PN-ABC-642

MODELLING SOIL CHANGES UNDER AGROFORESTRY

Rodney J. Cheatle, Peter Muraya and Anthony Young

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

ABSTRACT

Erosion control and the maintenance of soil fertility are closely related, and both are necessary to the achievement of sustainable land use. Trees, and hence agroforestry systems, have the potential to improve and maintain soil fertility, and to assist in erosion control. A computerized model, Soil Changes Under Agroforestry (SCUAF), is outlined. This has been initially developed as an input-output model for the cycling of organic matter, represented by carbon. Results from the model are presented for natural ecosystems (as a form of calibration), and for three types of agroforestry systems: rotational, spatial mixed, and spatial zoned.

Though input data were not ideal, the results demonstrate a robust model offering indications of the sustainability of agroforestry systems. Confidence developed as the model successfully predicted stable soil conditions in lowland humid forest, mature savanna woodland and intimate woody mixtures in spatial agroforestry. In rotational agroforestry, soil carbon recovery under natural fallow and decline associated with bare ground were also demonstrated. A prediction of considerable interest is soil carbon stability in zoned alley cropping systems at much higher crop: tree ratios than is the case for natural fallows in rotations.

Conclusions are that there is a potential for agroforestry systems to achieve land use that is both productive and sustainable; and that there is a need for research into certain critical areas of the plant-soil organic matter cycle, notably root production and turnover, soil organic matter transformations, and the tree clearance phase of rotations.

INTRODUCTION

Erosion, soil fertility and sustainable land use

In the older approach to soil conservation, the emphasis was on controlling the rate of soil loss, expressed as tonnes per hectare or millimetres of soil depth. Conservation measures were directed at reducing erosion to a presumed acceptable rate, called soil loss tolerance. Earlier attempts to assess the consequences of erosion for loss of production and in economic terms were made on the basis of reduction in soil depth. Extension work was often conducted on the basis that erosion control should come first, as a prerequisite to other agricultural improvements.

Recent research has changed this emphasis in several ways. It has been recognized that the effects of erosion are by no means limited to reduction in soil depth. Equally important are loss of nutrients, organic matter, and through the latter, deterioration in soil physical properties. This is leading towards an integration between two aspects of soil conservation: erosion control and maintenance of fertility. Both are necessary to achieve land use which is sustainable as well as productive.

Effects of trees on soils

The integration of erosion control with soil fertility maintenance has important consequences for agroforestry. There are a range of agroforestry practices related to erosion control, including practices primarily directed at this objective, such as barrier hedges, trees on bunds, barrier strips and terraces, windbreaks, and practices which have a range of purposes among which erosion control is one. However, equally important is the potential of land use systems based on agroforestry to be productive and at the same time, to maintain soil fertility and thus to be sustainable (Lundgren and Nair, 1985).

This is achieved through the beneficial effects of trees on soils. The effectiveness of trees in maintaining or increasing soil fertility is clearly seen in the soils under natural forest, the use of tree fallows in shifting cultivation, and in the practice of reclamation forestry on degraded land. The mechanisms by which trees achieve these beneficial effects include: increase in soil organic matter, through photosynthetic fixation, and transfer to the soil as litter and root residues; nitrogen fixation; nutrient recycling, through the taking up of nutrients by deep roots and return to the surface; improvement of soil physical conditions; and protection from erosion, and thereby loss of organic matter and nutrients (Nair, 1984, 1986; Young, 1985, 1986).

Among these mechanisms, the supply of organic matter by tree litter plays a key role. First, a balanced supply of nutrients is provided by litter decomposition and mineralization; secondly, soil physical conditions are maintained; thirdly, soil erodibility is reduced through effects of the organic fractions on structural stability; and lastly the litter cover itself is an efficient means of checking erosion.

The above considerations, namely the integral nature of erosion control and fertility maintenance, and the apparent potential of trees, and hence agroforestry systems, to assist in these two related aspects of sustainable land use, have been incorporated into a predictive model.

Objectives and reasons for choosing a carbon model

Soil Changes Under AgroForestry (SCUAF) was conceived as an integrated simulation model, with predictive capacity for assisting in the design and assessment of agroforestry systems that will minimise soil erosion and maintain or improve soil fertility.

As present, knowledge is less than is required for precise definition, and hence the identification of knowledge gaps and deficiencies in data, so as to suggest research priorities, are associated objectives. Solutions will strengthen techniques for land evaluation, and consequently lead to improvements in land use planning for agroforestry.

It is intended to develop a comprehensive model but constraints have meant concentration of work upon a single aspect initially. This has been the design, construction and testing of a carbon model.

The latter was chosen for the following reasons. In any soil system, organic matter inputs are subjected to decomposition processes. In the upper layers of a soil profile where materials are first concentrated, the organic fraction is active and humification proceeds rapidly. The complex organic soil fractions perform several roles. They are a nutrient bank for all nutrients, but play a special role in supplying nitrogen, phosphorus and sulphur, for these ions are never quantitatively important in the mineral fractions. McGill et al (1975, 1981) have demonstrated correspondence between soil carbon and flows of these nutrients. The high cation exchange capacity of organic materials provides for increased nutrient sorbing power. These facets are especially important in the context of the low mineral nutrient status acrisols and ferralsols (FAO; US, ultisols and oxisols).

Physical roles for carbon include the bonding of structural granules, and association with increased soil moisture retention capacity. Though an indirect measure, the determination of trends in organic matter (expressed as soil carbon) will be a most important indicator of soil conditions. In land use practices where organic removals, soil erosion and oxidation reduce the concentration of organic materials in the topsoil, the losses will necessarily be related to a reduction in productivity potential.

For agroforestry systems there are four particular strategies to bear in mind for the soil component. These are:

a. fertility maintenance
b. reduction of organic matter and nutrient losses
c. provision of additions to assist recovery of fertility
d. increasing the efficiency of resource utilisation

Quantity and kind of organic additions are very relevant to the first three strategies. Any successful modelling system must be able to isolate these aspects, and predict trends under a variety of land use practices. The output from SCUAF is designed to meet these needs. Examples of possible contributions of the carbon model, within the context of the four strategies, are considered in the text.

Functions and structure of the SCUAF carbon model

A schematic diagram of the most recent approximation of the carbon model is illustrated in fig. 1. The structure for process allocation pathways and system default values for functional conversion are recorded.

Represented is a fundamental cycle comprising nutrient uptake associated with carbon fixation, soil returns as organic litter, and the release of nutrients from that litter as a consequence of oxidation and mineralization. External exchanges provide the source for atmospheric carbon and organic additions, plus the sink for removals from the system. Functions of the system are completed within the model's soil and plant compartments.

There are four essential groups of data for input purposes:

a. environment
b. land use
c. plant productivity
d. soil processes

Environmental data permits setting up of the soil carbon bank and estimation of erosion losses from it. In the absence of measured erosion the FAO (1979) method is utilised for assessment.

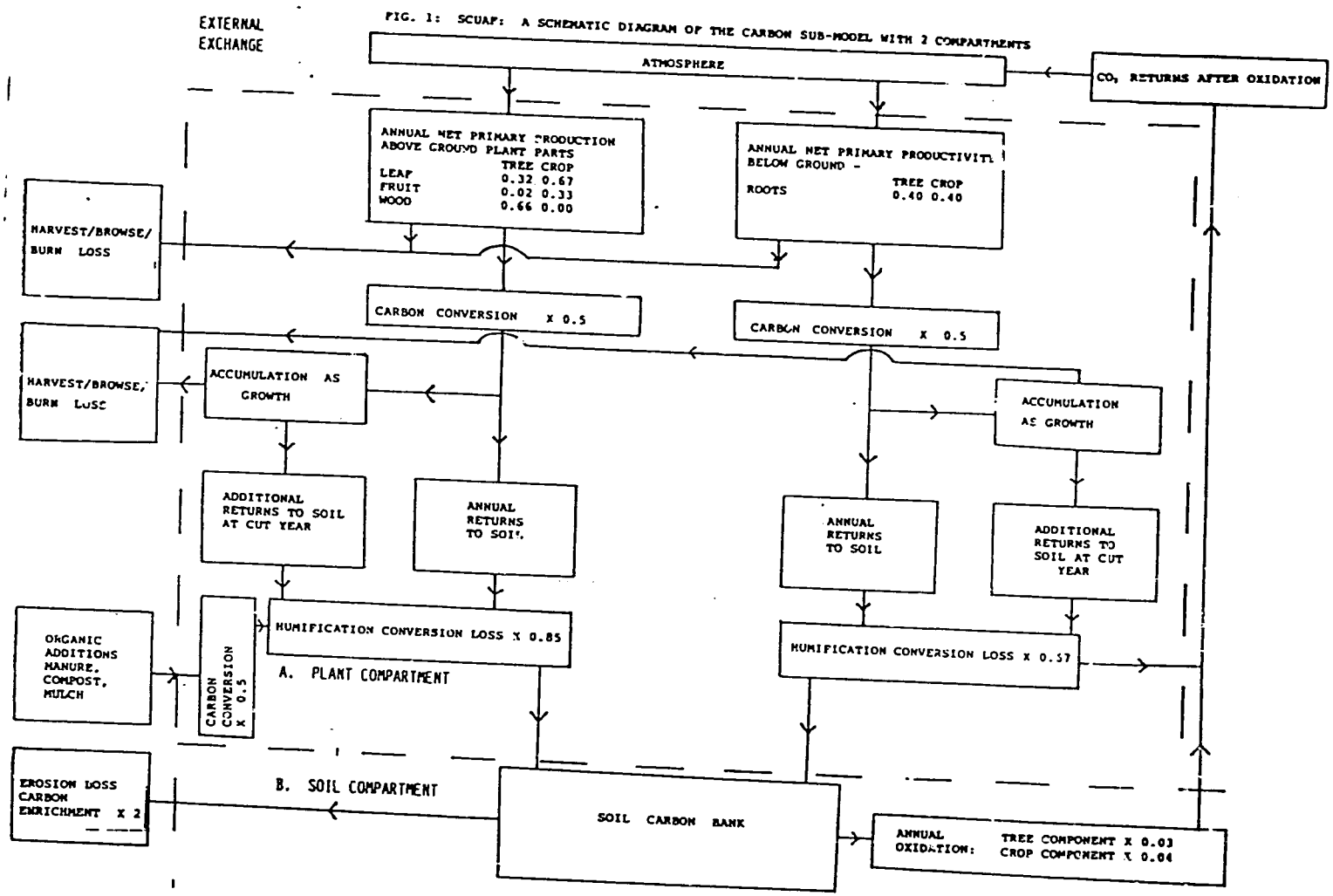
Land use data defines the agroforestry system, notably the relative proportions of land occupied by tree and crop in spatial systems, and the crop:tree ratio for rotations. Plant productivity denotes the quantities from tree and crop inputs to soil, retained as growth and removed from the system as harvest, browse, or in a burn. All the return, whether annual or at a cut year (the year of clearance in a rotation), are converted to soil carbon. In addition, constants are applied to account for oxidation of fresh inputs in the first year, and annual oxidation from the carbon bank. The residual of the initial oxidation is added to the soil carbon bank.

It is rare that a complete set of data for input are available for a site. To meet this situation, the model makes use of a system of default values, or best estimates of missing values. These are based in part on the data input on climate, slope and soil. For example root biomass and turnover are infrequently measured, so the model adopts values reported in specialised root studies. The user is given opportunity to change all default values. With input complete, the computer system will process the data and produce four time-series outputs. There are predictions of changes in:

a. soil carbon
b. soil erosion
c. harvested dry matter
d. biomass production

Available space does not permit a fuller description of the model. This can be found in Young, Cheatle and Muraya (1987), where examples of input and output data are also given.

FIG. 1: SCUAF: A SCHEMATIC DIAGRAM OF THE CARBON SUB-MODEL WITH 2 COMPARTMENTS



The efficiency of the modelling approach can be examined by resort to known case studies, by setting up and monitoring of empirical field experiments, or by theoretical approaches. Reported case studies provide a ready source of data for comparative purposes and can be examined relatively quickly. In this case, data have been extracted from published reports and entered into the model, the output from which has then been compared to the findings of the report authors.

Natural ecosystems in a steady state

Species-diverse forest constitutes the natural vegetation form on well drained soils for the humid tropics. Such forests are considered to have a relatively closed nutrient cycling system and to be in a state of equilibrium. Functional and structural evolution has assured efficient soil conservation. Certain mature savanna woodlands may also approach a similar steady state.

Steady state systems provide a baseline, against which alternative land use systems can be compared. Accurate prediction of deviation from baseline stability will be a measure of utility.

Time series stability for carbon over the longer term will be a feature of the soil compartment for steady state humid forest and savanna woodland. Perturbations will occur in the short term, notably due to seasonality in savanna regions. Any simulation should test these positions. For this purpose selected studies of tropical vegetation communities included:

a. Lowland tropical forest at Banco and Yapo, Cote D'Ivoire (Bernhard-Reversat, 1978)

b. Lowland tropical forest at Adiopodoume, Cote D'Ivoire (Lelong, 1984)

c. Highland tropical forest at Mazumbai, Tanzania (Lundgren, 1978)

d. Lowland savanna woodland at Korhogo, Cote D'Ivoire (Lelong, 1984)

Fig. 2 illustrates temporal soil carbon changes for these studies. It is of considerable interest that, for all cases the plot of soil carbon over a 50 year time scale exhibited an apparent steady state condition for soil carbon. This does suggest a general level of functional utility for the model, and possibilities for the comparison of soil carbon trends with those estimated for alternative systems. The cases cited and a few others act as type samples at a regional scale.

Rotational systems

Jaiyebo and Moore (1964) examined the effects of different fallow treatments and the consequences for subsequent maize cropping at Ibadan, Nigeria. This was not a study of biogeochemical cycling, or even of rotations. It was chosen to demonstrate that data can be adapted. Linking reported fallow data for bare ground, star grass and bush regrowth with yield data for maize enables study of 3 year crop:7 year fallow ratios. This consideration is limited to the bush fallow/

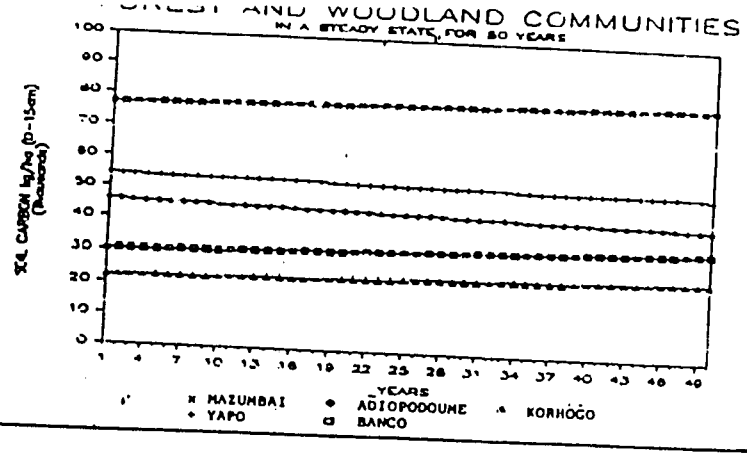

FOREST AND WOODLAND COMMUNITIES
IN A STEADY STATE, FOR 50 YEARS
TOT. CARBON kg/ha (0-15cm) (Thousands)
YEARS
MAZUMBAI
YAPO
ADIOPODOUME
BANCO
KORHOGO

Fig.3

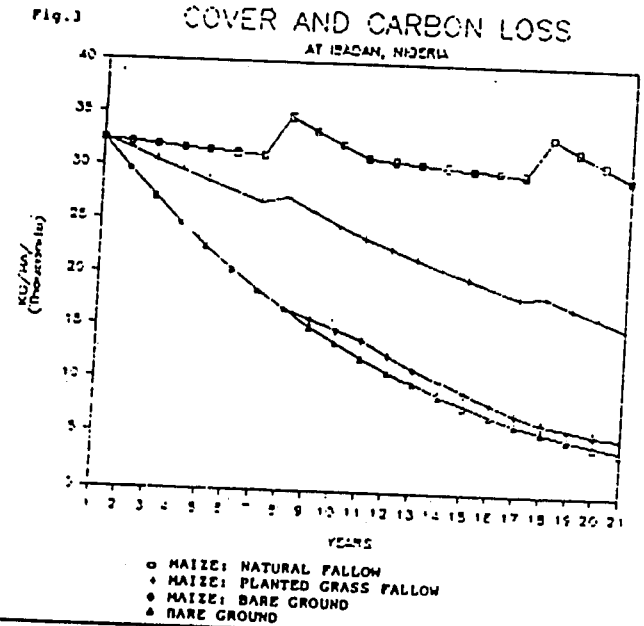
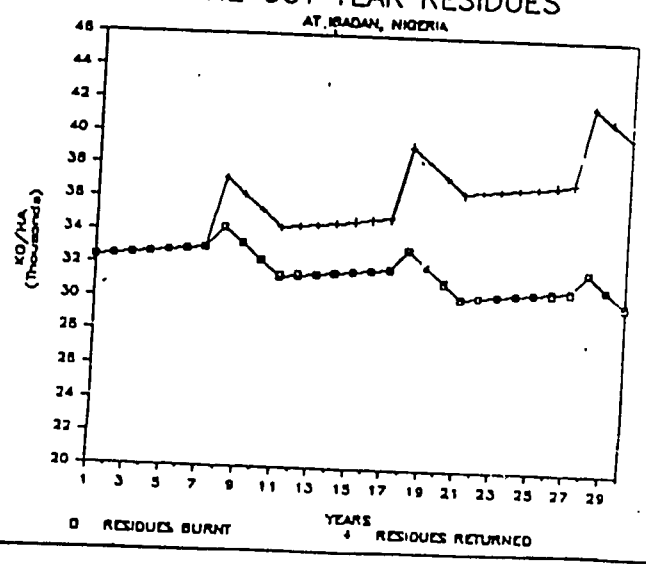

COVER AND CARBON LOSS
AT IBADAN, NIGERIA
KG/HA (Thousands)
YEARS
MAIZE: NATURAL FALLOW
MAIZE: PLANTED GRASS FALLOW
MAIZE: BARE GROUND
BARE GROUND

Fig. 4:


THE CUT YEAR RESIDUES
AT IBADAN, NIGERIA
KG/HA (Thousands)
YEARS
RESIDUES BURNT
RESIDUES RETURNED

shifting cultivation rotations of low-input small farmer systems.

Fallow length greater than 7 years may be required to permit full recovery under bush regrowth (Young, 1976, p. 114). The authors do report improvement in carbon levels for both grass and natural fallow types, when differences between measurements taken at termination of fallows are assumed to be treatment effects. The upper soil was suggested as the main arena for biochemical activity as chemical differences were identified only in the 0-10 cm layer.

Fig. 3 illustrates a relation between soil carbon trends and four of the land use options. These are:

Bush Fallow-Maize
Grass Fallow-Maize
Bare Ground-Maize
Bare Ground

The agroforestry system of natural bush fallow succeeded by maize demonstrates three graphical stems from left to right.

1. The trend in the fallow
2. A sharp upturn as a result of biomass inputs subsequent to bush clearance (cut year inputs).
3. A downstem steeper than the fallow, due for the most part to increased soil erosion in the crop vis-a-vis the fallow.

Overall, near stability is maintained, though decreases during cropping are matched only by cut year biomass inputs. This issue is discussed further below. In order to allow for the expected increase in soil carbon levels reported by the authors, some minor recalibration of the model would seem appropriate, though annual biomass inputs of about 6t ha yr derived may be inadequate for increasing soil carbon (Young, Cheatle and Muraya, 1987).

The indication of stability is important, as are the contrasts between the different fallow types. Due to productivity inputs recorded at levels insufficient to match losses due to erosion and oxidation, the grass fallow and bare ground systems are shown as unsustainable. These systems are associated with decreases in soil carbon over 20 years, with continuous bare soil being most affected. Three years of cropping after seven years of fallow does reduce the rate of net carbon loss slightly, vis-a-vis bare ground. There is support for a view that annual productivity returns from some grass fallows will not usually improve soil carbon levels in a humid environment (Kellman, 1969).

The decline in soil carbon as a consequence of bare fallow is expected. The exercise results in a successful discrimination. Natural fallow is predicted as more successful than grass fallow, while the conquences of bare ground are catastrophic. Crop:tree ratios greater than 1:7 are required. The results compare well with observed experience and the established steady state baseline.

Does a substantial contribution to soil carbon levels arise as a consequence of the clearance phase in rotations? This is an intractable problem illustrated in Fig. 3.

A steep decline in the cropping period is associated with some improvement in the fallow, the latter permitted by minor modifications. In both graphs the impact of organic inputs at cut year is most marked. The upper is a result of full residue return. In the lower case the assumption is that 90% of above ground biomass is lost by burning, and 50% of roots is returned as dieback.

For roots, information about turnover from slough and decay is inadequate, yet the interpretation of the model is that root contribution is important. Thus there is a requirement for detailed monitoring of the clearance phase, and of root contributions to the soil carbon bank, in order to resolve the present obscure situation.

This information need is emphasised by the enigma presented in Fig. 4. Given the biomass inputs at cut year, a one-year extension of the cropping period appears possible. With 90% of the above ground crop residues removed, reduction of one year is indicated, in spite of the cut year additions.

Workers have identified carbon decline in the clearance phase (Lundgren, 1978), and the black patches on aerial photography of shifting cultivation areas are mute testimony to a successful burn. The effective but ephemeral chemical amelioration provided by ash is well reported. Possibilities for retaining plant parts in spatially re-organised rotations so as to conserve organic matter are little explored, and even the proportion of organic returns at clearance are largely unknown.

Close monitoring of agroforestry systems will provide information so as to assist advanced calibration of the SCUAF model, from which better predictive extrapolations for agroforestry systems at other sites can be expected. Benefits of a successful modelling approach, for evaluation and planning, as a replacement for detailed field investigation and pilot studies, are obvious.

Fig. 5 is an extreme situation to stress the need for studies of the kind indicated. The figure incorporates three different kinds of output from the model. These illustrate the integration of process functions. The data base as provided by Jaiyebo and Moore has been modified to present a scenario of continuous cultivation without inputs. As soil carbon decreases, associated deterioration of soil chemical and physical properties leads to a rapid increase in total soil eroded annually. Actual carbon eroded rises in early years to accord with increases in soil erosion, but as soil carbon content declines the total for a proportional decrease also declines.

A predicted yield curve is not shown. This corresponds closely to the curve for carbon eroded. In this case the initial carbon level is of the order expected for well-managed agricultural systems in the region, and probably represents therefore a guide to equilibrium levels. Under continuous cropping in low input systems, both yields and carbon levels decline to very low levels (Cheatle 1975).

The definition of the carbon curve in Fig. 5 serves as a general indicator of changes in productivity potential for a low input system. Without inputs, such as those provided by efficient agroforestry, the systems grind to a halt.

Fig. 5: CONTINUOUS CULTIVATION

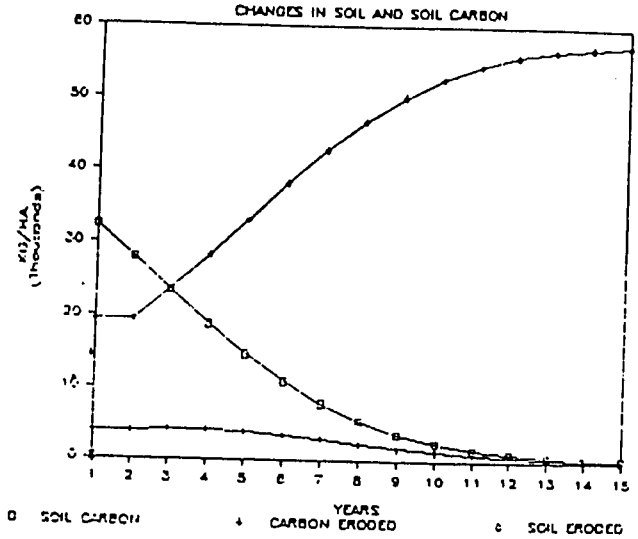


Fig. 6: COCOA

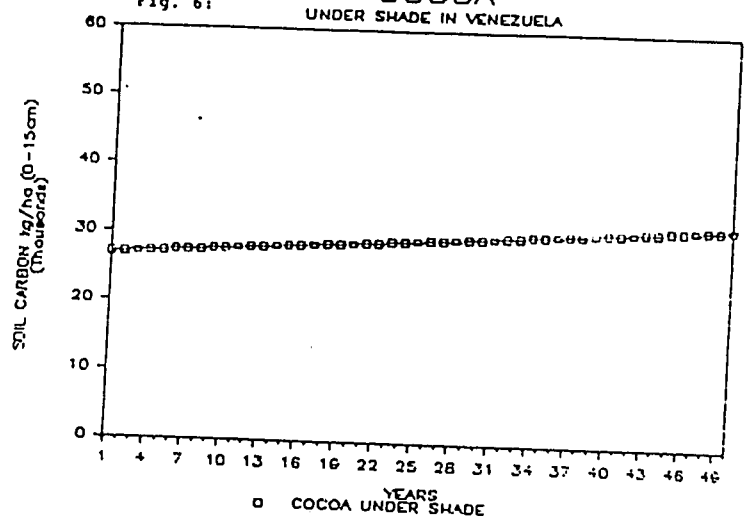
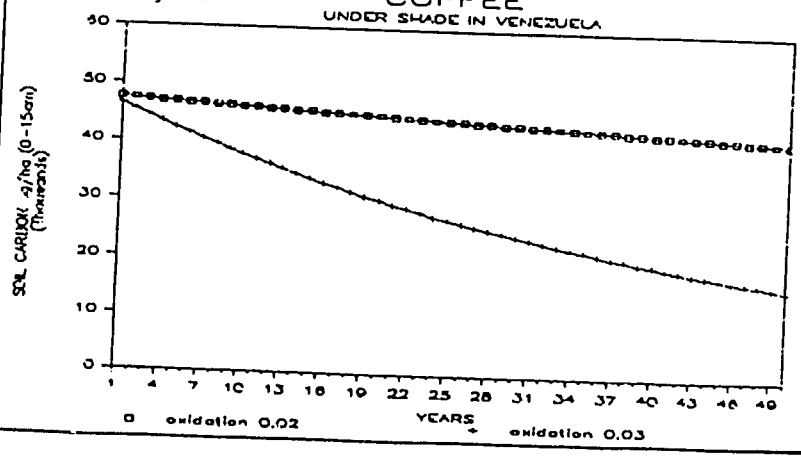


Fig. 7: COFFEE



SPATIAL MIXED AGROFORESTRY SYSTEMS

The work of Aranguren et al. (1982a, b) produced quantitative definitions of the nitrogen cycle following a one-year study concentrating upon litterfall at two sites in Venezuela. Cocoa under shade trees at a lowland coastal sub-humid site with irrigation inputs was one subject, while coffee under shade at a highland site was the other. The inference from the reports is that the systems are in a state of dynamic equilibrium.

Plotted soil carbon output for cocoa is shown in Fig. 6. For this well watered, closed canopy system, approximating forest conditions, the demonstration, of carbon in a steady state for fifty years is an indicator of system stability, and of model utility.

The default constant for annual oxidation of the soil carbon bank in the coffee agroforestry system is 0.03. In Fig 7 the temporal carbon changes over fifty years plotted with default level oxidation shows a decline in carbon from 47000 kg/ha to 20,000 kg/ha. This is a modest decline in the time scale, equivalent to about 500 kg/ha yr, or 0.03C% per annum in the upper 15 cm layer. For highland sites several arguments for reduction in the oxidation constant vis-a-vis lowland sites may be advanced. These include the depressive effects of lower temperatures and soil acidity. With the coffee case data rerun with oxidation calibrated at 0.02 a steady state is recorded. Thus an advantage of the simulated modelling approach is revealed. Operation on the default oxidation rate is suggestive of marginal instability. A problem for investigation is thereby identified. As rapid internal re-calibrations of the model are possible an oxidation constant for a steady state can be determined quickly. This process identifies a knowledge gap and points out the need for investigatory approaches, such as will derive improved information about decomposition processes.

SPATIAL ZONED AGROFORESTRY SYSTEMS

Kang et al (1981) reported a comprehensive study of alley cropping of maize with Leucaena leucocephala on a sandy soil (psammentic ustorthent) in the tropical forest zone at Ibadan, Nigeria. These authors accept that the bush fallow system of the forest zone has provided traditional farmers with an efficient and stable system, but point out that demands upon land from an increasing population result in shorter fallows and unstable farming systems. Reviewing the length of fallow period, Young (1976) outlines the following ratios of cultivation to fallow, necessary for the maintenance of organic matter at 75% of equilibrium levels for the vegetation communities described:

Rainforest	1:3 - 1:6
Moist Savanna	1:9 - 1:21
Dry Savanna	1:9 - 1:22

Experimental work with alley cropping has concentrated upon improved crop:tree ratios. Tree is virtually synonymous with fallow in this context. Improved efficiency is suggested providing that the alley cropping systems can maintain soil fertility and reasonable crop yields.

Where initial environmental conditions of at least moderate soil fertility and preferably well distributed rainfall in excess of 1250 mm annually, are found, Leucaena leucocephala can be considered as a tree component prospect for alley cropping. Kang et al (1981) consider that Leucaena leucocephala wil pump up nutrients from deeper soil layers below the rooting depth of maize. Vigorous growth associated with a deep, well-spread rooting system does suggest a traplike conserving effect. Nitrogen, sulphur, and phosphorus, nutrients usually bound within the organic fraction, can be taken up upon mineralization and not lost by translocation processes. A considerable advantage is that Leucaena leucocephala is an N-fixing species that can contribute to the N-budget of low input farming systems.

The above roles are important in soil conservation and considerable contributions to associated crops may be inferred. Recycled nutrients are passed to the companion crop in green manure, that is usually incorporated in the soil. Leucaena leucocephala responds vigorously to pruning and will yield high nitrogen green manure from 5-15 t ha/ yr DM. Partial support for Leucaena leucocephala is provided by the results of agricultural studies. These have suggested inputs of 10-12 t ha yr dm FYM., or other material as a usual requirement for sustainability of the organic matter fractions (Jones, 1971).

Reporting for 1979 and 1980 Kang et al (1981) record dry matter prunings of Leucaena hedgerows circa 5.5 t ha yr and maize grain yield from two crops circa 4.5 t ha yr. The latter is a very respectable yield relative to the 1 t ha reported for small farmers (FAO, 1984. Young, 1976). The crop: tree ratio utilized was 3:1. Compared to the ratios reported by Young (1976) a considerable improvement in land use efficiency is suggested.

After processing, the authors' data, output from the carbon model is shown for various tree: crop ratios in Fig. 8. These data are one means of support or refutation of sustainability. For the 3:1 ratio used by the authors the image presented is one of gradual decline, but this decline is very small, being of the order of 200 kg ha yr C. The crop:tree ratio of 9:1 is not sustainable, whereas the 1:1 ratio is. The 1:3 ratio is not only sustainable in terms of carbon but can be expected to assist in recovery. Here predictive capacity of the model is affording opportunity to assist in decision making about tree:crop ratios through investigation of the practical possibilities. The predicted sustainable crop:tree ratio of 1:1 contrasts with 1:8 as predicted for natural fallow recovery. The indication of improved efficiency of land use through agroforestry is exciting.

Yield of clippings incorporated with the crop will correspond with trends in soil carbon levels. Published yield data (Agboola, 1982; Brewbaker 1978, 1985; Mendoza et al, 1976; Hill, 1971; Pound and Martinez, 1983) suggest the reported yield is at the low end of a 5-15 t ha yr DM range. Fig. 7. provides an alternative perspective upon the investigative process. The author's original data denoting carbon stability for a 1:1 ratio with yield at 5.5 t ha yr dm is illustrated in Fig. 9 alongside that of three crop: tree ratios, all with a 10 t ha yr dm yield. The parallellism between the 1:1 ratio with yield at 5.5 t ha yr dm and the 3:1 ratio with yield at 10 t ha yr dm is striking. Clearly the model now provides a fresh sense of direction, towards an

Fig.8: ALLEY CROPPING : A SPATIAL SYSTEM

EFFECTS OF DIFFERENT TREE:CROP RATIOS

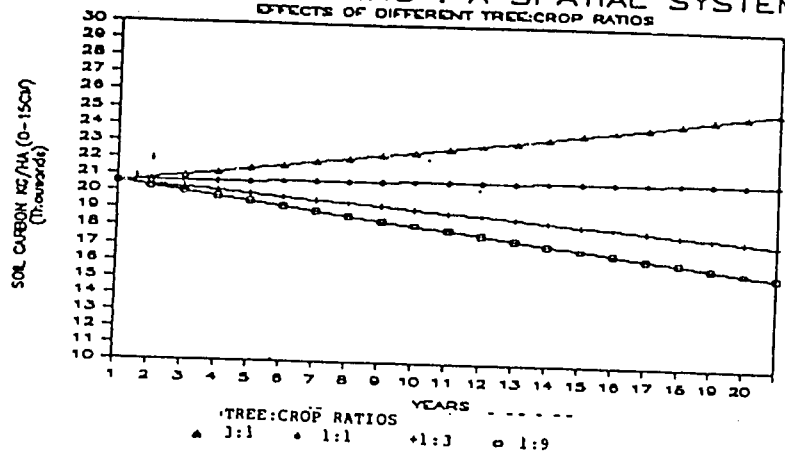
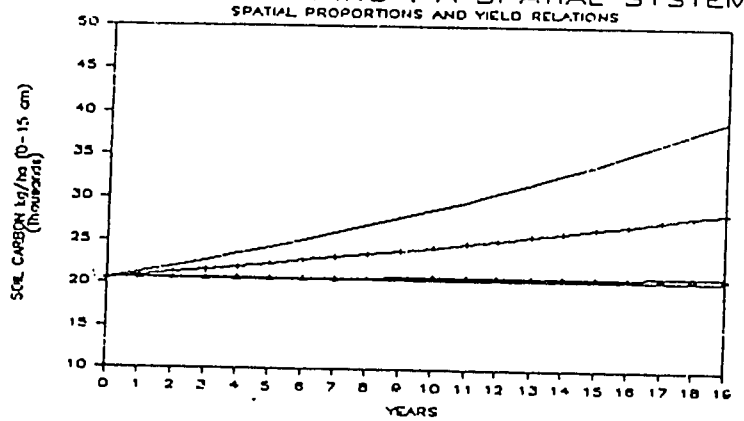


Fig.9: ALLEY CROPPING : A SPATIAL SYSTEM

SPATIAL PROPORTIONS AND YIELD RELATIONS



TREE CROP RATIO	YIELD OF MAIZE GRAIN Kg/ha
1:1	5
1:3	10
1:1	10
3:1	10

investigation to determine whether a higher yield target could be expected so as to improve land use efficiency even further. Within the limited contextual framework of the model there is expressed a view that alley cropping can operate at higher crop:tree ratios than is the case for either bush fallow or natural fallows in shifting cultivation.

There is also indication that annual organic additions must be of the order of 10 t ha yr dm to sustain soil carbon levels in this lowland humid forest zone. The high requirement predicted is supported by research findings from Ibadan (Juo and Lal, 1977). Good yield in the tree component is as important as in the crop.

CONCLUSIONS

The model as presented here is at an early stage of development, and the results are highly provisional. It is hoped that their presentation will result in constructive criticism, leading to improvements in the structure of the model and calibration of its critical values.

The examples given are based on published data. Despite the fact that these examples have been selected, from a much larger number reviewed, as providing the most comprehensive data available, they nevertheless reveal serious deficiencies. In particular, few existing studies give satisfactory data on root production, and scarcely any on the rate of root decay and turnover; yet the results from the model show that this factor is of considerable importance. Another deficiency is our limited knowledge of the nature of different soil organic matter fractions and their rates of loss. Measurements of bulk density and other soil physical properties are often unavailable.

Despite these problems, the early results from the SCUAF model reveal exciting possibilities. Predictions of stability in mature natural ecosystems, and correspondence with other research findings suggest preliminary utility of the model for assessing agroforestry systems. Present indications are that well designed and managed agroforestry can be productive and sustainable, and in certain situations improve the efficiency of land use. The integral nature of erosion control and fertility maintenance has been demonstrated, through showing the consequences of erosion for loss of soil carbon. It is intended to extend the model to give an input-output treatment of nitrogen and other nutrients.

The main conclusion is the identified need for research directed at supplying comprehensive data on carbon and nutrient cycling under agroforestry. This should include comprehensive measurements of carbon and nutrient cycling, especially in relation to soil erosion and other aspects of the soil compartment. With development the SCUAF model will assist assessment, and computer aided design of agroforestry systems once a representative data base is available. The need for such research has been widely recognized. It is central to the Tropical Soil Biology and Fertility Programme, forms part of the Commonwealth Science Council's Agroforestry Project, and is a major component of ICRAF's planned Agroforestry Research Network for Africa (Swift, 1984, 1985; Commonwealth Science Council, 1986). The present results from the SCUAF model should be regarded as promising hypotheses. They could become established facts only if knowledge can be improved in the critical areas of plant-soil organic matter and nutrient cycling.

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