity is the next 25 years, the working group agreed that the greatest opportunities for contributions of crop protection research fall into 6 broad research imperatives. These imperatives do not include all the important research opportunities, but only those believed to have the greatest potential for impact. These six broad research imperatives are as follows:

1. Research on the development of integrated management systems for stable crop production suited to various styles of agriculture.
2. Research to increase understanding of the fundamental biology of pests.
3. Breeding for stable resistance to plant pests.
4. Expanded research towards the development of biological control.
5. Better pesticides and better use of pesticides.
6. Innovative approaches for plant protection.

For all classes of pests, first priority should be given to research for developing integrated management systems to protect and ensure stable crop production. Stable production is not assured by total reliance on a single control method, but is more likely to occur when the burden of crop protection is shared by a number of control methods. For example, in the case of weeds the combination of methods might include mechanical tillage, herbicides and crop rotations. In the case of plant pathogens and insects, the combination of methods might include resistant crop varieties, biological control agents, and cultural measures, and when these fail then chemical pesticides would be employed. With the no-tillage style of agriculture, a pre-planting herbicide is followed by the surface interseeding of crops (e.g., wheat followed by soybeans) to produce a dense soil cover which requires the minimum of treatment with a post-emergence herbicide.. For all classes of pest-control problems, the most efficient and sound approach to the development of integrated management systems for crop protection is to use the methods of systems science.

Indispensable to crop management systems is intensified research to increase the understanding of the fundamental biology of pests. Indeed inadequate knowledge of the pests themselves is a major constraint on the development of superior control methods and of integrated management systems for crop protection. The inadequacies vary greatly with the pest in question. Nevertheless even for the major pests our ability to devise fully adequate crop protection strategies is impaired by serious lack of information on some aspect of one or more of the following areas: epidemiology, population dynamics, detection and sampling methods, genetics, behavior, developmental biology, life cycles, dormancy, survival, virulence, mode of action and host specificity.

For the control of pest insects and plant pathogens, but not for weeds, the first priority should be assigned to breeding the crop plants for stable resistance. For weeds, however, the higher priority must be given to developing the use of chemical herbicides. A large number of improved herbicides are becoming available, but the number of weed scientists is everywhere grossly inadequate to conduct the research needed to find the best ways of using these selective tools of vegetation management. Moreover information is simply not available to assess the extent to which the natural resistance of crops to weeds through allelopathy can be applied in agriculture. Important isolated cases of allelopathy may be developed, but this mechanism may not have broad application in protecting crops from weeds other than forage species in rangeland, because the biological agents characteristically attack a particular species of weed but not the entire undesired flora that competes with the crop.

It may be generalized that for the control of insects and plant pathogens the necessary integrated systems are best generated from an extensive knowledge of the biology of the pest, built on the foundation of crop resistance and supplemented by the exploitation of biological control agents, with pesticides being held in reserve for use when a breach in these defenses occurs. For weed management, on the other hand, herbicides are the primary tool to supplement mechanical cultivation and managerial methods such as crop rotation, and may even be a substitute for the cultivation and rotation of crops.

Finally the working group felt that significant resources should be channeled into the possible discovery and development of innovative methods of pest control. Developments in several diverse scientific disciplines may unexpectedly converge to form the basis of a new technology. Studies have shown that on the average the time from conception to first realization of a new technology is 19 years. We should always be ready and able to take advantage of unexpected developments in the broad field of science and technology which may be significant for crop protection.

CLASSIFICATION OF RESEARCH IMPERATIVES

1. Research necessary for development of integrated management systems for stable crop protection suited to various styles of agriculture.
    - (a) Identification and quantitation of the basic biological and physical parameters of a particular pest system,
    - (b) Characterization of modeling of the dynamics of the individual pest systems in quantitative terms,
    - (c) Development of an overall descriptive model of the total crop-pest ecosystem,
    - (d) Development of a management model by expansion of the crop-pest model to include control methods,
    - (e) Development of an implementation model for practical crop protection.
2. Increase understanding of the fundamental biology of pests.
    - (i) Assessment of genetic plasticity of pest species,
    - (ii) Studies in population genetics of pests,
    - (iii) Determination of the mechanisms of stress survival in pests,
    - (iv) Assessment of genetic exchange among plant pathogens,
    - (v) Selected studies on vital processes in the developmental biology of pests.
3. Breeding for stable resistance to plant pests.
    - (i) Development of resistant cultivars,
    - (ii) Conservation of resistance germplasm in germplasm preserves,
    - (iii) Investigation of host-pest interactions in germplasm preserves,
    - (iv) Search for additional sources of resistance,
    - (v) Search for sources of competitive

ability (e.g. allelopathy),
    (vi) Identification of mechanisms of resistance and allelopathy.

4. Expanded research for the further development of biological control.
    (a) Search for areas where effective biological control occurs,
    (b) Identification of specific biological agents responsible for control,
    (c) Evaluation of biological agents in practical agriculture,
    (d) Analysis of physical factors and biological agents for the stabilization of control,
    (e) Development of mass-culture and release methods,
    (f) Combinations of the biological agents to obtain the widest effectiveness,
    (g) Incorporation of the use of biological agents into crop production systems.

5. Better pesticides and better use of pesticides.
    (i) Development of a diversity of selective chemicals,
    (ii) Development of novel chemicals for specialized uses,
    (iii) Improved strategies for utilizing available pesticides,
    (iv) Measures for avoiding the consequences of pest resistance to pesticides,
    (v) Elucidation of mode of action and metabolism of pesticides.

6. Innovative approaches for plant protection.
    (i) Genetical control methods for certain pests,
    (ii) Remote sensing for control operations against migratory pests,
    (iii) Controlled-release formulations of pesticides,
    (iv) Chemicals for modifying insect behavior,
    (v) Innovation on a variety of fronts.

DETAILED STATEMENT OF RESEARCH IMPERATIVES

1. RESEARCH TO DEVELOP INTEGRATED MANAGEMENT SYSTEMS

Crop production often fails to be reliable when it is based on a single pest-control method. Stable production is more likely to be achieved when the burden of crop protection is shared by a number of control methods. Moreover, approaches to crop protection must be adapted to changes in production technology, be economically and environmentally sound, and in addition socially acceptable. Integrated management systems of crop protection (19) are needed for various styles of agriculture ranging from large-scale and heavily capitalized operations to the small-scale and labor-intensive situation in developing countries. The designing of such systems for crop protection is strongly facilitated by the assembly and correlation of the relevant data according to the methods of systems science (21).

Five sequential phases can be identified (14), the research element in terms of biological discovery being particularly high in the initial ones, while the latter and final phases are mainly developmental, refined by supplementary heuristic research.

(a) Identification and quantitation of the basic biological and physical parameters of a particular pest system. This often requires research on biological and ecological factors such as elucidation of developmental cycles, dispersal, survival of each developmental stage, and overwintering. Many of these factors must be quantitatively expressed as functions of the physical and biological environment. Such information can be obtained only throv painstaking research.

(b) Characterization or modeling of the

dynamics of the individual pest systems in quantitative terms. Data on dynamics must be acquired through studies under a variety of environmental conditions.

(c) *Development of an overall descriptive model of the total crop-pest ecosystem*. This comprehensive model must be based on the models of individual pest populations and of the crop. Considerable research in the field is needed to validate the model.

(d) *Development of a management model by expansion of the crop-pest model to include control methods*. Research is needed to adapt this model to the use of combinations and sequences of control methods, as well as the use of methods one at a time, and to allow for variations in production practices. For certain pests, research to establish economic density thresholds is necessary to complete this phase.

(e) *Development of an implementation model for practical crop protection*. The implementation model consists of the best combinations of measures as indicated by the management model. Implementation requires considerable research on (i) improved methods for detection, sampling, monitoring and prediction of the population states for pest, crop and biological control agents, (ii) improved environmental monitoring systems to assess meteorological conditions that affect the biological elements described above, and (iii) extended applications of communication systems to enable rapid information flow from field sensors to the interpretative analysis facility. In turn practical recommendations must be sent to the grower or decision-maker for timely response.

The development of such management systems for crop protection is greatly facilitated by the use of high-speed computer and other modern technology. However the availability of such technology is not a prerequisite to using the logic of systems science for development of integrated crop protection systems. Furthermore, implementation systems need not be highly sophisticated, although the use of real-time weather acquisitions systems which interface with biological monitoring outputs are helpful in certain cases for the rapid delivery of information to the decision-maker.

The five research imperatives which follow, although valid in their own right, would be of maximum value when executed for the purpose of providing the constituent technology needed to devise and achieve highly effective systems for crop protection.

2. RESEARCH TO INCREASE UNDERSTANDING OF THE FUNDAMENTAL BIOLOGY OF PESTS

(i) Assessment of the genetic plasticity of pest species

In devising pest management systems for any existing pest problem, it must be remembered that plant pathogenic organisms, pest arthropods and weeds are capable of altering their characteristics and enlarging their geographic distribution. The pressures of the control methods can induce changes in their characteristics, and the great increase in intercontinental air travel often enlarges their geographical range. Stable control measures presuppose stable pests. It is clear that research should be applied to anticipating these probable developments rather than responding to the serious control failures that they would incur.

Several lines of inquiry are particularly relevant to this problem. A study of the variability to be found in the pest at the host's epicenter would go far towards revealing the range of potential varieties that might confront us. A forewarning of possible future host-pest interrelationships may be obtained by screening the entire available range of germplasm of both the pest and the host.

(ii) Studies on population genetics of the pest

There are indications from studies of fungal pathogens in the field that populations may show quantal differences in fitness. Research techniques are becoming available to measure changes within a species of its survival characteristics, ability to spread, infection capabilities, and pest densities. These techniques should also be applied to detect and measure changes in a given population over time (e.g. from year to year). Studies on the underlying genetical factors for these characteristics then become essential to reveal the manner in which this phenomenon of population genetics is determined and modulated. With insect pests, the finding that European corn borer populations in Iowa differ from those in New York state in the pheromone mixtures to which they are sensitive illustrates the importance of population characteristics in devising control strategies for a given area. Problems in weed control have scarcely been directed to such research channels at the present time.

(iii) Determination of the mechanisms of stress survival in pests

It is imperative to study pest species at the points in their life-cycle which are weakest or at which they are most in jeopardy. The carryover of the pest from one growing season to the next depends upon its resistance to the stress applied, whether it be low temperature, drought, flood, or the drastic tillage or removal of all food and shelter which may occur in normal agronomic practice. Therefore full assessment should be made of the survival characteristics and mechanisms of the pest species to these various stress factors; particularly relevant are the phenomena of diapause and dormancy. These will serve as a guide to improving the existing plant protection practices, as well as to devising new ones.

(iv) Assessment of genetic exchange among plant pathogens

The genetics of plant pathogenic bacteria and viruses is poorly understood, in contrast to the wealth of information available about their medical counterparts. We now have the ability to extend the study of molecular genetics to plant pathogens in order to (a) assess the capacity of these pathogens for genetic exchange leading to evolution of new races and strains, and (b) probe molecular mechanisms of virulence and host specificity by mutant analysis and construction of isogenic strains.

It is known that many genera of bacteria contain accessory genetic elements called plasmids which are capable of autonomous replications. These elements are often infectiously transmitted from cell to cell and can act as vectors for chromosomal genes. Plasmids of animal pathogens are known to carry determinants for virulence, multiple antibiotic resistance, and new metabolic capabilities. Plant pathogenic bacteria contain plasmids but in most cases their functions are as yet unknown. It has also been shown that plant pathogens can accept plasmids from other genera. Due to the enormous potential for the rapid distribution of genes by plasmid vectors, the role of plasmids as determinants of virulence and sources of resistance to pesticides should be assessed.

(v) Selected studies on vital processes in the developmental biology of pests

Basic physiological research can reveal weak points in the processes of growth, development and reproduction in the pests which may be highly relevant to the optimization of control procedures. The biochemical factors which control the transition from one stage or condition to the next, e.g. moulting and dormancy in arthropods, germination and dormancy in weeds, and germination and infectibility in fungi, are usually hormonal in nature. This calls for basic research of the highest quality to achieve understanding of the factors which inhibit or induce these processes. Particularly important is the study of the biochemical processes which determine virulence in pathogenic microorganisms and host selection in insect pests.

3. BREEDING FOR STABLE RESISTANCE TO PLANT PESTS

Plant varietal resistance to damage by pathogens (23) and by insects (27) is a most desirable and effective control method for plant pests. In weed control the phenomenon of allelopathy, the inhibition of growth of one plant species by chemicals released from another species (25), has not been extensively explored in weed control. Typically varietal resistance is environmentally compatible, safe for humans, and provides maximum economy and convenience for the farmer. Although a number of years of research are usually required to produce a resistant variety, and although the length of time that resistance will remain effective in a given variety cannot be predicted, experience has shown that the return on investment for research on plant resistance is exceeded only rarely by other methods of plant protection (22).

Resistant varieties are completely compatible with all other methods of pest control and indeed often enhance their effectiveness. Even low levels of plant resistance may be sufficient to reduce substantially the need for pesticides and other control measures. Thus suitable resistant varieties whenever available should be used as basic components of integrated systems of plant protection.

(i) Development of resistant cultivars

The use of specific monogenic resistance often has given protection of short duration only. This has been especially so against pests which have very high rates of multiplication. For such pests, it is likely that mutations will occur which overcome the resistance of the crop and that such mutant pest strains will become predominant in the pest population. General (nonspecific) resistance and tolerance which have polygenic bases usually provide some protection and are not readily overcome by mutant strains of pests. Thus every effort should be made to use genes for general resistance and tolerance obtained from diverse sources, and to add to them the genes for specific resistance (5). Indeed genes for specific resistance, general resistance and tolerance are miscible in all proportions and should be so used in crops to give marked stability.

If diverse genes for resistance are available, several crop lines can be developed (isolines) in each of which resistance is determined differently. These lines can then be sown together to form a stable multiline cultivar. Alternatively when a number of different genes for specific resistance exist, they may be combined into a single cultivar with immunity extending to many mutant pest strains.

(ii) Conservation of resistance germplasm in germplasm preserves

Germplasm in seed banks represents a fraction of the species diversity in nature. Germplasm in such banks is subject to some risk of loss, but more importantly it is sheltered from further evolution through selection pressures from the interactions of the host with its pest and antagonists, predators and hyperparasites.

Germplasm preserves should be located in the centers of origin, where coevolution can continue in all biological entities involved, and where germplasm of each entity can be collected by future scientists for study and incorporation into desired cultivars and biological control systems.

(iii) Investigation of host-pest interactions in germplasm preserves

Current concepts of host-pest interactions have been derived largely from studies in laboratories, greenhouses and farm fields. Precise understanding of these interactions is vital to the proper use of resistance germplasm. Such precise understanding would be more reliably derived by analyzing the ecology of hosts, their pests, hyperparasites and their equivalents, in natural ecosystems by means of conventional techniques.

(iv) Search for additional sources of resistance

Globally the rapid expansion of acreage under cultivation and the widespread use of new high-yielding cultivars is endangering many wild species of plants with potentially useful germplasm as well as local races of cultivated crops. Therefore, such plant populations should be sampled systematically, their seed should be preserved, and the value of their germplasm should be assessed relative to today's need. Wild species have contributed many useful traits. For example *Avena sterilis* from Israel and North Africa provided the cultivated oat with genes for resistance to several diseases, as well as for high yield, high protein content, and heat tolerance. Similar opportunities appear to exist for cassava, potato, and many other crops.

(v) Search for sources of competitive ability (e.g. allelopathy)

Although plant breeders have successfully incorporated both insect and disease resistance into cultivars of many crops, there has been no concerted effort to develop crops with increased levels of weed resistance. Two mechanisms for weed suppression by crops have been proposed: (a) allelopathy, and (b) superior ability to compete for a critical growth factor.

Allelopathy occurs widely in natural plant communities, and has also been discovered in accessions of several important crop plants e.g. cucurbits. Whether wild progenitors of many of our important crop plants may contain high levels of these natural herbicides as a mechanism for survival should be investigated. Although naturally occurring plant toxins have demonstrated a high level of activity against various weeds, the heritability of these factors in crop plants has not been assessed.

Some crops have a superior ability to compete with weeds for critical growth factors such as specific nutrients, water, and light. Cultivars specifically bred for more vigorous canopies or root systems should provide at least a partial degree of weed control. Either of these two mechanisms would provide a valuable new strategy for weed control.

Creation of crop plants with the ability to suppress weeds would allow reduced inputs of energy into the cropping system. Crops exhibiting allelopathy could be grown not only for production of food but also for suppression of weeds in a crop rotation system, provided they do not suppress the subsequent crop.

(vi) <u>Identification of mechanisms for resistance and allelopathy</u>

An understanding of the cellular and biochemical events which cause resistance and allelopathy is needed in order to devise more rapid screening procedures in plant breeding. It would also serve to develop novel control methods, such as the induction of resistance in normally susceptible crops by applications of a chemical. For the long term, such understanding is required as a basis for genetic engineering to enhance resistance by providing multiple biochemical mechanisms in a single cultivar. In addition, such knowledge would permit an assessment of the possibility that certain biochemical processes causing resistance or allelopathy may inherently limit plant productivity.

In some cases the bases for the virulence of pathogens and for the host preference of insects and of nematodes (29) are understood, but a wider understanding would be of value in breeding. Partial chemical characterization of the toxic metabolites produced by certain fungal pests has been useful for quickly identifying host cultivars resistant to the pathogenic species which produce them. Chemical characterization and knowledge of biosynthesis of these metabolites should lead to laboratory prediction of the pathogenic potential of pest species.

4. EXPANDED RESEARCH FOR THE FURTHER DEVELOPMENT OF BIOLOGICAL CONTROL

It is imperative to discover and identify all possible biological control agents, determine their interaction with physical and biological factors in the environment, and develop management principles for their use in practical agriculture.

Biological control of plant pests has been utilized in agricultural practices since 1886, when the vedalia beetle was successfully introduced into California to control the cottony cushion scale attacking citrus (17). Since that time, literally hundreds of natural insect enemies have been introduced from many parts of the world into various countries to control at least 223 insect pests. In Australia, the prickly pear was controlled in the 1920's by introducing the caterpillar Cactoblastis cactorum which feeds upon it and infects it with a pathogenic bacterium. The oak root fungus has been controlled effectively for many years by fumigating the soil with carbon disulfide to alter the constitution of the microflora to one antagonistic to the pathogen (2).

There are now a number of instances of biological control solving important crop problems, but the technique has not achieved wide application. Since a basic level of biological control probably exists for every pest, - and indeed all weeds have their pests-, it appears that its characteristic role is as a component of integrated pest management systems involving a multifaceted and coordinated attack on the pest. Biological control is especially suitable for use against insects and plant pathogens in the developing countries because of its relative permanence, low capital investment, and freedom from sophisticated managerial problems. In all countries it has the advantage of being environmentally non-polluting (11,13).

Although biological agents may occasionally suffice as the sole suppressive weapon, (e.g. the vedalia for the scale insect of citrus already mentioned, Chrysolina beetles for St. Johns wort, the fungus Peniophora gigantea for Fomes annosus infection of pine) they usually are employed in concert with other techniques. The control potential of natural enemies is often jeopardized by the application of persistent broad-spectrum insecticides, and their virtual obliteration in some cotton areas has so aggravated the problem of insecticide-resistant tobacco budworms that it can result in the collapse of cotton production, as in northern Mexico. Crop protection practices which conserve these natural enemies, and especially the substitution of more selective and less persistent insecticides, are urgently needed.

To satisfy the overall imperative for expanded biological control, seven principal research areas should be exploited, usually in sequence, by the following actions:

(a) Make worldwide searches for areas of effective biological control or pests,

(b) Identify and investigate the specific biological agents responsible for maintaining the pest equilibrium at a low level in the indigenous areas,

(c) Evaluate selected biological control agents under conditions of practical agriculture in the application area,

(d) Analyze physical factors and biological agents necessary to stabilize biological control under conditions of practical agriculture,

(e) Develop superior methods for mass culture and release of primary biological control agents, with particular reference to the propagation on artificial media,

(f) Use combined biological control agents of the important pests to obtain suppression of all life-stages in all ecological niches,

(g) Integrate the biological control agent with all other components of the agroecosystems under conditions of practical agriculture.

While most of the natural enemies of the important insect pests have been identified and often exploited, the search has been less complete for biological control agents of plant pathogens and weeds. The most profitable areas of search usually have been the native habitat of the insect pest, the weed, or the disease. Selected areas, usually with climatic conditions similar to that of the problem area, are visited by an investigator who determines the parasites and predators of the insect pest, the parasite on the weed, or antagonists operative against the pathogen. With plant pathogens it is necessary, by means of selective culturing and selective soil treatment, to determine the groups of microorganisms responsible for the biological control. With insects, attempts are made to free the parasite from secondary parasites before it is exported.

Biological control of insects or weeds is generally accomplished by a specific one-to-one relationship between a single parasite or predator and the pest. While the control of root pathogens usually involves several microorganisms, that of aerial pathogens may involve a single antagonist. The cultural practices and soil treatment methods that contribute to the successful biological control of plant pathogens must be identified and evaluated. For insect control, the methods of importing, maintaining, and increasing the parasites or predators must be developed before they are put to the test in practical agriculture.

As a next step, the biological control of plant pests must be tested under field conditions in the application area. This is done by repeated release of parasites and predators against arthropod pests, or by inoculation of pathogens against weeds. For the control of plant pathogens, antagonistic microorganisms may be introduced by: (a) inoculating of plant propagules; (b) favoring resident antagonists by manipulating cultural practices; (c) inducing a persistent shift in the soil microflora by chemical treatment to favor antagonists; (d) using a selective fungicide that favors antagonists or the production of an antibiotic by it. Effectiveness of control is then evaluated by detailed studies of the level of persistence of the pathogen as well as the amount of disease produced. Such evaluations must be based on testing and evaluation over several years and in several representative agricultural areas.

The relative success of an introduced biological-control agent can depend on many physical and biotic factors, some of which may be manipulated in an agricultural system. For example, the suppression of root rots in wheat by bacteria is enhanced and extended by moist soil conditions. Other sources of manipulation are cultivars with low water consumption, delayed seeding, irrigation, and reduced fertilizer usage. Inimical biotic factors, such as the natural enemies of the control agent, may be taken in hand, e.g. soil fumigation to suppress detrimental competitors before a pathogen-controlling microorganism is introduced. More research is needed on such biotic and physical influences if maximum benefits from biological control in agriculture are to be achieved.

The development of procedures for relatively inexpensive mass culture and release of biological control agents is fundamental to their practical and wide-scale use. Such agents as insect parasites and viruses cannot yet be cultured apart from the host. For example, Trichogramma egg-parasites for release (26) are conventionally reared on insect eggs such as those of the Angoumois grain moth, rice moth, or wild silkworm. Development of "synthetic" insect eggs would be a substantial research advance. Fungi and bacteria, on the other hand, are commonly reared in large quantities on synthetic media.

There is also a need to produce or select mutant strains of biological agents which are better adapted to climatic extremes and more suited to varied agronomic practices.

Advanced methods of dispersal by spraying, aircraft release, etc. are needed to promote the rapid and uniform distribution of the biological control agent throughout the crop-pest ecosystem.

Present technology suggests that suppression of major pests by a single biological agent does not always provide long-term permanence and stability of pest suppression; this situation applies equally well to biological and to chemical agents. Therefore it is essential, especially when combating pest species of foreign origin, to reestablish biological suppression on as wide a scale as possible. The objective should be to provide a spectrum of natural enemies attacking the pest in all its life stages and ecological niches. Ideally the natural-enemy complex for insect and weed pests should involve both invertebrate and microbial species.

Since biological control is particularly sensitive to interference by incompatible control measures, the key to its incorporation into integrated management systems lies in systems analysis, by which the search may be systematically conducted for compatible combinations of resistant varieties, narrow-spectrum chemicals, cultural controls, etc. Stabilization of losses from plant pests below an acceptable economic threshold level through such integrated plant protection remains the underlying principle of biological control

The principal impact of biological control is that it can dramatically decrease the input of pest-control chemicals onto crop areas. For example, successful control of the alfalfa weevil has been attained by a single suppressive spray of methyl parathion applied early in the spring; at this time the primary parasite Bathyplectes curculionis is dormant in its protective cocoon, and later emerges unharmed to regulate the weevil population below the economic threshold.

In certain cases, a biological control procedure may entirely eliminate the necessity for pesticide applications. Control of Phytophthora cinnamomi on avocado in Queensland, Australia has been maintained for 37 years by favoring the indigenous species of antagonists by means of adding organic matter and calcium to the soil, using ammonium-producing fertilizer, and maintaining adequate levels of phosphate and magnesium.

The total impact of research on biological control is that it promotes a pest-control method that is not only non-polluting, but also is relatively inexpensive and labor-saving, requires minimum capitalization, and is well suited to developing countries.

5. BETTER PESTICIDES AND BETTER USE OF PESTICIDES

(i) Development of a diversity of selective chemicals

That part of plant protection which is concerned with insect pests is at present severely handicapped by the fact that the present-day insecticides fall into a very limited number of chemical groups. What is needed is the discovery and development of selective chemicals in new toxicant groups (15). In the existing situation any resistance engendered by one insecticide will abolish the effectiveness of a high proportion of the compounds available. The introduction of new toxicants in different groupings would provide materials to which cross-resistance would be likely to extend. There are now important pests, such as the tobacco budworm on cotton, populations of which have reached the point of resisting all the insecticide groups at present available, and there are others to which only one chemical group remains effective. Fortunately this general problem has scarcely appeared in the herbicide field, although with fungicides resistance to one of the first systemic fungicides (the benzimidazoles, e.g. benomyl) is becoming a serious problem (4).

A diversity of narrow-spectrum insecticides is preferable to a limited number of broad-spectrum compounds for insect control because it diminishes the chances of mortality among the natural enemies of the pest. Unfortunately the toxicity of broad-spectrum insecticides has all too often extended to many other forms of animal life, including man. The longevity and fate of the pesticide in soil is a vital consideration (12). Insecticides selective to the pest species, if low in mammalian toxicity, would greatly reduce undesirable ecological disturbances in non-target and crop-target areas and be readily integratable with other complementary insect management systems. A proposed approach is an expanded effort in the evaluation and optimization of the selective characteristics of potential new insect control agents prior to commercial development. But it must be remembered that the development and clearance of a new pesticide now costs about $7.5 million, and the average time for its acceptance into commercial practice is over seven years (30).

It is likely that in the foreseeable future the conventional anticholinesterase insecticides will be supplemented by such materials as juvenile hormone mimics (18), chitin-formation inhibitors such as diflubenzurone (24) and many other types of materials having unusual modes of action against insect pests. Programs of synthesis centered around the basic structure of certain natural products (e.g. Nereistoxin from marine worms) have already demonstrated promise as a source of effective pesticides (e.g. Cartap for the rice stem borer). Three of our most important groups of insecticides have been developed by this process, e.g. the carbamates from structural optimization of physostigmine from *Physostigma venenosum*, bioresmethrin and prothrin from the pyrethrins of *Chrysanthemum* flowers, and the insect growth regulators from juvabione and Juvenile Hormone I and II. Just as a diversity of selective insecticides is needed to cope with the multiplicity of arthropod and fungal pests in an orchard, so a similar diversity of herbicides is needed to cope with the complex of weed species in a field crop.

The overall strategy of emphasizing diversity in mode of action should minimize the risks of failure by providing multiple options and great flexibility for varying economic and environmental situations. It affords a greater potentiality for solving unforeseen problems, and enhances the possibilities for uniquely valuable combinations of agents and delivery systems.

(ii) Development of novel chemicals for specialized uses

Plant growth regulators have already been employed experimentally to control superfluous late-season fruiting which in the case of cotton can promote the survival of infestation by pink bollworm and boll weevil. This type of approach can be considerably extended. Possibilities exist for stimulating or inducing dormancy of resting stages of pests, which combined with other suitable agronomic practices could result in pest control. Fungal infection might be counteracted by chemicals that stimulate host defences either by direct action of the chemical on the host or by alteration of the nutritional status of the plant. Possibilities exist for altering the host-pathogen environment with chemicals so as to make it incompatible with infection. Biological-control mechanisms could be stimulated with appropriate chemicals. New ways of broadening the utility of valuable crop protection agents should be sought. The discovery of synergists for useful selective pesticides, and of safeners for chemicals that have desirable pesticide activity but a degree of crop phytotoxicity (6), would add novel chemicals to the pest-control arsenal; an example is the addition of compound R-25788 to the herbicide EPTC to produce the safe formulation Eradicane.

(iii) Improved strategies for utilizing available pesticides

The shift in emphasis to safer and environmentally more acceptable compounds has opened up opportunities to reassess materials currently not widely used in integrated control system. Such compounds may now prove to be economically useful in such systems and could be valuable as components of programs designed to delay the onset of resistance problems. An example would be trichlorfon, an insecticide of low mammalian toxicity, essentially nonpersistent, and as a stomach-poison relatively safe to non-target organisms, which has been almost neglected for agricultural use in the United States; yet it is the most widely used insecticide in China and the U.S.S.R.

Fenitrothion, a very safe derivative of methyl parathion, is not registered for agricultural use in the United States. However, it is used widely in Asia, Japan, and the U.S.S.R., resulting in a striking reduction in cases of human organophosphorus poisoning. There are undoubtedly many other examples of insecticides already registered for various uses which have been neglected as useful control agents because of low efficacy, yet which may have excellent environmental properties and may be more compatible with the newer integrated pest management systems than the insecticides in large-scale use at present. The social acceptability of such compounds will require reeducation not only of the recommending agencies but also the consuming public.

The use of the newer photostable synthetic pyrethroids such as prothrin (NRDC 143) and others, offers the promise of reducing the total environmental burden of chemicals applied against some important pests by at least an order of magnitude. In addition, through appropriate formulation, synthetic pyrethroids have the potential for efficacious use against a wide spectrum of pest species.

Since present-day methods of spraying are extremely wasteful of material, improvements in application technology are vitally necessary in order to optimize the delivery of insecticide to the target pest, thus achieving a great reduction in the total amount of chemical and spray volume demanded. Ultra-low volume (ULV) techniques constitute a beginning against this problem, an orchard sprayer recently developed on this principle obtaining excellent insect control with a 50-90 per cent reduction in insecticide requirements and a 99.5 per cent decrease in total gallonage applied.

(iv) Measures for avoiding the consequences of pest resistance to pesticides

Insecticide-resistant populations are now known in more than 150 species of plant-feeding insects and mites and in more than 20 species of fungal diseases of plants. Of particular importance is the resistance to organophosphorus insecticides now known in more than 50 of these agricultural pests, and the resistance to the benzimidazole group of systemic fungicides (4). Certain crop pests, such as tobacco budworm on cotton, have developed resistance to many types of commercially available insecticides. In most cases, however, pesticides may still be found that can successfully control the resistant populations.

Yet control failures continually occur, the grower being taken by surprise because no forewarning was obtained by testing the susceptibility levels of the target population. Wherever a pesticide is repeatedly and continuously employed, the development of resistance in the target population should be expected, especially in arthropod pests. The same may prove true when systemic fungicides are used against fungi and antibiotics against bacteria. In order to avoid the economic waste of control failures and stabilization of the resistance, a forewarning should be obtained by periodic testing of the target population's susceptibility level.

It is therefore recommended that: a) standard test methods should be devised, to increase the number of species covered to include as many pest species-groups as possible; b) a systematic surveillance should be maintained by periodic testing of the pest species throughout crop-growing areas under a pesticidal regime; and c) as soon as a new resistant population is encountered, its cross-resistance spectrum should be ascertained in order to discover a back-up pesticide to remedy the situation. The organization ultimately responsible for such surveillance would logically be the national department of agriculture.

Whereas individual weed species have rarely developed resistance to herbicides, the continued use of herbicides results in a shift of the composition of the weed flora from the susceptible to the more intractable species, thus substituting a flora which is resistant to that herbicide. Fortunately there is such a diversity of herbicides available that this problem may be remedied.

(v) Elucidation of the mode of action and metabolism of pesticides

There are still strong reasons for placing reinforced emphasis on the elucidation of the mode of action of pesticides. Such knowledge should lead to a clearer understanding of fundamental biological processes, thus providing information pertinent to the entire question of enhancing crop productivity. Knowledge of mode of action (8) can also lead to more effective development and use of pesticides.

The ultimate level of effectiveness of any pesticide can, to a certain extent, be minimized by the level of pesticide which reaches the target and the extent of detoxification which can be achieved by the pest. Good progress has been made with such studies in insects, but relatively less is known of these processes as they relate to herbicide and fungicide uptake, translocation and metabolism. This is perhaps a reflection of the overall lack of information at the cellular level on metabolic processes in weeds and fungi, and further emphasizes the need for more basic research on this topic.

6. INNOVATIVE APPROACHES FOR PLANT PROTECTION

(i) Genetic control methods for certain pests

The sterile-male release method, successfully applied for control and eradication of the screwworm, has also achieved success against certain species of fruit flies, and may well be exploited for use against the codling moth, pink bollworm and boll weevil. An innovative method in itself, this approach may be further innovated by the development of release methods such as those based on insect-pest strains carrying chromosomal translocations, or a combination of dominant lethal factors coupled to a meiotic drive. These newer genetical methods would exert a suppressive effect on the pest population that would increase in each generation after the release. Methods of genetical control are applicable to large-scale wide-area situations, and are suitable for developing countries.

(ii) Remote sensing for control operations against migratory pests

The use of radar to locate migratory swarms has aided in the control of the desert locust, cotton bollworms and leafworms, and the spruce budworm, by means of airspray application. Such operations in which sensing and application are integrated enable the target pests to be attacked with precision over wide areas. Further innovation of this method is intimately interwoven with the rise of the subscience of aerobiology.

(iii) Controlled-release formulations of pesticides

Initially developed by impregnating pesticides with granules of inert mineral carriers, present-day innovation has investigated absorbent matrices such as polyvinyl chloride, acrylic resins and butyl rubber as carriers for pesticides and attractants. Matrices can be found which leave no residue in the environment, e.g. gelatin, pectin and lactic acid polymers. The advantage of slow-release formulations is that they can modify the persistence of the pesticide, to fit the demands posed by the life-cycle of the target species.

(iv) Chemicals for modifying insect behavior

The odors that govern insect behavior, namely mating attractants (pheromones), food attractants and oviposition attractants, have been widely exploited as control agents in recent years (3). In the last 17 years, insect pheromones have been demonstrated in more than 150 species and chemically identified in some 40 species. A mixture of the volatile attractant methyl eugenol with the insecticide naled has successfully prevented the oriental fruit fly from establishing itself in California. Futher innovative research is recommended with the objective of identifying the chemical odor cues not only for the widest possible range of the pest species, but also for their predators and parasites.

(v) Innovation on a variety of fronts

The discovery and use of chemicals to force the premature germination of weed seeds is a promising innovative method, illustrated by the recent isolation and identification of strigol as the germination principle for witchweed (7). The development of a seed treatment which would enhance the survival and germination of surface-seeded crops would enable high production to be obtained from low-energy-consuming agriculture systems based on reduced or no tillage. The possibility of displacing a virulent plant disease with a hypovirulent one has recently been demonstrated in the chestnut blight fungus (28). There are more possibilities (16) under this pest-control subimperative than the working group can imagine.

IMPACT OF THE IMPERATIVES IF THEY WERE FOLLOWED

Success in the first imperative, to achieve pest management by the methods of systems science, would provide stability in crop production, with its attendant benefits in terms of human nutrition and of economic predictions. Each of the recommended subsidiary imperatives, namely basic biological studies, pest-resistant cultivars, biological control, chemical-control agents, and innovative methods, will play their part in progressively raising and refining the degree of the plant protection achieved in both individual and group-action programs. Thereby the mistakes and excesses of the past will be circumvented, and the net result will be the reconciliation of food production with environmental quality. On the other hand, if these imperatives are not followed, our persistence along the old well-worn paths will lead to instability and serious shortfalls in crop production.

SUGGESTION FOR THE IMPLEMENTATION OF THE IMPERATIVES

Successful attainment of the hopes of this conference depends upon the degree to which interdisciplinary studies can be applied to the relevant problems; in such an enterprise, the role of research administrators becomes pivotal in ensuring that the details of research are correlated with the main practical objectives, and that there are feedbacks between grantors and grantees.

Since these research objectives have global connotations, especial importance attaches to international networks concerned with such phases in plant protection as biological control, plant resistance germplasm, pesticide resistance monitoring, and the general field of systems science. Within countries existing support for agricultural research including plant protection should be strongly supplemented by a competitive peer-review grant program.

From the experience of our Working Group, it is concluded that the stimulation afforded by interdisciplinary discussions should not be allowed to lapse, but should be continued by means of the holding of regional conferences on plant protection at reasonably frequent intervals.

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ENVIRONMENTAL STRESS

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INTRODUCTION

The environmental stresses which limit crop productivity are many and varied and include drought, cold, heat, salt, toxic ion, and air pollutants. They cause extensive losses and are the basis for unrealized production potential. Alone or in combination these stresses constitute the primary limiting factor(s) for increasing and expanding production in many, if not most, of the world's food crops. Some stresses are so overwhelming that they may influence the fate of an entire crop in a brief period while others have a more chronic long-term effect. Research and development aimed at overcoming environmental stress limitations and increasing production have been notably successful in many crops and can provide the basis for significant future progress.

Man presently cultivates approximately 11% of the earth's land surface (1). This is about 44% of the total land surface that is judged to be arable or potentially suitable for cultivation. The present arable area is estimated at 1.4×10^9 hectares and this could be increased to 3.2×10^9 hectares (2). Much of this largely untapped land resource is too dry, wet, cold, hot, salty, rocky, steep or subject to other stresses and limitations to be tilled with present technology. Increasing population and food and fiber requirements dictate that crop losses must be lessened, and that production be extended to lands and climatic areas which are marginal by present standards.

Population growth in itself consumes prime agricultural land and may create direct stress on crops associated with deteriorating air quality, e.g. air pollution could significantly reduce fresh market vegetable production near large metropolitan areas.

Atmospheric pollution may have farther-reaching indirect effects on crop production if we fail to maintain air quality and hence trigger atmospheric changes which alter climate. The potentially devastating effects of subtle climatic shifts are described in Dr. Bryson's address to the Conference. The fact that such shifts may occur whether or not we preserve air quality adds further impetus to stress research aimed at crops and technologies tailored to a changing environment.

EFFECTS OF ENVIRONMENTAL STRESSES

Environmental stresses result from normal events which become unbalanced. While the plant survives most such stresses, productivity decreases. Therein is the challenge - to find ways to alleviate environmental stress so that productivity can be increased or stabilized.

The stresses considered were primarily those associated with extremes of water availability, temperature, ions in soil and pollutants in air. Specifically, emphasis was placed on stresses imposed by drought, low temperature including freezing (below 0°C) and chilling (above 0°C), heat, toxic ions excess water and air pollutants. No attempt was made to quantitate the relative impact of these stresses on world-wide crop production, but the order of listing in the preceding sentence is a gross approximation. Other environmental stresses such as wind, blowing sand or dust, hail, or hard dense soil may also damage the plant or reduce its productivity as do biotic stresses from insects, diseases and weeds. The information on radiation and carbon dioxide stress may be found in the Carbon Input report; drought, salinity, ion toxicities, and soil oxygen tensions in the Water, Soil, and Mineral report; stress interactions with pests in the Plant Protection report.

Temperatures, both high and low, produce dramatic stresses. Freezing temperatures can either kill or severely damage plants, but many plants are remarkably able to withstand very low (liquid N_2) temperatures (-196°C) at certain times of the year (3). Others, especially tropical plants, may be damaged by chilling at temperatures well above freezing (12° to 14°C) (4).

Water stress (drought) may be dramatic or very subtle. Even very small stresses which produce no visible symptoms cause the plant cells to lose turgor (pressure within the cell), and to stop growing. Plants may fail to flower and fruit under water stress, or the subtle reductions in productivity may only become apparent at harvest. Water stress from drought may be alleviated by irrigation; however, if the soil becomes saturated with water it excludes the oxygen necessary for the roots, and water and mineral nutrient uptake is impeded. In effect, water stress can result from both too much and too little water.

Water used for irrigation often contains dissolved salts, and as water evaporates from the soil or is transpired by plants, salts remain in the soil. Accumulation of salts produces salinity which reduces the plant's ability to take up water. Salinity can render both water and soil unusable for plant production.

Toxic ions such as Al haunt certain soils. This reduces productivity or may cause crop failure. Plants vary in their ability to tolerate toxic ion stress. The addition of lime to the soil can reduce the toxic ion stress by increasing the pH, thereby making some ions insoluble.

Air pollutants of all kinds constitute an additional environmental stress. Air-borne oxidants are insidious. Obvious damage is visual, but more subtle effects occur which may reduce the productivity of the plant and lead to premature senescence. Some plants tolerate air pollution stress very well - others are extremely sensitive. Little is known about the processes involved.

SOME LIMITING FACTORS AND CONCERNS

The working group considered and discussed certain areas of concern which were beyond their charge and scientific expertise; no formal group action was taken on these issues, some of which are elaborated below.

More refined and accurate weather forecasting would greatly improve the ability of agriculturists to recommend management practices that would increase crop yield, e.g., via adjustment of planting dates to avoid drought stress, excess water, or frost at critical stages such as germination, flowering or harvest. Efforts towards improved long- and short-range weather forecasting are encouraged.

Much of the food consumed in the world is produced by subsistence farmers on small farms in developing regions. Better information is needed on the food crops they rely on, in order to intelligently plan and implement research aimed at solving food shortages in the areas of greatest immediate need. The contribution of such food crops is difficult to assess because a large proportion never enters market channels. Exclusive or undue research preoccupation with the seven major food crops (maize, soybeans, wheat, rice, potatoes, sugar (cane and beets), and dry beans) would seem ill-advised.

It would also be short-sighted not to emphasize research on reducing postharvest losses and on food storage preservation, handling, and distribution. Postharvest losses of perishable food crops are a particular problem in subsistence farming operations, and great gains could be made by applying existing technology. World hunger will be a problem if we produce enough food, but fail to improve distribution.

The conferees recognize: that increasing world food supply will not, in itself, solve the problem because population growth is too rapid; that agricultural practices to overcome environmental stress should emphasize approaches that do not require large amounts of energy, water, or other finite resources; that an accurate international inventory of world food reserves would be desirable; and that nutritional quality must be improved as well as total food supply; the prediction that environmental stress research can have a major impact on increasing world food production is based on the following rationale and examples:

Stress research has successfully provided the basis for increasing productivity and reducing losses in many crops. Examples range from improved irrigation practices to breeding/selecting new varieties of tropical crops resistant to chilling damage below 15°C (4).

Information is at hand to increase productivity by attenuating stress or avoiding stress limitations. A general Conference imperative addresses the point of putting this knowledge into practice - particularly in developing parts of the world where many people engage in subsistence farming (see Conference Imperatives section).

Minor modifications of crops or microclimate, within our current biological and technological capabilities, could markedly increase crop productivity under stress.

Numerous examples are available. Thoroughly researched models have been used to predict, for example, that world rice production would decrease by 45% or 137 million metric tons if there was a global fall in temperature of 0.5°C in the 0°-20° latitudes and a 1.0°C fall in the 20°-40° latitudes. If this climate change were accompanied by a 10 to 20% reduction in rainfall, an additional 12% reduction in world rice production is predicted (5). While very minor shifts in world climate could cause catastrophic reductions in food production, equally minor shifts in crop tolerance to sub- or super-optimal levels of temperature, water supply, nutrients, or salinity could greatly enhance productivity.

Breeding approaches seem particularly promising in this regard because plant species growing on the earth today are the product of more than 55 million years of evolution. During that time great environmental changes have occurred, giving rise to an ever changing array of environmental niches. Evolution was a random and chance process involving a variety of biological mechanisms controlled by numerous genetic systems. Hence, present day plant species, with their attending gene pools, are the product of thousands of generations of random and chance hybridizations and natural selection.

Wild plant species are conservative in nature, with survival paramount and productivity incidental. They do, however, provide an extremely valuable genetic resource to scientists in developing high-yielding cultivars adapted to stress.

The International Rice Institute has screened thousands of rice cultivars for drought resistance. Several promising lines have been hybridized to recombine drought resistance with yield increases which, to date, range up to 50% or higher (6). Advances of this type are also promising in winter wheat (7) and potato

(8) improvement programs where genetic sources of freezing resistance are now being incorporated into breeding programs which could add 2°C or 3°C to the hardiness of these crops.

In the case of wheat this would make it possible to displace large acreages of spring wheat with winter types which yield 25 to 40% higher because they efficiently utilize the more adequate supply of water available in early spring in most continental climatic areas.

Autumn frosts cut off the production of potatoes in most regions, and frosts can occur every month of the year at high elevations in the tropics where potato is the dietary staple for millions of subsistence farmers. These farmers now plant part of their land to relatively unproductive wild species of potatoes which are more frost-resistant than cultivated varieties to insure that there is some crop.

A wide variety of other improvements in crop stress resistance or micro-climate could result in reduced losses, increased productivity, and conservation of the world's finite supplies of water and petrochemical resources as follows: (i) trickle irrigation provides a slow continuous supply of water to crops while requiring less total water; (ii) overhead sprinkling cools heat-stressed crops and is also used to protect tree-fruit blossoms from spring frosts (9), replace orchard heating practices which pollute the air and require high energy inputs (10); (iii) use of impervious barriers in the soil keeps surface water in the root zone of crops grown on sandy soils; (iv) breeding barley varieties tolerant to aluminum toxicity would be valuable for the acid soils of the tropics covering large areas of Brazil, Colombia, and other parts of the world; and (v) breeding heat-tolerant millets would be valuable for the tropics. Identifying or synthesizing chemicals which can be applied to crops to induce slight increases in tolerance to heat, frost, or air pollutants at critical stages of development such as flowering or germination; chemicals which delay spring bloom in crops particularly susceptible to frost damage at this critical stage; chemical or light treatments to induce early onset of dormancy or hardiness in autumn in perennial tree fruit or nut crops subject to damage from early autumn frosts, or to losses of natural hardiness and subsequent injury during unseasonably warm periods in mid-winter (11); identification of chemicals which can be sprayed on crops to reduce water loss from leaves and reduce water stress.

Several viable alternative means may increase world food production of crops in environments where stresses are the primary factors limiting production. Multiple cropping, or growing several crops a year, is for example, an effective means of increasing production. Very often, however, our ability to adopt multiple cropping systems of production is limited by stresses, e.g. seasonal hot, cold, wet or dry periods. Crops that mature in a short growing season, or which tolerate these stresses, are needed to circumvent such limitations. Interplanting of crops that complement the micro-climate may also be examined.

The identification and measurement of metabolic responses to stress in plants has potential value in programs for crop management. Although answers to many fundamental questions are lacking, sufficient basic information is already available on some aspects of the metabolism of stressed plants to permit the development of reliable metabolic criteria for selection of stress-tolerant plants, and for assessing the degree of stress to which a plant is being subjected. One successful approach has been to follow the sequence of metabolic events occurring in response to a defined constant stress and to compare tolerant and susceptible lines for species. Such research should enable the identification of the protective responses of most general occurrence, which could then serve as sound criteria for selection in breeding programs. It would also identify the symptoms associated with the onset of stress that might best be used to detect and quantify stress in field and laboratory situations.

Proline has been identified as a metabolite that may serve as an indicator of drought, salt or cold stress. The imino acid proline accumulates as the free acid in leaves of many species subjected to moderate water stress; examples include wheat, barley, corn, perennial rye grass, Lolium temulentum, Bermuda grass, Carex spp., Ladino clover, kidney bean, jackbean, turnip, swiss chard, radish, lemon, lime, sunflower, tobacco and tomato (12).

Characteristically, free proline accumulates to 10-100 times the level found in leaves of well-watered plants; accumulation begins within a few hours of the onset of stress and continues at a high rate for several days. Levels of 2-10 mg free proline per gram dry weight are typical of drought-stressed plants. No other free amino acid shows a large increase during water stress and many tend to decline in concentration. In barley, the accumulation of proline can be elicited in non-stressed plants by application of abscisic acid, a naturally ocurring plant hormone (13). Analogous increases in free proline levels have been reported for plants exposed to salt or cold stress (14).

The extent of proline accumulation by seedlings of 10 barley cultivars exposed to defined water stress with solutions of polyethylene glycol was strongly correlated with their field performance in drought-prone environments (15), suggesting that an estimate of proline accumulation in seedlings could be a useful selection screening test for drought resistance. Such a test need not be totally destructive as only a single leaf need be sampled.

Plants evolve ethylene in response to stress by ozone, water stress and chilling. A marked increase in the rate of ethylene evolution occurs in many plants in response to a variety of stresses, including mechanical injury, chemical injury, disease, chilling and water stress. The stimulation of ethylene production usually begins within an hour of the onset of stress and tends to decline within 24 hr after stress is relieved. The precursor(s) of stress-induced ethylene is not well known, although stress-induced ethylene is derived at least in part from methionine in leaves subject to ozone fumigation or to toxic chemical sprays (16) and in Morning Glory flower tissue damaged mechanically (17). Stress-induced ethylene may be involved in the control of abscission of damaged organs.

It has been reported that the increased ethylene evolution following exposure to ozone can be used to rank plant species and cultivars according to their ozone sensitivity (18). Intact petioles of cotton plants showed ethylene production rates that closely followed changes in leaf water potential throughout the day in unwatered and watered plants (19). Ethylene evolution in detached leaves of Valencia orange has been highly correlated with relative turgidity (20). The pattern of ethylene evolution in plants exposed to e.g. defined water stress should be determined to assess the value of ethylene production as an index of sensitivity to drought.

It is widely recognized that exposure of plants to a given stress often confers tolerance to other stresses. Levitt (21) suggested a general tolerance hypothesis involving a common mechanism associated with the development of tolerance to seemingly unrelated stress. Abscisic acid has recently been implicated in a regulatory mechanism facilitating cross-adaptation in plants to diverse stresses (22).

Thus many investigative approaches offer great potential for attenuating environmental stress and improving crop productivity.

MAJOR RESEARCH IMPERATIVES

Approaches to stress research for increasing crop productivity fall into 3 major categories. Two of these, genetic improvement of crops, and modifications (physiological) of plants or their environments have been illustrated by a number of specific examples in the Introduction. Less apparent, but equally vital is expanded research aimed at elucidating the biological bases of injury and resistance.

In short, we do not have good information on the scope and nature of environmental stress injury and yield reduction in crops; nor, with rare exceptions, can we answer two seemingly simple questions: How do stresses injure plants? How do some plants avoid or tolerate stress?

Our ability to accurately assess research priorities, to select for and develop hardier crop varieties, to find chemicals that increase resistance, or to modify the micro-climate of crops to reduce stress, would be greatly enhanced if we had these answers. The three major stress research imperatives are therefore to:

I. manipulate crops or their environments in ways which avoid or reduce stress injury and increase productivity;

II. exploit the genetic potential for developing new varieties of crops resistant to environmental stresses;

III. elucidate the basic principles of stress injury and resistance in plants, and to evaluate the scope and nature of stress damage to crops.

In terms of achieving our ultimate aim of increasing crop productivity, concurrent research emphasis on all three is imperative. Elaboration of these imperatives will illustrate the range of endeavors which may be considered.

EXPANDED RESEARCH IMPERATIVES

I. Manipulate crops or their environments in ways which avoid or reduce stress injury and increase productivity.

   A. Develop crop management systems and cultural practices which reduce exposure of crops to stress. Apply existing knowledge about the limiting stress factors in specific crops and areas to selection of optimum seeding dates, varieties, multiple cropping, inter-cropping, irrigation, fertilizer practices, etc. Develop packages of technology which have application at the farm level. Emphasize research on important crops, particularly in subsistence farming areas, and make use of predictive models which include assessment of costs and economic impact.

   B. Reduce stress by modifying the microclimate in the vicinity of the crop. Emphasize research on practices with low energy requirements and on crops particularly amenable to microclimatic manipulations, e.g. mulches, overhead sprinkling, wind barriers, inter-cropping, etc.

   C. Attenuate stress damage to crops by applying treatments (e.g. chemicals) which increase resistance to the stress or facilitate recovery following stress exposure. Emphasize exploratory research to identify effective treatments based on information from expanded Imperative I. A, B, and C.

II. Exploit the genetic potential for developing new varieties of crops resistant to environmental stresses.
   A. Collect and evaluate germplasm of major crop plant species for stress resistance and coordinate this on an international basis. Provide staffing and facilities for rapid accession, storage, retrieval and exchange of data on stress resistance and for supplying plant materials.
   B. Apply information from expanded Imperative I to identify selection criteria, develop selection tests, and plan breeding program strategy. Emphasize development of techniques for rapid screening of large seedling populations for resistance to the limiting stresses on specific major crops.
   C. Select and/or breed food crop varieties for increased levels of tolerance to stresses which seriously limit crop productivity. Emphasize research on crops, problems, and in areas where current technology cannot solve the problem.

III. Elucidate the basic principles of stress injury and resistance and to evaluate the scope and nature of stress damage to crops.
   A. Elucidate the basic mechanisms of stress injury in plants (physiological, biophysical, biochemical).
   B. Elucidate the basic mechanisms of stress resistance/avoidance in plants (cellular, anatomical, morphological), and the mechanisms by which some plants acclimate to certain stresses (environmental

triggering stimuli and the biological responses they elicit).

C. Achieve an understanding of plant growth and productivity under stress. Identify the limiting stress(es) on specific crops, in specific production areas, at specific stages of development. Identify the impact of non-lethal stresses on productivity.

RESEARCH IMPERATIVE INTER-RELATIONSHIPS

There are too many stresses, climatic zones, and crops, and too little knowledge (see I.A) to permit intelligent assignment of priorities among the expanded research imperatives. Each of the stresses, from water, cold, heat, ion, and air pollution, was assessed by different members of the working group, and the group as a whole decided that it would be inappropriate and mis-leading to rank research imperatives in any priority order.

IMPLEMENTATION RECOMMENDATIONS

The conferees considered several ways of accelerating progress. These included the two general Conference Imperatives submitted by the group re: a scientist manpower assessment, and training programs to speed adoption of new technology in developing areas (see I.A). These appear elsewhere in the overall Conference Report.

In addition, the sub-group considered (but took no formal collective action on) other means for speeding progress via improved communication and cooperation. Three examples follow:

1. Establish an international catalog of scientists engaged in stress research. A start has been made in North America in this direction (in cold hardiness research) via the Plant Hardiness Workers mailing list and Hardiness

Research Council being developed at the University of Minnesota. This effort could be expanded to include workers in other types of stress research, and extended internationally. The Plant Growth Regulator Working Group organizational format could also be explored. In any case, better and more regular communication between stress researchers would likely be most beneficial, especially in areas like heat stress where there is either very little research going on or poor international communication between researchers. In contrast, air pollution and low temperature stress researchers, at least those working on temperate zone crops, seem relatively well informed on who is doing what and where.

2. Organize regular international workshops or Gordon-style conferences in specific areas of stress research.
   For starters a Workshop on rapid stress selection methods and instrumentation for use in breeding programs could be most worthwhile if it included a good mix of physiologists and breeders actively engaged in the identification of selection criteria (Imperative II. B), and development and utilization of selection techniques in genetic improvement. The lack of good methods, or their inappropriate application restricts progress in this area.
   Controlled selection for stress resistance in crops is a complicated business, and uncontrolled field selection programs which depend on a "test freeze or drought" are often slow and ineffective. Since plants with good tolerance to one type of stress are often resistant to another (e.g. plants which are cold resistant may also be resistant to heat and drought (21)) such a Workshop

would provide a good opportunity for getting scientists in different fields of stress research together. The increased ethylene evolution from plants under stress, and build-ups of proline in stressed plant tissues are readily assayed and might provide useful indirect means of measuring tolerance to marginally injurious stresses.

3. In his address to the Conference Dr. Wortman stated that "the opportunities indeed the requirements, for interdisciplinary work to achieve solutions of some of the major biological problems are becoming known. Increasingly in the biological sciences, as in the physical sciences and engineering, real teamwork on real problems, with an emphasis on rapid progress toward well-defined goals, will be demanded. The time-frame in which all of us will be working is entirely too short for any other posture".

   This approach has particular merit in many areas of stress research because of the interplay of climate, and physical stresses, and the physiological, biochemical and genetic responses they influence. Stress research teams and international networks of scientists with common goals would probably be productive, as for example an international network on improving freezing tolerance in winter wheat. Team research would expand if funding patterns put a premium on joint interdisciplinary research.

IDENTIFYING AND IMPLEMENTING RESEARCH IMPERATIVES

The questions of acquiring adequate lead-time and resources hinge largely on institutional, governmental and international decisions on agricultural research priorities and on the assignment/availability of fiscal and scientific manpower resources. Environmental stress conferees contributed a general conference imperative (see Conference Imperative section of this report) aimed at an assessment of scientific manpower resources and development of plans for research funding and implementation. It proposes, in short, that agricultural research manpower be assessed and that planning inputs be sought from agricultural scientists when policy decisions are made on whether and how best to channel funds to implement research on increasing food productivity.

WATER STRESS

Review: Recent reviews of water relations and water stress have been written (23) and a good overview of interrelationships is available (21). Crop productivity can be limited by moisture excess or deficit (drought). Both can occur during the same year on the same crop.

Excess water reduces soil aeration and thus the supply of oxygen available to roots. Under poor aeration, nutrient and water uptake by the plant are seriously inhibited. Excess water also slows the warming of soils in the spring and restricts beneficial microbial activity. Some plants cannot live when submerged for more than a few days.

The mechanism of tolerance to prolonged root flooding (anaerobiosis) has been studied in a broad range of plants. Three general characteristics distinguish flooding-tolerant and intolerant plants.

(a) Flood-intolerant plants show a rapid increase in the rate of glycolysis coupled to an increase in alcohol dehydrogenase (ADH) activity during anoxia. In addition, alcohol accumulates to toxic levels. On the other hand, flood-tolerant plants show no acceleration of glycolysis and little or no change in ADH levels (24) and no accumulation of ethanol. ADH behavior in roots of corn and subterranean clover has recently been correlated with flood tolerance and has been proposed as a selective criterion.

(b) Flood-tolerant species tend to accumulate non-toxic organic acids (especially malate) as end-products of glycolysis, whereas intolerant plants produce ethanol and malate levels fall. The ratio of the tissue contents [malate]/[succinate] is a sensitive indicator of flood tolerance, which shows marked changes several days before growth responses to flooding become evident (25).

(c) Roots of flood-tolerant species may be able to make effective use of nitrate as an alternative electron acceptor to oxygen during anaerobiosis. Nitrate reductase activity, as measured by an *in vivo* assay technique, increased in tolerant species upon flooding (26).

Drought stress, even of small magnitude, can cause yield reduction if it occurs at critical stages of growth. Closure of stomata caused by lack of moisture reduces carbon dioxide exchange and thus reduces photosynthesis. Roots do not extend in dry soil, nutrient uptake is reduced, and reduced levels of the growth regulators cytokinins and gibberellins in drought stressed roots may effect important metabolic processes. Drought is the most serious stress on photosynthesis in the field and is probably the single most limiting factor influencing terrestrial plant productivity.

Proline accumulation in plants under drought stress serves as an example of metabolic alterations. The major factor in the accumulation is increased synthesis via α-ketoglutarate and glutamate (27). When water stress is relieved, proline levels decline rapidly (28); this decline is due to oxidation of proline via glutamate and α-ketoglutarate to CO_2, to conversion to other amino acids and to incorporation into protein. Proline synthesized during adverse conditions may be important in the phase of recovery from drought.

RATIONALE

To increase and stabilize plant productivity under adverse environmental conditions, sharp focus needs to be given to understanding the basic adaptive mechanisms to plant water stress.

Water potentials in plants are influenced by electrolyte transport, biochemical transformations, cell-wall elasticity and other factors. Changes in tissue and membrane permeability can occur as a result of changes in membrane composition, spatial arrangement between membrane molecules, changes in electrochemical potentials, or the ionic environment of membranes. Thus it is reasonable to assume that plant and cell water potentials and membrane permeability are controlled metabolically. Similarly, the response of plants under conditions of water deficits may be metabolically regulated. The choice of the appropriate method of approach in research may be governed by the following three premises: an understanding of plant adaptation to water stress and of the wide range of genetic variation will assure success if coupled with wise selection and management options; there is no universal definition of plant water stress, but it must be defined for the particular plant, response, and condition; the influence of fluctuations in environmental water stress over time has yet to be defined for most crop plants.

RESEARCHABLE PROBLEMS - RECOMMENDATIONS

The research approaches proposed can be placed into three general categories: consideration must be given to the physiological responses of plants under water stress; the structural system within a plant under water stress must be defined; it must be learned how to manipulate plant genetics and management effectively.

Physiological research is needed to determine (i) the initial events occurring in plants during the onset of stress; (ii) the metabolic responses of stressed plants; (iii) how these responses interact in a dynamic environment to affect water stress resistance in plants; and (iv) to identify the mechanisms which enable the plant to compensate for the effects of water stress.

In the case of the specific example of proline metabolism: the relationship between proline accumulation by seedlings and drought resistance or yield of mature plants should be investigated in a wider range of species and cultivars; the nature of inheritance of the capacity to accumulate proline should be studied as is being done in barley. Sensitive simple non-destructive methods for detecting the onset of proline accumulation should be investigated. A recently developed *in vivo* technique (29) which depends upon the loss to the incubation medium of transpired water of tritium from metabolites tritiated at specific positions may be suitable. More basic information is needed on the value of proline accumulation to the plant, on the competition for NADH between mitochondrial electron transport and proline production during drought, on the extent to which proline accumulation is a general feature of stress other than drought and on the possibility that previous exposure to unfavorable conditions may potentiate the proline accumulation response.

Research is needed on the structural system of plants along the following two lines: (i) elucidation of the path of water flow from the soil through the plant and leaf to the atmosphere in order to establish how plants sense internal water stress; (ii) determination of the effect of plant morphology (leaf shape and size, stomata distribution, plant posture, root distribution, etc.) on the exchange of gases (particularly water vapor) and energy (collection of solar radiation and the dissipation of heat by transpiration, radiation, or convection).

Research is needed on plant manipulation and crop management in order to: (i) genetically combine drought resistance with other desirable traits to stabilize and increase yields; (ii) improve plant water use efficiency by genetic means; (iii) develop crop management practices to stabilize and or increase yields; and (iv) develop management practices to increase water use efficiency.

In many areas, adequate water supplies are available to minimize water stress on plant growth for maximum production. However, plants that have been grown under low water stress for a time become more susceptible to short periods of stress such as could be caused by a sudden temperature increase or a delay in irrigation; yields of irrigated corn and wheat may be drastically reduced in such cases (30).

Water and other management inputs are influenced by the timing of photosynthate partitioning. For example, under full irrigation, beet sugar yield could be increased if partitioning of photosynthate to sugar synthesis rather than vegetative growth could be regulated after adequate top growth is achieved. In regions where late potatoes are killed by frost, triggering an earlier switch from top growth to tuber bulking could increase yields significantly.

Most food crop production depends directly on rain. Thus production on much of the arable land is severely limited by inadequate and poorly distributed precipitation during the growing season. Untimely rainfall may stimulate rapid, excessive shoot growth in drought-resisting cultivars that wastes the precious deep-soil moisture needed to mature the crop (31). New drought resistant cultivars are needed that do not over-respond to temporary periods of slight water stress.

Poor rainfall distribution is a major problem in the North American cornbelt. Typical cornbelt varieties are particularly sensitive to drought at pollination time because the yield is determined at this time. Drought resistant corn varieties are needed.

Preseason estimates of soil moisture coupled with long-range weather predictions for the growing season could assist the farmer in determining optimum planting dates, fertilization, crop selection, etc. in order to maximize production. Periodic updates of predictions would indicate needs for adjustment in stand density or for the supplemental application of fertilizers. Crop growth simulation models that incorporate quantitative relationships of response of plants to water stress would be useful.

CHILLING

Review: Temperatures above freezing (between 0° and about 15°C) cause chilling injury in a number of plant species including many crop plants of tropical or sub-tropical origin; several of which are major food crops in the temperate zones (4, 32). Corn and rice, for example, sustain severe losses as a direct result of chilling injury as do numerous subtropical fruit, vegetable, and root crops which are important staples in the diets of many people. The fleshy edible portions of these tropical crops are also subject to chilling injury after harvest and during storage.

Chilling injury is manifest in a variety of physiological dysfunctions including: growth cessation, germination failure, photosynthetic inhibition, abnormal ripening and disorders during storage.

Current evidence indicates that chilling injury results from low temperature induced phase-transitions (crystallizations) in cell lipids (4). Such transitions drastically alter or destroy cell membranes and interfere with associated processes such as water transport, chloroplast function, and enzyme activity to mention a few. There is preliminary evidence that certain types of sublethal heat damage may also involve lipid phase-transitions.

RATIONALE

If lipid phase-transitions prove to be the key event in chilling injury at the cellular level, scientists would have a rare opportunity to apply such basic knowledge to the solution of real and immediate chilling damage problems on food crops. Every effort should be made to explore rapidly these opportunities, and to determine whether lipid phase-transitions are also important in other types of stress damage to crops.

RESEARCHABLE PROBLEMS - RECOMMENDATIONS

(i) The known information and imperatives concerning the biological basis of chill stress suggests that the following research actions be taken: Pursue the preliminary experimental evidence that treatment of chilling-sensitive seedlings with chemicals (polar bases or fatty acid derivatives) induce changes in the polar head groups or unsaturation of fatty acyl side chains, respectively, in plant lipids. These changes appear to enhance resistance to chilling in treated seedlings (33). Perhaps chemical seed treatments could be used to improve germination of sensitive plants in cool seasons.

(ii) Further elucidate the role of lipid phase-transitions in chilling injury. Systematically dissect the membranes of chill-sensitive and chill-resistant plants to determine the molecular basis of sensitivity and resistance. This information could be most useful to the plant breeder in identifying genetic sources of resistance.

(iii) A concerted effort should be made to develop and design rapid, quantitative, non-destructive resistance screening techniques for use on large plant populations in breeding programs. Examples might be a method involving non-destructive photometric scanning of lipid phase-transitions in seedlings; measurements of ethylene evolution (by gas chromatography) or proline accumulation (by the tritium loss method (29)). As previously noted, ethylene is evolved and proline accumulates in many plants exposed to injurious but non-lethal stresses.

(iv) Chilling resistance in sensitive plants covers a range from 0° to 20°C at the extremes. Theoretically there should be room for genetically improving resistance by several degrees. This would be highly significant in attenuating yield loss in the field and postharvest losses in cold storage.

(v) Determine whether and/or to what extent lipid phase-transitions may be involved in other types of temperature injury to crops (e.g. heat and freezing injury). Include research on reducing losses of chilling sensitive commodities in storage. For example, reducing storage losses by 30% would be just as significant, and perhaps more readily achieved than increasing yield by a like amount.

(vi) We know that many crops are subject to chilling injury (i.e. corn, rice, coconut, banana, peanuts, tomatoes, sorghum, sugar cane, cotton, sweet potatoes, and many, if not most, tropical fruits and vegetables). There is relatively little information on the ranges of sensitivity and the extent of damage under field conditions in major production areas. This information would be useful in planning research and assessing priorities.

FREEZING

Review: Freezing injury and resistance in crops covers a wide range of environmental stresses and plant responses. Hardiness in plants ranges from about -1°C to somewhere below -196°C. Some plants are totally incapable of acclimating to freezing stress while others may increase in hardiness by 50° to 100° during a two-week period in the autumn and survive when all of their free water is frozen (34). On a given day in winter the hardiness of adjacent tissues in the same plant stem may differ in hardiness by 20°C (35); the water in one of these tissues may start freezing at -1° to -5°C while in another supercooling may persist until the temperature drops below -40°C (36). On a given crop the "weak link" limiting survival and productivity may be spring frost in one production area, midwinter minimum temperature in another and fluctuating winter temperatures or fall frosts somewhere else. By the same token, different parts of the plant, or plants at different stages of development, may be particularly susceptible to freezing damage in one year or one locale (e.g. crowns, flowers, roots, dormant flower buds, leaves, living cells in the wood, the cambium, etc.). Symptoms may range from death to a gradually debilitating decline in productivity from secondary causes over a period of years (37). Freezing injury is a major limiting factor to plant growth and survival in the tropics (particularly at high elevations) just as it is in the arctic and temperate zones.

The role of water: Freezing stresses basically involve water transitions. Water is a complex and dynamically structured component of plants. Its physiological properties and distribution are affected by the polymer systems of the tissue as well as by various classes of solutes. Water transitions during freezing begin with crystallization, but this new phase competes with all other phases of water association and causes a sequence of transitions which continue until the system is again at equilibrium. Analysis of energy relationships in freezing is a key factor in identification of traits that involve water and its interactions with plant substances (38).

Techniques have been developed for analysis of (a) phase transitions; (b) crystal growth patterns; (c) stress vectors; (d) freezing kinetics; and (e) thermal transitions (38). The analytic results of such studies are being used to derive a more precise characterization of stress components.

Priorities: In short, freezing injury and resistance is a complicated field of stress research (21), but one which offers scientists and farmers many opportunities for greatly increasing food production and for reducing losses. While our understanding of freezing injury and tolerance/avoidance is incomplete in many respects our ignorance does not preclude us from making significant progress in increasing production of crops subject to freezing stress. It does, however, make the task somewhat empirical and slow.

For this reason, a balanced approach towards the major categories of Environmental Stress Research Imperatives (I, II, and III) is recommended. In short, do what can be done immediately to improve crop production by modifying the environment, manipulating the crop or breeding more resistant crop varieties. Concurrently, a prompt resolution should be sought for the unresolved mysteries of freezing injury and resistance which limit progress.

Rationale: Some recent advances in basic knowledge and applications of technology have been made by interdisciplinary teams working on freezing stress problems. These include

(i) Demonstration of a translocatable hardiness-promoting factor, possibly a hormone, in some woody plants which are capable of acclimatization (39).

(ii) Discovery that some plant tissues survive in nature by supercooling to temperatures as low as the spontaneous nucleation point of water (around -40°C), and that death occurs in such tissues at the moment of freezing (36).

(iii) Development of a model for predicting and means for regulating the time of flowering and fruiting in tree crops through the use of overhead sprinkling to regulate plant temperatures and adjust the length of the dormant period, thereby, avoiding spring frost damage to blossoms (9). The plant development model developed for peaches in Utah, is now being tested and may have application on other tree crops (40).

Efforts should be made to isolate and identify the naturally occurring hardiness promoting factor. A chemical spray that could trigger acclimation would have widespread agricultural applications on semi-hardy crops.

The supercooling phenomenon may provide breeders with a definitive selection technique for flower bud (41), or wood hardiness (35).

Team approach: These advances have been the product of efforts by small teams of research colleagues with diverse expertise (e.g. horticulturists, biophysicists, climatologists, physiologists, and biochemists). Team research approaches should be fostered and encouraged wherever practical via institutional patterns of funding and rewards. Better communication and interaction between the physical scientist and the plant scientist would probably lead to a better understanding of cold and heat stresses, and to improved methods for measuring and overcoming the stresses. Scientific synergism has been exemplified between plant breeders and physiologists. Knowledge of physiological stress control mechanisms, although incomplete, has enabled plant breeders to approach their mission in a systematic manner and with a higher probability of success. Physiologists and plant breeders must, as a first step, identify the stress components which limit productivity and survival. Differences exist for tolerance to stress among tissues and these may vary with the crop being investigated. An understanding of breeding behavior facilitates prediction of the probability for obtaining seedlings which contain the desired component. Knowledge is lacking in this area because of limited work both on the physiological bases of resistance and the genetics of its inheritance.

Germplasm with adequate variability must be available in a form that can be utilized. There is a present danger that valuable germplasm will be lost because of the lack of a comprehensive rational system for collecting and preserving germplasm on a national or international basis. This is particularly important in vegetatively propagated perennial crops which are genetically vulnerable.

The potential for breeding hardier crops is good, especially via a systems approach developed by teams of breeders and physiologists. Genetically hardy varieties provide a solution which reduces requirements for intensive yearly management, new equipment, and fossil fuels. It is applicable in developing countries, because it requires only the planting of hardy cultivars no matter how labor intensive or extensive the production systems may be. This is particularly true for long-lived crops because of their recurring and continuous interactions with extreme climatic events.

Winter wheat breeding: Freezing injury to fall-seeded (winter) wheat is a major production limitation in the temperate climatic regions of the world. Low soil temperatures in winter restrict the areas in which production (survival) is possible. Winter rye, hardy grasses, and spring cereals are grown where it is too cold for winter wheat production. Because winter hardiness is a complex trait, genetically and physiologically, a systematic approach is needed to understand and manipulate the many variables that affect survival. Winter hardiness involves general adaptations dependent on an optimum combination of a large number of genes.

The heritability of plant traits that affect winter survival in wheat and barley have been determined by cooperative research between physiologists and geneticists (42). In the case of winter wheat, exploitable genetic variation for cold tolerance exists in the broad range of germplasm available (e.g. Triticale) and immediate progress is possible. Numerous crosses have been made between exotic cultivars with winter hardiness and commercially acceptable cultivars. Superior genotypes are being identified.

For example, in recent screening of germplasm under high and low crown moisture regimes, approximately 20 cultivars had hardiness ratings more than twice as great as modern, commercially grown varieties (7). If these hardiness levels are genetically incorporated into commercial winter wheat cultivars, thousands of hectares of winter wheat now under cultivation should sustain less low temperature damage and hundred of thousands of hectares now committed to winter rye and forage grasses and spring cereals in the world could be shifted to winter wheat production. While hard red spring wheat provides the highest standard of bread quality, this would have a major impact on total food production since winter cereals yield 25 to 50% more than spring-sown types because cool spring temperatures, and a generally reliable supply of winter soil moisture favor growth and high yields.

<u>Researchable Problems - Recommendations</u>: In addition to the research recommended in the preceding examples, a variety of other approaches and examples were identified including:

(i) Select and breed for late blooming stone fruit cultivars; for pome fruits and berries which do not lose hardiness rapidly in mid-winter following unseasonal warm temperature (11); for flower buds of peach, cherry, and apricot which can survive -40°C; and for sunscald resistance in thin-barked tree species.

(ii) Seek alternative sources of cheap energy for reducing environmental stress. This is necessary because methods for alleviating temperature and moisture stress involve substantial expenditures of energy to modify the microclimate. Example: Orchard heating is capable of raising temperatures 1-3°C. This is more than the protection afforded by chemicals, cultural treatment, or cultivar choice. Overtree sprinkling can be used to delay bloom by as much as two weeks (9). This is at the outer limit of delays achievable genetically and is well beyond that possible by other cultural methods.

(iii) Study the nature of the reversible acclimation attained from continuous cold exposure, with the goal of inducing or retaining this increment of hardiness (3). Example: Acclimated fruit buds of peach and cherry can undergo reversible acclimation of 6 or 7°C (peach) to 12°C (cherry) during continuous exposure to low temperature (43). Comparable increases are probably achievable in other tissues. If it were possible to control or induce this phenomenon it would nearly eliminate dormant season crop losses in the Pacific Northwest and comparable deciduous fruit growing areas (e.g. northern Chile).

(iv) Develop comprehensive economic models to help in assessing the relative values of alternative protection strategies under changing economic conditions. Example: Many cultural practices can be changed to provide small increments of freezing protection. These changes involve costs, direct or indirect that must be assessed. Example: Up to 1°C of frost avoidance can be achieved in some areas by raising the bearing surface of tree crops 10' higher by means of pruning and training. This is counter to current trends of orchard design and would entail sacrifices in harvest costs, safety and perhaps other factors which should be assessed.

(v) Institute a screening program for chemicals to increase freezing resistance. Example: Ethephon applied in September to sweet cherries increases fruit bud hardiness by 1-2°C and delays bloom 2-8 days. Yield increases of up to 100% have been measured (44). Other less successful instances of chemical induction of hardiness have been recorded on deciduous fruits but there has been no extensive or systematic effort to assess the cryoprotective properties of chemicals. One or 2°C of protection could extend the growing season and reduce injury on many annual and perennial crops.

Tissues within a plant differ in hardiness. Toxic compounds resulting from degeneration of injured cells may result in indirect secondary damage, including subsequent interactions with disease organisms which often invade freeze injured plants (37). These processes have received little research attention. A better understanding of freezing injury side-effects and plant repair mechanisms is needed for development of crop management practices to minimize stress effects and/or to facilitate rapid recovery.

HEAT

Review and Rationale: There is mounting evidence that high soil and air temperatures have a marked effect, reducing crop productivity in both temperate and tropic areas. However, the number of scientists identified or involved in high temperature research is limited and there is limited interchange between individuals, international centers, and commercial companies conducting research on heat stress. Better communication and research coordination is needed. Heat and drought stress are intimately interrelated, as when a hot wind blows over a dry land crop. As a result reductions in crop yield directly attributable to high temperatures are poorly defined and understood. When stomata close as a result of drought stress, evaporative cooling is reduced and plant temperatures frequently increase to levels where vital processes such as photosynthesis are seriously affected.

In the case of grain sorghum, it has been demonstrated that there is sufficient variability among genotypes to select for heat tolerant lines and breed this trait into hybrids (45). Photosynthesis has been shown to remain near optimum in selected heat-tolerant lines at high temperatures which completely stopped photosynthesis in commercial hybrids (46). In Nigeria, inhibition of seed germination and seedling growth in soybeans has been associated with high temperatures (47).

The extreme effects of heat are fairly obvious, e.g. irreversible denaturation of proteins vital to the life of the cell. Sublethal effects, however, are less well defined and of considerably more importance to crop productivity.

Heat effects on proteins are well known, and certain enzymes are more susceptible to heat damage than others at temperatures which occur in nature (21, 48). So-called "heat lesions" occur as a result of the metabolic inbalances caused by inactivation of key enzymes.

Drought may involve similar indirect metabolic effects, and repair and recovery mechanisms are important in both cases. Freezing damage, on the other hand, is more direct and less subtle in many instances, e.g. the membranes of a frozen cell may be completely destroyed. Lipid phase-changes are known to be temperature-dependent and to play a role in chilling injury.

Researchable Problems - Recommendations: The following examples illustrate some current research areas on heat stress which may lead to improved crop productivity. Advances which would speed progress include resolution of the mechanisms of resistance and tolerance, and development of better techniques for measuring heat stress.

(i) Define the stage of plant development on specific crops at which the stress occurs, and at which maximum reduction in yield results, e.g. reduced number of grains in the panicle resulting from heat induced blasting of flowers (49). Heat stress imposed on seeds during drying prior to storage may also reduce viability and vigor.

(ii) Investigate possible advantageous effects of stress pretreatment on subsequent growth, development and yield of crops. For example, brief heat exposures (4 hrs. per day for 4 days) to sorghum seedlings resulted in a 7% increase in grain yield of field grown plants (49).

(iii) Measure separately heat tolerance, heat avoidance, drought tolerance and drought avoidance under field conditions, and determine interactions by simultaneous measurements of these parameters.

(iv) Identify crops which are capable of hardening (acclimating) to heat stress, and then define the range of hardening possible and the conditions which trigger and promote the process.

(v) Characterize the metabolic effects of heat stress, e.g. on photosynthesis, respiration, and partitioning of photosynthate (50).

(vi) Examine the mechanisms and rate of recovery from heat stress; the potential of cultural practices (tillage systems, time of cropping, misting - evaporative cooling, etc.) for reducing heat stress; and stress injury and tolerance. In the latter case the possible role of lipid phase-transitions in heat damage should be investigated.

ION TOXICITY

Review: Excesses of certain mineral ions are major limitations to food crop production in many soils of the world. Examples are: (i) Al toxicity coupled with P unavailability in vast areas of acid soils in South America (Campo Cerrado of Brazil and the Llanos of Colombia) and also in acid subsoils of the Southeastern U.S. A recent soil survey (51) showed that at least 50% of the subsoils in Brazil (2nd 6 inches of the profile) are 50% Al saturated. In the Campo Cerrado area surrounding Brasilia, an estimated 50,625,000 hectares are affected. Aluminum toxicity in subsoils causes shallow rooting, drought susceptibility, and poor use of subsoil nutrients (52). (ii) Al, Mn and other metal ion toxicities in acid mine soils and waste disposal sites (53).

Many ion toxicity problems are not economically correctable with conventional liming and fertilization practices, but plant species and varieties within species differ widely in tolerance to toxic ion stress. Several such differences are known to be genetically controlled. Hence, selection and breeding offers a promising approach for tailoring genotypes with greater tolerance to excesses (or imbalances) of mineral elements in soils.

Aluminum tolerance in barley, for example, is controlled by one major dominant gene (54). In wheat, two or three major genes plus modifiers, appear to be involved (55). Manganese tolerance in alfalfa is reportedly controlled by additive genes having little or no dominance (56).

In some plants, physiological traits associated with metal tolerance have been identified. Aluminum-tolerant varieties of wheat and barley and inbred lines of corn do not decrease the pH of their root zones as do sensitive lines (57). Tolerant lines may

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In some plants, physiological traits associated with metal tolerance have been identified. Aluminum-tolerant varieties of wheat and barley and inbred lines of corn do not decrease the pH of their root zones as do sensitive lines (57). Tolerant lines may or biochemical characteristics associated with tolerance and use these as screening tools. Plant varieties that differ in tolerance may also be used as indicators of present or potential ion toxicity problems in soils, and as tools for studying basic aspects of mineral nutrition.

(iv) Seek and include plants having wide differences in tolerance to ion toxicities in the world germ plasm collections.

(v) Develop cheaper and more effective P fertilizers for Al-toxic P-fixing soils of the tropics. A possibility might be raw rock phosphate and rock phosphate that has been fused with Mg silicate.

(vi) Develop an international newsletter to share ideas concerning the genetic regulation of plant nutrition.

Research progress along the lines recommended could increase crop productivity and world food supply in a variety of ways. Examples of the beneficial effects to be achieved by Al-tolerant cultivars are;

(i) Al-tolerant genotypes that produce deeper root systems and make better use of nutrients and water in acid subsoils would extend the acreage of crops into soil regions not previously suited to the crop.

(ii) Al-tolerant varieties could produce acceptable (economic) yields with lower inputs of lime and P fertilizers on the present acreage.

(iii) Al-tolerant varieties could facilitate the use of so-called "acid soil rotations" involving barley and potatoes or sugarbeet and potatoes.

(iv) Plants having superior tolerance to excess Al, Mn and other mineral elements could facilitate and reduce the cost of revegetating acid mine soils.

(v) P-efficient genotypes tolerant to Al

would increase production on the high
Al, P-fixing soils of the tropics.

See the report of the Water, Soil and Mineral Working Group for a discussion of salinity which constitutes another important type of ionic stress to crops.

AIR POLLUTION

Review: Air pollution is most commonly associated with the activities of man. Ultimate control lies in eliminating pollution problems via prevention and abatement technology. Air pollution stresses are associated with air movement patterns. Stringent pollution controls in a certain region may cause relocations of pollution sources to other geographical localities.

Air pollution is a stress that burdens man and natural ecosystems as well as crops. Its effect may involve decreased productivity, risk to health and well-being and deterioration of natural areas. Consequently, the costs and benefits involved in alleviating air pollution stress cannot be measured in terms of crop productivity alone.

When it is economically or socially unacceptable to reduce crop losses by controlling air pollution at the source it must be done at the receptor. The research recommendations which are presented address that situation.

Air pollutant effects on crops are complex. They involve interrelationships of pollutant mixtures under a variety of stress conditions, including both abiotic and biotic stresses. Research has shown that some pollutants may predispose plants to attack by insects or infection by pathogenic fungi (62).

A key limiting factor to assessing priorities is inadequate information on losses in crop productivity. Possible approaches include development of measures to minimize losses including (i) the selection and development of tolerant cultivars, and (ii) the achivement tolerance by modifying cultural practices (e.g. application of anti-oxidant chemicals) and by modifying the nutrition of plants.

Currently, the most important gaseous pollutants are sulfur dioxide, oxidants (ozone and peroxyacetyl nitrate), hydrogen fluoride, ethylene and nitrogen oxide. Dust, pollens, heavy metals (lead and cadmium), and some agricultural chemicals, acid aerosols, chlorine, hydrogen chloride, ammonia, and radioactive elements are also of concern. Because new air pollution problems will probably emerge, current research efforts should seek basic principles and patterns with broad application.

Since most pollutants arise from man's activities, especially in urban-industrial areas, the greatest threat to food crop productivity is near the urban centers. Air movement, however, spreads the pollutants to affect crops over long distances and across political borders such as is occurring in Western Europe or the northeast U.S.

Vegetable and fruit crops grown for fresh market are perhaps of greatest concern since they are produced near or in the urban centers. Vegetables frequently experience the greatest economic loss (64). Major field crops such as soybeans are damaged in some areas (65).

Rationale: High priority is placed on research to assess the impact of stress on crop productivity and to elucidate the basic mechanisms of pollutant injury and tolerance in plants. It was concluded that an understanding of the modes of action of air pollutants is essential (i) to provide sensitive indices and early indicators of pollutant stress; (ii) to provide criteria for selecting tolerant plants; (iii) to establish air quality criteria; and (iv) to aid in the efficient selection of production management procedures or chemical application to minimize pollutant impact.

Assessment of air pollution effects on the quantity and quality of crop productivity is also essential to establish effectively priorities for research manpower and dollars. Such productivity assessments provide fundamental data for the establishment of both emission and air quality standards to protect human welfare. They also provide basic information for cost-effectiveness determinations relative to abatement programs, and are required to determine the degree to which air quality must be improved if significant improvements in crop productivity are to be realized.

The development of 3 countermeasures to air pollution stress effects on crop productivity were recommended as follows:

(i) Abatement of pollutants at their source. This approach is not succeeding in spite of large efforts and expenditures. Many authorities expect the future to bring greater pollution stresses, not smaller, as the population increases.

(ii) Development of pollutant-resistant crop varieties by plant breeding and selection. Progress has been made and relatively resistant varieties of many crops are now known. However, the resistant varieties do not, in many cases, combine other desirable characteristics, and breeding for resistance has a long way to go before air pollutant stresses are no longer a problem to crop productivity.

(iii) Chemical treatments that protect plants from pollutant injury. The damaging effects of atmospheric ozone on plants can be experimentally reduced by chemicals, including several commercial fungicides, growth retardants, and reducing agents of natural and synthetic origin (66). None to date provide economically feasible means of effectively and reliably protecting crops produced in areas where ozone pollution is high enough to suppress yields. Some promising new chemicals are being tested. In preliminary field tests yields have been increased on some ozone-sensitive cultivars in areas where the seasonal ozone concentrations range up to 0.10-0.12 ppm. Yields of less sensitive cultivars did not increase under similar treatments.

Researchable Problems - Recommendations: Research needs were identified in the following order of priority:

(i) Determine the morphological, physiological and/or the biochemical basis of pollutant tolerance. For example, rapid closure of stomates due to exposure to pollutants may increase tolerance to pollutants. Light can influence the tolerance to some air pollutants such as nitrogen dioxide and peroxyacetyl nitrate (67).

(ii) Determine the ability of the plant to metabolize, detoxify or compartmentalize the pollutant. For example, it has been demonstrated that plants are capable of metabolizing some pollutants such as SO_2, but foliar injury occurs if the rate of absorption exceeds the rate of metabolism (68).

(iii) Assess repair and injury processes in air pollutant stressed cells. For example, studies have shown that factors such as metabolic pools or light may influence the rate of membrane repair and allow the return of the tissue to a normal condition (69).

(iv) Determine the factors influencing pollutant penetration into cells and transport in the plant.

In addition, the following needs for assessment studies were identified:

(i) Determination of the potential for productivity losses in major food, fiber and forage crops from pollutants and pollutant mixtures.

(ii) Determination of the interaction between air pollutants and factors, such as environmental stresses, plant types, and biological pests which potentially limit crop production.

(iii) Development of models utilizing data from the productivity assessment studies to measure and predict the impact of changing air quality on crop production.

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PLANT DEVELOPMENT PROCESSES

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INTRODUCTION

What will be the progress in plant improvement over the next several decades? Will there be quantum increases in productivity or will increase occur at a steady rate? Crop production can be increased only through changes in management practices, including pest control, genetic improvement of the plant, or through the interaction of management and genetic improvement. Traditionally yield advances have been achieved by people with strong agricultural orientation, using knowledge from closely related disciplines. Traditional approaches have led to steady increases in crop yields. Support of such efforts must be continued and expanded to meet the awesom demands of the future. Improvement of crop yields has been achieved principally by the combined efforts of management specialists, plant pathologists, entomologists, and plant breeders. The accelerated progress required for feeding rapidly expanding world populations depends on bringing biochemists and plant physiologists into direct and active participation with those teams whose mission is genetic and cultural improvement of crop productivity (1).

The focus of this paper is upon the physiological and developmental processes which underlie and determine crop productivity and quality, and upon the biochemistry and genetics of these processes. The goal is to identify those plant processes and characteristics which can be used by plant breeders in manipulating plant genotypes to give expression of maximum crop yield potential or to delineate areas where more research may identify such processes and characters. This task is complex because yield expression results from interaction among gene systems, developmental processes and the environment.

High yield will result only when efficient interception, absorption and photosynthetic utilization of light energy is achieved. Maximum economic yield also requires the optimum partitioning of accumulated photosynthate into those plant organs or components that constitute economic yield. Thus, yield is achieved primarily by two multiple-gene directed processes, namely photosynthate accumulation and partitioning. Optimum diversion of photosynthate to the plant organs implies regulation of the partitioning processes. This regulation must achieve balance among growth processes conducive to optimum growth of the economically important organs in the environment in which the crop will be produced.

With knowledge of the mechanisms of these controls, beneficial manipulation of plant development might be attained through application of chemicals to the crop.

All stages of the plant's life cycle are influenced by control of development and differentiation and by their interaction with the environment. A specific response during seed filling or germination may have effects on yield, just as variation in time of flowering obviously alters partitioning between vegetative and reproductive growth.

There are "internal" controls over plant development, the most widely recognized being the hormone system. Variations in tissue content of auxins, gibberellins, cytokinins, and abscissic acid attend all changes in plant development. We don't know how changes in hormone content cause the switch in stage of development, or if they are merely correlated responses.

External environmental factors, such as day-

daylength and temperature, frequently bring about a switch in plant development. The light regime exerts major influence both through photosynthesis and through other control systems. The light-induced photochemical changes in the phytochrome molecule are reasonably well understood, but the mechanism(s) through which phytochrome change mediates control over so many plant developmental processes remains unknown.

Internal tissue concentrations of the hormones vary in correlation with photoperiod triggering of plant developmental processes, but the causal vs. response relationships are not understood. Temperature together with daylength and light quality interact to affect plant development. For instance, low temperature sometimes reduces or eliminates photoperiod effects, and high temperature greatly increases their intensity. Operating through a completely separate mechanism called vernalization, "low" temperature is required to trigger flowering, and similarly tuber formation, of some crops. Again, variation in hormonal content of differentiating organs and tissues is correlated with temperature-caused changes in development, but neither the mechanisms of vernalization control nor the interaction with hormones is understood. Additional hormonal interactions appear in response to stress factors such as high temperature or drought.

The correlated effects of changes in hormonal concentrations, phytochrome effect, temperature mediated vernalization and increased metabolic rates are the best recognized controls of plant development and differentiation. It is certain that additional control systems are yet to be discovered in plants.

Cell differentiation is central to all biology and is being studied in microorganisms and animals, and also in plants. Although many features of cell differentiation are common to all organisms, there are also special features in plants which require separate study. A fuller understanding of the process has many implications for crop production, being especially important in relation to the problem of regeneration of whole plants from cell cultures, which promises many new avenues in plant genetics and breeding.

Development can be regarded as a process directed by timely and selective gene expression. There is clearly a close relationship between development and genetics, and there is great need for better understanding of the molecular mechanisms controlling gene expression. Such understanding of basic biological science is part of the necessary background against which we operate at the whole plant level, in the improvement of crop production, and is necessary to guarantee future progress.

I. PLANT CELL AND TISSUE CULTURE

A. INTRODUCTION

Recent advances in the culture of plant cells and tissues *in vitro* have provided a novel technology which permits the application of microbiological methods to higher plants (2, 3). By employing populations of haploid or diploid cells as experimental material, it is possible to utilize the genetic, physiological and biochemical procedures developed with microorganisms to analyze and modify higher plants.

Plant cells can be grown on agar indefinitely as masses of unorganized cells (callus) or in liquid suspensions. Generally, the cells require mineral salts, a carbon source, several vitamins and hormones to support growth and proliferation. Cells grown in suspension culture appear to be unorganized and do not show any obvious structural or biochemical evidence for functions other than continued division. However, when suspended and cultured under suitable conditions, the cells of some species can be induced to differentiate, yielding complete plants. The process of morphogenesis from unorganized cells may occur either by embryogenesis in the absence of exogenous hormones or by organogenesis induced by cytokinins.

Significant advances have been made in defining techniques for isolating protoplasts (4). Protoplasts are generally obtained by treating cells or tissues with a range of hydrolytic enzymes (cellulases, hemicellulases, pectinases, etc.) in media containing osmotic stabilizers. The most common materials for protoplast isolation are leaf tissues and cells from suspension cultures. Isolated protoplasts can be cultured, and in some cases they reform a cell wall and undergo division. Although continuous divisions do occur from protoplasts of a few species, the lack of such proliferation for most crop species remains a serious limitation to capitalizing on these methods in crop improvement.

Protoplast fusion can occur spontaneously during isolation, or it can be induced chemically. Fusions between protoplasts obtained from different genera can be accomplished with a high frequency, yielding heterokaryons and often dividing hybrid synkaryons. Major problems still exist in identifying the hybrid cells, in isolating the hybrid clones and in regeneration of the intergeneric synakaryon to an organized plant.

Haploids have been obtained by anther cultures in at least 18 plant genera. However, large numbers of haploids have been obtained from only a few species. Of the economically important plants, the procedure has been particularly successful with tobacco (*Nicotiana spp*). Haploids can be obtained in reasonable frequency by methods other than anther culture in a range of crop species including corn (*Zea mays*), potato (*Solanum tuberosum*), alfalfa (*Medicago spp*.) and barley (*Hordeum vulgare*).

Doubled haploids have been used commercially in corn and are in the testing stage in barley. Haploids of potato and alfalfa provide opportunities for new breeding methods and methods of germplasm transfer from wild to cultivated species.

Cell and tissue culture methods should be developed with all economically important plant species, but these new techniques will not replace conventional breeding methods of plant improvement. They provide only another tool with which to attack problems related to plant improvement and are complementary to methods. Like many new approaches, cell and tissue culture will probably be very effective with some plants and in attacking some problems. They will certainly not be a panacea for solving all plant improvement problems. However, the unconventional approach of cell and tissue culture does offer the possibility of unique experimental manipulations not otherwise possible.

B. RESEARCH IMPERATIVES: SHORT TERM

1. Determine how to regenerate whole plants of the major crop species.
2. Adapt and apply the techniques of somatic cell genetics to the goals of understanding genetic modification, organization and regulation in higher plants.
3. Perform mass selective screening for traits of agronomic value, as well as for processes involved in the agronomic expression of components.
4. Cell and tissue cultures might be used for preservation of germplasm of vegetatively propagated species.
5. Two currently applicable techniques (5) of *in vitro* culture in plant improvement are: (a) recovery of pathogen free plants and (b) rapid vegetative increase of new clones and cultivars.

The first is especially important in vegetatively reproduced crops such as potato and sugar cane, and it is predicted that the second will become very important in forest crops and in certain orchard crops. The techniques now available should be applied to a wide range of crop species.

C. RESEARCH IMPERATIVES: LONG TERM

The following are areas in which absence of proper techniques limit progress.

1. Severe limitation of cell culture technology stems from limited knowledge of plant physiological and biochemical processes. The recognition and recovery of genetic variation *in vitro* is dependent upon distinct cellular phenomena. Further research will provide insight into the molecular and cellular mechanisms underlying agronomically important traits. The biochemical and physiological components of whole plant characters must then be duplicated *in vitro*. Selection schemes which recover variants for processes unique to higher plants must be developed. There are almost certainly limits as to the types of variants which can be recovered *in vitro*. Selective systems designed to recover mutants in basic metabolism have a high probability of success. Mutant systems attempting to modify tissue specific characters or characters unique to certain differentiated states would have a lower probability of success. If a character is not expressed by cells in culture, then it is impossible to select for variants of that character *in vitro*. At the present time, *in vitro* methods are inadequate for attempting to modify complex developmental characteristics. This area requires further research.

2. An area which holds promise for increased crop productivity is increased genetic diversity. Fusion of protoplasts from different species is one approach to increasing genetic disparity.

In many instances, the goal of increasing genetic diversity is not limited by hybrid production but by the integration of evolutionary divergent genomes. Sterility and lack of recombination between the genomes do not permit the potentially novel germplasm to be utilized. In vitro techniques often reveal ways to circumvent this problem. Research which focuses on inducing, recognizing and recovering chromosomal changes in somatic cells should be encouraged. These techniques should particularly attempt to develop methods to induce chromosome loss. There is also a need for techniques to induce and recover genetic recombinants from somatic cells. In this fashion, in vitro culture can be used in conjunction with sexually and somatically produced hybrids where incompatibilities present barriers to growth and development. Tissue from the hybrids might be cultured in vitro, subject to the treatments which cause genetic alterations and then regenerated into plants. Fertile individuals which display the derived combinations of characteristics could then be recovered from the population of regenerated plants.

3. Cell culture techniques offer the possibility of exploring the importance of genetically different organelles and cytoplasms to plant improvement. In normal sexual reproduction, the male gamete contributes little or no cytoplasm to the zygote. Somatic hybridization allows the production of cells which are hybrid for their cytoplasmic components. Genetic utilization and manipulation of these cytoplasmic hybrids should permit a more refined analysis of the importance of these components in plant improvement.

4. Long term approaches to genetic engineering should be encouraged. Such speculative goals as accomplishing genetic transformation, transduction and plasmid transfer may provide a future source of genetic variability as well

as an analytic technique to define the genetic organization of crop plant species.

II. CONTROL MECHANISMS OF GROWTH AND DEVELOPMENT

(Whole Plant Development)

A. INTRODUCTION

Many problems at the interfaces between organ development and genetics, the understanding of which would greatly assist genetic improvement of crops, have been identified (6, 7, 8). Some might be solved through existing knowledge of plant development and its control systems, including especially knowledge of plant hormones. Progress is limited by lack of fundamental knowledge of the mode of action of hormones and of how the several hormones interact to control plant organ development.

Environmental control of plant development is also a phenomenon of central importance. Our understanding of environmental influence on plant growth is growing, especially with regard to the phytochrome system. However, there is need to study the mechanisms of the phytochrome system in greater detail and extend the studies to growth control by several environmental factors. Such studies are especially needed in relation to breeding for stress resistance. How can highest possible yields be obtained in the presence of drought, salinity, low or high temperatures, etc.?

The basic importance of competition within the plant for nutrients, including partitioning of photosynthates and distribution of inorganic nutrients, cannot be overlooked. The mechanisms controlling the partitioning of photosynthates and nutrients demand immediate attention.

B. RESEARCH IMPERATIVES: SHORT TERM

1. Fruit development and tuber formation

a) Factors regulating mobilization of assimilates by developing seeds and fruits are poorly understood. Investigation of factors limiting number and size of fruit and of the interrelationships of assimilate supply with fruit size and set would help clarify many of the limitations to increasing yield. The role of inhibitory interactions between the developing seed and fruit set and reduced size, should be investigated. Similar investigations of tuber and root formation should be made for root crops.

b) The biochemistry of seed development in relation to nutritional value, including protein quality in grain legumes should be thoroughly studied. With nutritional (amino acid) balance, the same amount of food, (rice, corn or beans) would provide more adequate and better nourishment for more people.

2. Flowering

a) Factors affecting abscission and abortion of flowers obviously influence yield and should be intensively investigated.

b) Internal and external factors controlling timing, intensity and duration of flowering have a direct effect on economic yield of grain (seed) crops. A delay of a few days in flowering can lead, when the growing season is sufficiently long, to a large yield increase in crops such as beans. This delayed flowering and higher yield was achieved in the field by extending daylength with electric lamps. A few minutes of low intensity light in the middle of the night may have a similar effect. Genes affecting maturity and the photoperiod influence on flowering should be identified; the effects on yield should be determined, and the mechanisms of influencing yield should be investigated.

c) For some crops, plants producing only female flowers are fertilized with pollen from selected plants to produce seed of hybrid cultivars. Understanding the mechanisms of sex expression could permit more widespread use of hybrid vigor.

3. Vegetative Growth

a) Factors controlling leaf area accretion rates in relation to expansion and early season establishment of optimal leaf area need further elucidation. The effect of different leaf characters and canopy arrangements on efficiency of light interception and utilization of absorbed light energy on yield needs additional investigation.

b) Internal and external factors affecting tillering should be determined, together with the mechanisms regulating these processes.

c) Factors affecting root architecture and development and their relationships to root functions in uptake of nutrients and water are poorly understood. Also the effect of soil environments on root growth need to be investigated more thoroughly.

d) Relationships between stem growth and productivity should be clarified, particularly with respect to dwarf as compared to tall varieties.

4. Seedling Establishment

More uniform and reliable establishment, particularly with vegetatively propagated crops, would give increased yield. Better understanding of seed physiology would help to achieve the required better plant stands.

C. RESEARCH IMPERATIVES: LONG TERM

The solution of many of these problems requires a better understanding of the hormonal control of growth and development. Better knowledge of differentiation of plant organs is especially needed. Long-term basic research on the biochemistry and mode of action of plant hormones is essential. Further work is required on the effect of interaction between the several different hormones in the regulation of such processes as stem, leaf, fruit and root growth. Special attention needs to be directed towards the hormonal regulation of flowering and tuberization, since better understanding of these processes could clearly be used in breeding higher yielding cultivars.

Since plant growth and development are profoundly modified by environmental factors, better understanding of the plant response and control mechanisms involved are central to more rapid crop improvement. We need more knowledge not only about phytochrome controlled responses, but especially about stress factors such as high and low temperature and drought.

Chemical regulation of crop growth and development offers great opportunities for more efficient production. Identification of effective chemicals is under considerable study by industrial organizations. The proposed basic studies of hormone action would facilitate improvement of crop yields of appropriate chemical applications.

III. RESPONSE TO ENVIRONMENTAL STRESSES

A. INTRODUCTION

Vagaries of climate and variations in water supply, plant pest populations, soil types, agronomic practices and increasing problems with chemical pollutants provide an ever-changing background of stress conditions against which crop plants are produced and against which cultivars and management practices must be tested before their possible impact can be evaluated. There is a growing body of knowledge about the gross effects on crops of extremes in soil aeration, pH and heavy metal toxicity (1), extremes of air temperature (10) and atmospheric contaminations, and about competitive interactions between plants (11). Rates of improvement of crop productivity could be enhanced by better understanding of the physiological and genetic bases of these effects and by applications of what is known to plant breeding programs.

B. RESEARCH IMPERATIVES: SHORT TERM

1) A better understanding of the physiological and genetic bases of response to extremes of soil characteristics would accelerate breeding for resistance to stresses. What are the genetic ranges for tolerance to poor soil aeration, poor drainage, pH, salinity-alkalinity, low levels of essential nutrients and poor soil structure factors? What are the genetic and physiological mechanisms of these tolerances? As an example of possible accomplishments, barley varieties resistant to above normal levels of aluminum have been developed. High levels of aluminum are characteristic of lateritic soils which cover huge areas of the globe. Breeding of crops tolerant to high levels of heavy metals or deficiencies in micro-nutrients is readily possible.

2) Better understanding is needed of physiological and genetic bases of response to environmental extremes of temperature, atmospheric contaminants, light intensity, humidity, oxygen and CO_2. As an example, increases in winter hardiness of wheat and barley could lead to major increases in yield over vast areas of the globe.

3) Physiological and genetic bases of response to competitive interactions within and between plants. Much of the realized gain in crop productivity of current as compared with past cultivars is derived from closer between-row and within-row spacings. Higher plant population densities did not give increased yield for the old cultivars (12). Knowledge of the genetic and physiological factors controlling response to population density would greatly increase efficiency of selecting for higher yield. It would save much research effort if leaf display characteristics, canopy

arrangements and physiological processes facilitating yield response to plant population density were understood.

C. RESEARCH IMPERATIVES: LONG TERM

1) Research to uncover the causes of tolerance to heavy metals or to deficiencies in water, micro-nutrients and other reactions to stress.

2) Research in the area of intergeneric interspecific crosses to extend the genetic range for stress reactions.

3) Research in stress physiology, including biophysical approaches to understanding freezing, drought and heat stresses.

IV. PRESERVATION AND GENERATION OF GENETIC VARIABILITY

A. INTRODUCTION

Modern improved cultivars are rapidly replacing indigenous land races of many crop species. These modern cultivars are superior in resistance to certain diseases, in yield, etc., but much of the existing diversity of plant genes resides in these rapidly disappearing land races. With this disappearance, it may prove impossible to find resistance to new races of plant diseases or to new insect pests.

B. RESEARCH IMPERATIVES

1. Collection, maintenance and description of genetic resources. As an example of the value of preservation of indigenous germplasm, rice (*Oryza sativa*) varieties bred by the International Rice Research Institute were found to be susceptible to the brown plant hopper (*Laodelphax striatellus*). The "Green Revolution" improvements in rice would have been completely nullified if one or two rice lines, among thousands tested from the rice germplasm bank, had not been found to be resistant to the

pest (13). The resistant line was crossed to the high yielding cultivar and the insect resistance was combined with the high yielding capability.

2. Genetic analysis and recombination.

Many important genes will only be expressed, and therefore identifiable, in very specific environments, and some will be expressed only in combination with certain other genes. Therefore, it is essential to search for genes in different environments and genetic backgrounds. Germplasm banks are the only means of assuring the continued availability of these genes. Novel systems, such as enforced outcrossing via genetic or chemically created male sterility should be devised to permit recombination and expression and analysis of these genes.

V. PLANT DESIGN AND VARIETAL DEVELOPMENT

A. INTRODUCTION

Plant breeders, plant pathologists and entomologists have a long history of successful cooperation in developing new high yielding varieties. Increased productivity due to combined efforts of the physiologist and plant breeder are more difficult to find. Two examples of such collaboration are increased sugar percentage in the sugar beet and changes in daylength sensitivity in many crops. It is relatively easy to handle large numbers of measurements of these two traits and the measurements have real economic meaning. Physiological processes are not usually readily measurable in the field on large numbers of plants. For the most part, plant improvement through breeding (aside from pest control) has been based on empirical tests without understanding the basic physiological processes being manipulated.

B. RESEARCH IMPERATIVES: SHORT TERM

1) Identify the significant physiological,

morphological and architectural components giving rise to high yield, good nutritional quality and environmental adaptation in major food and fiber plants. For example, the new short-strawed varieties of wheat and rice have been amazingly successful. The quantum jumps in yield resulted in new conceptual ideotypes (model plant types for high yield) (14). A more thorough understanding and identification of the significant physiological, morphological and architectural component relationships would help in the building of better plant models (ideotypes) for other geographical (environments) areas and for other crops. Once the basic concepts are understood, the models are transferable to other crops and other areas.

2) Identify sources of genetic variability and diversity for the architectural and physiological components of yield.

3) Efficient, inexpensive and novel techniques for screening of genetically variable populations for the physiological and biochemical components of yield should be devised. For example, large numbers of plants could be screened for nitrogen uptake using a fluorescent dye; diastase activity in the seed can be measured using colorometric tests similar to those used for diabetes.

4) Devise breeding or management strategies to overcome physiological and genetic constraints to recombining components into a single or common genotype. For example, developmental constraints prevent the combination of high numbers of fertile tillers per unit area and high numbers of seeds per head in barley, and this negative relationship is a barrier to higher yield. There is now evidence that in a chance-segregate this constraint has been uncoupled genetically and physiologically, giving rise to increased yield.

Special dwarf rootstocks for tree fruits provide a means for using high density spacings with specific geometric designs to permit better light distribution and give increased yield over conventional large trees on an area basis.

C. RESEARCH IMPERATIVES: LONG TERM

In many ways the long term basic science requirements of this section are identical to t those of the other subdivisions of the plant development section. Two areas are unique. One is the need for more research on the requirements of nutrition, especially human nutrition, and the changes needed in plant proteins, vitamins, anti-metabolites and carbohydrates to meet the needs of the ever expanding world populations. The second unique area is a need for mathematical modeling of the entire yield system (15). This would enable us to put the system together and to learn how variation in component parts of the system affect the system as a whole and also the output (economic yield) of the system.

VI. BASIC RESEARCH

A. INTRODUCTION

A major need is to encourage fundamental studies in plant physiology, genetics, development, breeding, and agronomic adaptation employing major economically useful species as test organisms.

B. RESEARCH IMPERATIVES

1. Understanding of plant biology would be enhanced many fold if all aspects of the genetics, biochemistry,and physiology of one or two economic species were studied in detail. Knowledge acquired through this concentrated effort would facilitate more rapid progress in understanding the problems of all plants and in breeding for improved crop productivity.
2. A second need is to encourage novel research approaches to basic understanding of growth, development, genetic architecture, control mechanisms, screening and evaluation,

plant design, varietal development, quality, ecological adaptation, and cropping systems in diverse environments.

Detectors and associated instrumentation should be developed which could, for example, be passed hourly, daily or weekly over a field of segregating or otherwise diverse genotypes. This device might detect rates of phytosynthesis, dark respiration, protein synthesis, biomass accumulation, nitrate reductase activity or activity of other enzymes, etc. This would facilitate "remote sensing" and "computer assisted" selection of superior plants and of identification of inferior plants for comparative physiological and genetic studies. Plants achieving yields via different pathways could be identified as parents with potential to contribute complementary characters to their progeny.

IMPLEMENTATION

We have purposely retained generality in writing these imperatives for the obvious reason that crops and crop production are specific to regions. It is to be expected that basic information will be transferable between crops and between regions, but the relative importance of a problem may be determined by the region in which the researchers are located and by their individual and collective talents. The specific imperatives can best be determined by the people and the research teams of the area.

While urging the implementation of team research, we suggest constraint in how such teams are put together and how they are oriented. Not all people work well together. Some extremely productive scientists work best when not constrained by the needs of an organized group. Administration must serve the important purpose of establishing a favorable climate for cooperative research without disregarding the human element present in all science.

The over-riding imperative which has emerged in this section is the need to add mission-oriented plant physiologists to the existing teams of plant pathologists, entomologists and breeders and to create new teams. We believe that the six general imperatives developed here are a goo/ place to start. The specific imperatives can be worked out *in situ*.

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We gratefully acknowledge the individual contributions of the group of scientists attending the Plant Development section. It fell to a few of us to try to condense and coordinate the many suggestions of the group, and it must be our lot to accept the criticisms of those in attendance where we have failed to do so properly.

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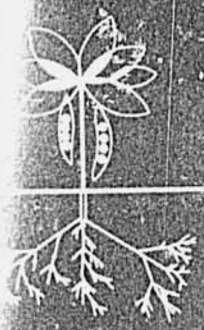

The International Conference on Crop Productivity-Research Imperatives was planned with the recognition that an exploding population and an increasingly affluent society impose a more acute challenge to agriculture than ever before. The focus of the Conference was on the fundamental biological processes that control productivity of economically important food crops. The Conference was held October 20-24, 1975 at Harbor Springs, Michigan.

A distinctive feature of the Conference was its organization into a plenary session-workshop format. Six discussion groups were concerned with: Nitrogen Input; Carbon Input; Water, Soil and Mineral Input; Plant Protection from Pests; Environmental Stress (Air, Water, Salinity, Temperature) and Plant Development Processes. The reports of the six groups not only discuss what were considered the most important fundamental biological processes that limit crop productivity but also identify research imperatives deemed essential to rapidly advance the knowledge of these processes. Attention must now be directed toward assuring their implementation and application to the various crop production systems of world agriculture.