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SCUAF

Version 4

**A Model to Estimate Soil Changes Under
Agriculture, Agroforestry and Forestry**

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Alternatively, both can be downloaded directly from the project web site at:

<http://cres.anu.edu.au/imperata/imperat1.htm>

SCUAF Version 4

A Model to Estimate Soil Changes Under Agriculture, Agroforestry and Forestry

Anthony Young*, Kenneth Menz†, Peter Muraya§ and Chrysogon Smith

Introduction

SCUAF is a computer model which predicts the effects on soils of specific land use systems under given environmental conditions. It is designed to include the distinctive features of agroforestry—that is, land use systems which include both trees and crops—and the original meaning of the acronym was ‘Soil Changes Under AgroForestry’. However, it can also be used to compare agroforestry systems with land use under agriculture or forestry, treating these as limiting cases of agroforestry—agriculture with 100% crops and 0% trees, forestry with 0% crops and 100% trees. Hence, SCUAF can alternatively be construed to mean ‘Soil Changes Under Agriculture, Agroforestry and Forestry’.

SCUAF is a process–response model. In outline, the user specifies:

- the physical environment
- the land use system;
- the initial soil conditions;
- the initial rates of plant growth; and
- the rates of operation of soil—plant processes.

The land use system is based on two plant components: trees and crops. The primary basis for description of this system are the proportions of trees and crops in each successive year. Other elements of the land use system are additions (organic additions, fertilizers), removals (harvest, losses), prunings (of the trees) and transfers (e.g. transfer of tree prunings to soil under crops). The effects of roots are modelled in addition to

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those of the above-ground parts of the plants (leaf, fruit, wood). An animal component is not modelled, but can be indirectly included in the land use system (p.28).

The model provides an annual simulation of:

- changes in soil conditions; and
- the effects of soil changes upon plant growth and harvest.

Examples of outputs are shown in Figure 1.

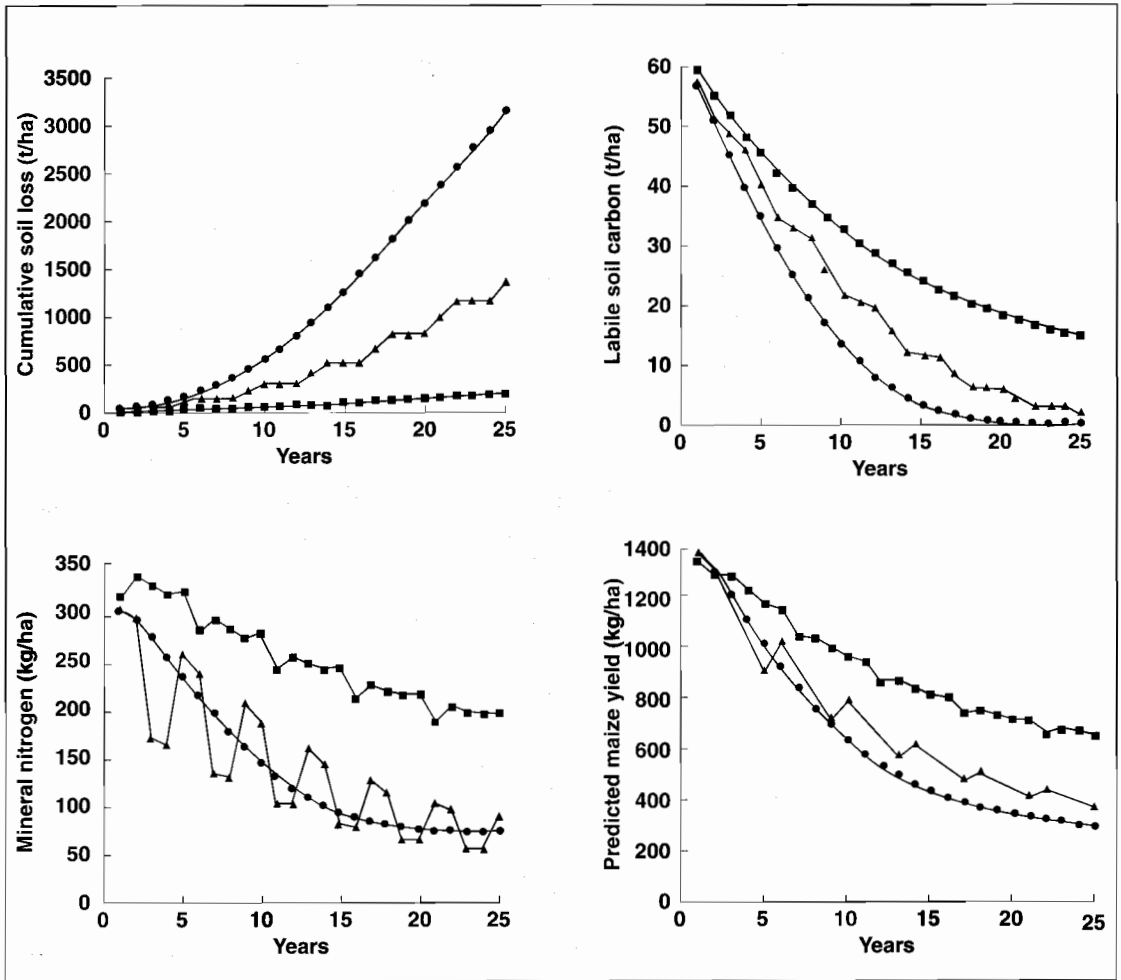


Figure 1. Examples of applications of SCUAF (from Nelson et al. 1996a).

SCUAF is not a plant growth simulation model. The user enters the initial rates of plant growth (trees, crops, and their component parts) as biomass increases per year. The model then estimates the effects of changes in soil properties upon subsequent rates of plant growth.

The soil conditions and processes covered are:

- soil erosion—its rate and effects;
- soil organic matter, represented as carbon;
- plant nutrients—nitrogen and phosphorus; and
- tree/crop competition for nutrients.

Besides conventional crop harvest, the harvest may include crop residues, and harvests of fruit, fodder, or wood from trees.

Version 4 of SCUAF does not model soil water or its availability to plants. This was tried, but it was found to be essential to simulate soil water changes on a short-term (e.g. 10-day) basis, something that is not possible within the annual framework of SCUAF.

All of the values employed in the model, parameters and variables, are accessible to the user. There is a set of default values, varying according to the physical environment: climate, soil, slope, etc. This has two purposes: to provide reasonable estimates for variables that have not been measured, and to save time when rapid runs of the model are needed (e.g. in education). However, the user can see **all** values on screen, and is invited to alter them to correspond with field measurements or their own preferred estimates.

SCUAF is primarily intended for simulation over periods of the order of 10–20 years, i.e. for the assessment of land use sustainability within the medium term. It can also be applied to long-term simulation, provided the user is aware of the pitfalls inherent in long-term extrapolation.

The major advantage of SCUAF is its ease of operation. To anyone familiar with basic soil–plant relationships, including nutrient cycling, the processes involved are largely self-explanatory from their descriptions in the inputs section. There are no hidden ‘black boxes’—areas where something happens of which the user is not made aware. Students rapidly learn to operate the model, and has been used (independently of its authors) in a number of published research papers. It is much less complex than some comparable simulation models.

A review of modelling changes in soil properties, including principles and summaries of some major models, is given in Young (1994). Among reviews of modelling in agroforestry are those in ASIT (1991), Muetzenfeldt and Sinclair (1993), Sinclair and Lawson (1997) and Young (1997, Chapter 9).

Applications

SCUAF can be used in research, in education, and in planning and development. Its principal uses are:

In research, before field or laboratory experimentation:

1. To aid in the design of experiments:
 - a. to explore concepts and generate hypotheses;
 - b. to predict whether the hypotheses on which the experiments are based can plausibly be expected to produce the results proposed.
2. To show the data that are needed if predictions of the behaviour of a soil–plant system are to be made.

In research, after experimentation:

3. To understand and interpret results from experiments.
4. To extend the results of experiments to:
 - a. management treatments which were not included;
 - b. different environments.
5. To extend the results of experiments over longer periods, predicting consequences in the medium or long term.
6. To show what advances in knowledge are needed to improve the accuracy of predictions.

In education and training:

7. To help in understanding the functioning of plant–soil–land-use systems.

In planning and development:

8. To compare the effects of systems of agriculture, agroforestry and forestry.
9. To make management recommendations for specified environmental conditions.

The applications to research illustrate the close relations between modelling and field or laboratory experimentation. The minimum length of field experiments needed to obtain useful results is 3 years in agriculture, 5 years in agroforestry and 10 or more years in forestry. Any possible means of improving design, and avoiding wasted effort, is valuable.

Extending experimental results to different management treatments (use 4a above) is especially valuable in agroforestry owing to the large number of variables in field trials: tree species, spacing, pruning regimes, fertilisation, etc. Questions of the type ‘Suppose we had removed/retained the prunings, or used a less competitive but slower-growing tree species, what might have been the result?’ will often arise. Since most field trials are conducted on only one site, the value of interpreting their results for different environments (use 4b), drier or wetter climates, or for more fertile or less fertile soils, is apparent.

Extrapolation of results over time (use 5) is highly important, since many of the soil benefits claimed for agroforestry refer to the medium or long term, and it is difficult to obtain funding to conduct long-term trials. The dangers of extrapolation are well known, any errors becoming self-reinforcing over time; but as with soil management in general, it is vital to the assessment of sustainability to have some indication of longer-term changes in soils and their productive potential.

Models can be a valuable aid to education (use 7). In teaching simulation can take the place of field experiments, and models can greatly aid the understanding of systems. A few practical classes with an easily-usable model such as SCUAF can give an insight into 'what is happening' in the main types of soil and soil-plant processes, such as erosion, organic matter maintenance, litter decomposition, and nutrient cycling. Problems of the type 'For the environment, agroforestry system, and input data specified, does agroforestry give a greater relative benefit with or without fertilizer?' can be set. They can be investigated by modelling, possibly with different members of a class taking different environmental conditions. The educational value comes not in finding the answer but in understanding why it should be so.

Comparison between land management systems (use 8) is critical wherever it is proposed to change existing land use. A common case is to evaluate the consequences of an agroforestry system compared with annual cropping, or with perennial crop monoculture. In marginal environments, it is essential to explore whether reclamation or protection forestry is needed for effective conservation, or whether some element of crop or animal production can be included through reclamation agroforestry. Modelling can simulate the effects of the alternative systems, based on the same environmental data, as a means for comparing them.

To generate management recommendations (use 9), also called prescriptive modelling, is an ultimate aim but one not yet reached in most branches of agroforestry. It is certainly not yet possible, for example, to construct a viable 'expert system' to produce species and management recommendations for hedgerow intercropping. If SCUAF can be calibrated for a particular region, so that its predictions are found from experimental data to be reliable, then it could be extended to produce management recommendations for specific sites.

SCUAF as the basis for economic analysis

While it does not directly include an economic component, SCUAF can be used to provide input and output values for economic analysis. For example, by showing the trends in soil fertility and their consequences for plant growth over periods of the order of 20 years, it provides a basis for analysis of the economic aspects of sustainable land use systems.

The types of data directly relevant to economic analysis are, for each year of the land use system:

Economic inputs:

- land areas under trees and crops, as a basis for assessing inputs of seed, labour, etc.;
- fertilizer inputs;
- pruning practices, as a basis for their labour requirements.

Economic outputs:

- harvest, from trees and crops, including crop yield, fodder, fruit, and timber or fuelwood;
- soil properties at the end of the model run, as a basis for assessing change in the capital value of land.

Examples where SCUAF results have been applied to comparative economic analyses of land use systems are given below.

SCUAF can be applied to the economic analysis of soil conservation measures, showing:

- consequences of land use systems without conservation (other than that which is intrinsic to the system);
- effects on the soil, and thereby on plant growth, of reducing rates of erosion by adding conservation works.

Bioeconomic modelling

A framework for combining biophysical and economic analysis is shown in Figure 2. Data from research trials permit calibration of SCUAF for local conditions. The SCUAF model then simulates two sets of outputs: changes, over time, in soil properties (including erosion and fertility), and in plant growth (trees and crops). The assessment of environmental costs or benefits is based on trends in soil properties.

Parallel with the above, farm surveys provide the costs of inputs and the prices of outputs. These are linked with the land use systems represented in the model, which may include both actual land use and proposed improvements. The resulting data can be input to an economic model to give net present value or other measures of economic success. This approach has been applied in the last group of research reports listed below.

Published applications of SCUAF

Potential applications of Version 1 of SCUAF were illustrated in Young and Muraya (1988) and Cheatle et al. (1989).

Version 2 has been used in the following cases:

- Young (1991): illustrative examples.
- Vermeulen et al. (1993): comparison of soil changes under natural savanna woodland and maize monoculture in Zimbabwe.
- Fagerström and Karlsson (1994): evaluation of agroforestry systems for land use planning in Vietnam.

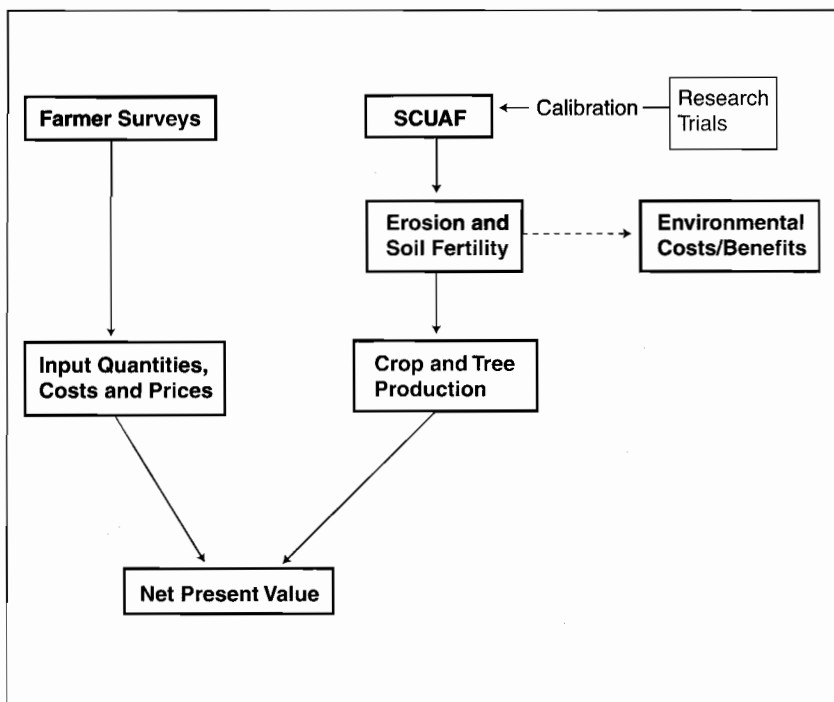


Figure 2. Framework for use in bioeconomic modelling (Grist et al. 1997).

Published applications of Version 4 to date are:

- Young (1994): comparison of contour hedgerows with the conventional contour-bank soil conservation system at three fertilizer levels.
- Grist and Menz (1996), Menz and Grist (1996), Nelson et al. (1996a,b, 1997), Grist et al. (1997), Magcale-Macandog et al. (1997), Magcale-Macandog and Rocamora (1997): a series of reports on land use systems in Southeast Asia in which the physical outputs from SCUAF are combined with economic analysis.¹
- Young (1997, Chapter 9): comparison of four agroforestry systems with crop monoculture.

¹ The earlier of these studies used Version 2, converting subsequently to Version 4.

Outline of the Model

This chapter outlines how the SCUAF model functions. Individual inputs and outputs, together with further details of the simulation, are described in Chapter V.

The SCUAF model can be described in terms of three sections:

- the plant section;
- the soil section; and
- the effects of soil changes on plant growth.

The plant section (Figure 3)

There are two plant components, called *trees* and *crops*. Each component is divided into four *plant parts*:

- *leaf* (herbaceous matter);
- *fruit* (reproductive parts);
- *wood* (above-ground woody parts);
- *root* (below-ground parts).

There is no wood crop from herbaceous crops and grasses.

The user specifies, for each year of intended modelling, the *land use system*. This is input for a succession of time *periods*, e.g. 3 years cropping followed by 5 years of tree fallow. For each period, the user specifies:

- *areas*: the respective areas under trees and crops.
- *additions*: material brought into the plant–soil system:
 - *organic additions* (mulch or compost from outside the system, farmyard manure);
 - *fertilizers*.
- *removals*: material taken out of the plant–soil system:
 - *harvest*;
 - *losses* (e.g. burning).
- *standing biomass*: the fraction of each plant part which remains at the end of the year;
- *prunings and transfers*:
 - whether the trees are pruned;
 - the fractions of prunings, and of natural litter, that are transferred from the area under trees to the soil under crops.

As well as the annual harvest, there may be an additional harvest in a *cutyear*, a year in which the tree component is felled, coppiced or pollarded. The annual harvest will normally include crop fruit, and sometimes tree fruit or tree leaf (as fodder); the additional cutyear harvest will often include tree wood.

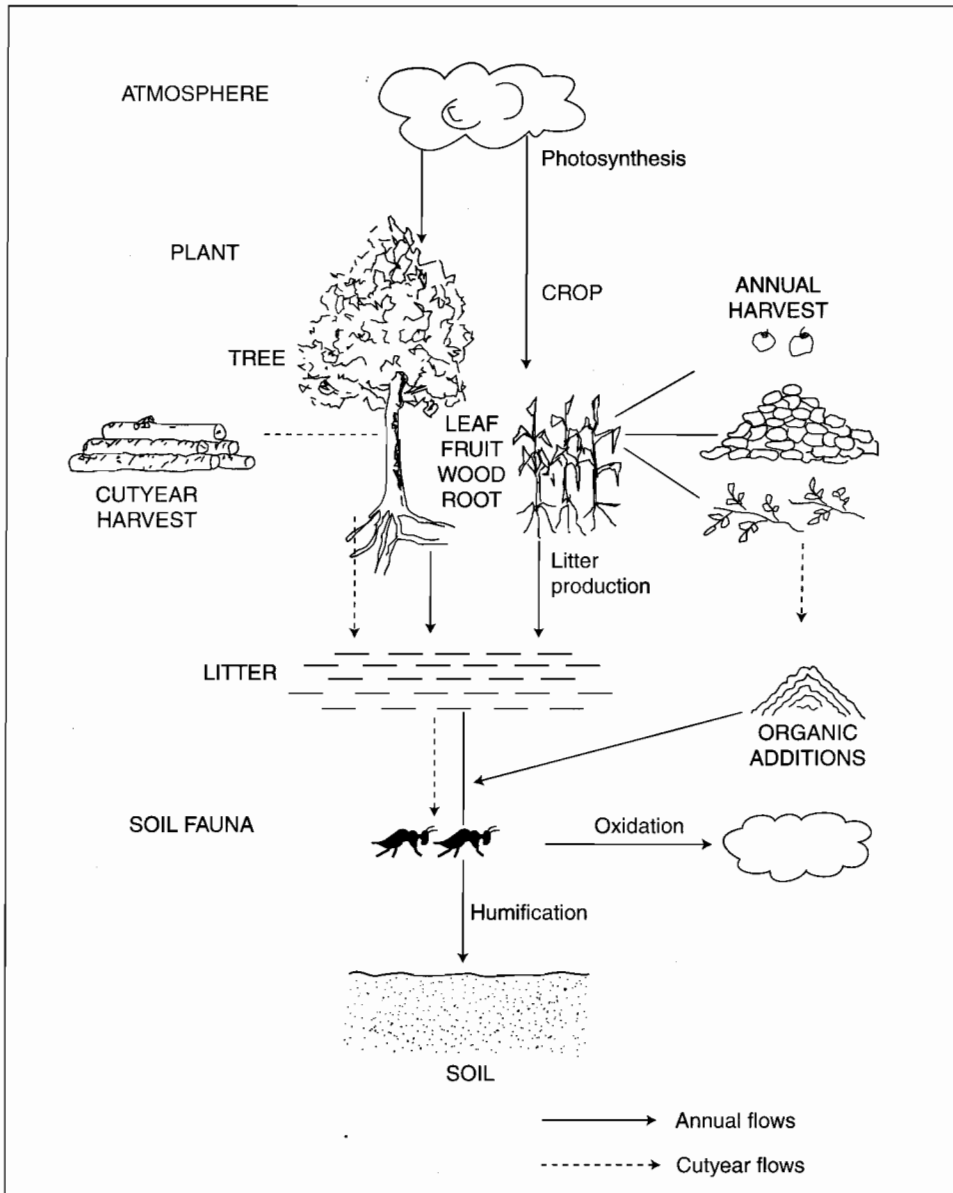


Figure 3. SCUAF: the plant section (Young and Muraya 1991).

The user also inputs:

- initial *rates of plant growth*. These rates will be modified by the simulation;
- the *composition* of each plant part, as percentages of carbon, nitrogen and phosphorus.

The model then calculates which plant parts are added to the soil. This is obtained by taking plant growth, subtracting standing biomass, annual harvest, cutyear harvest, and losses, and adding additions (Figure 3).

The resulting value, the addition of plant residues to the soil, is transferred to the soil section of the model. Using the specified composition of plant parts, together with *conversion losses* (such as oxidation of carbon), the inputs of carbon, nitrogen and phosphorus to the soil are calculated.

The soil section

There are three elements to modelling of the soil section: erosion, soil organic matter (represented by carbon), and nutrient cycling. Changes in erosion are modelled for the land use system as a whole, but changes in carbon and nutrients are calculated separately for the *soil under trees* and *soil under crops*.

Soil erosion

Erosion is modelled by a simplified version of the universal soil loss equation (USLE, now RUSLE) (Wischmeier and Smith 1978; Renard et al. 1997):

$$\text{Rate of erosion (kg/ha)} = R \times K \times LS \times C$$

where R = *rainfall factor*, K = *soil factor*, LS = *slope factor* (length and steepness) and C = *cover factor*. The cover factor is treated separately for the tree and crop components, and an adjustment made for the specific effect of the tree component in agroforestry systems, called the *tree proportionality factor* (see p.25). Based on the topsoil content of carbon, nitrogen and phosphorus, together with an *enrichment factor* for eroded sediment, the losses of these elements through erosion are calculated.

The rainfall and slope factors remain constant over time. The soil factor changes with increases or decreases in soil organic matter, and the tree and crop cover factors change with changes in rates of plant growth; the user may also change these factors for different periods. Hence, the calculated rate of erosion increases or decreases with time. The user may also re-set the cover factors at the start of a new period in the land use system.

Soil carbon (Figure 4)

The soil carbon cycle is similar to that in many comparable models, based on principles set out in the classic study of Nye and Greenland (1960), modified to take account of the different fractions of soil organic matter now recognised. Three such fractions are commonly recognised (with some variations in nomenclature): active, labile and stable (Young, 1997 p.100).

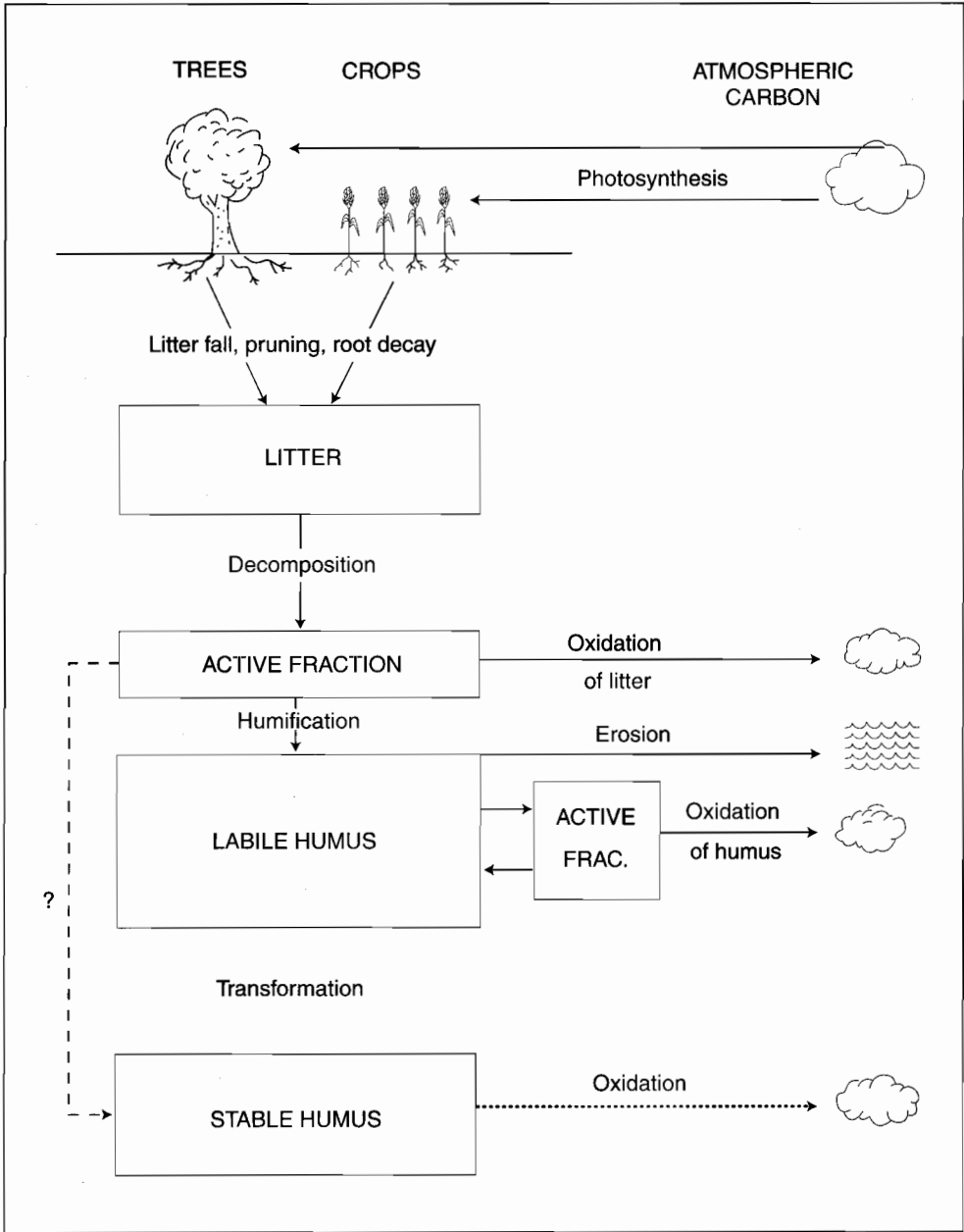


Figure 4. The soil carbon cycle (Young 1997).

In SCUAF, the active fraction, the carbon that is present in the bodies of soil organisms, is not modelled as a carbon store. Instead, it is treated as two processes: the loss by oxidation of carbon (and nitrogen) during conversion from litter to humus; and the annual loss of these elements from humus. Hence, the soil carbon present at the end of each year is taken to be made up of two fractions:

- *labile carbon*, decomposing at rates of a few percent per year, and hence a half-life of the order of 3–5 years in tropical soils and some 10 years in temperate soils;
- *stable carbon*, decomposing slowly and remaining in the soil for periods of more than 50 years.

Changes in soil carbon are then estimated as follows (Figure 4):

Gains: *humification* of plant residues (above-ground and roots);
 organic additions;

Losses: *erosion*: loss of carbon in eroded soil;
 oxidation: annual oxidation losses through soil organisms,
 at different rates for labile and stable carbon.

Stabilisation: conversion of labile to stable carbon.

Nutrient cycling (Figure 5)

The cycles of nitrogen and phosphorus are based on the stores and flows conventionally employed in soil science, agriculture and forestry, adapted to include the distinctive feature of agroforestry systems, the presence of tree and crop components. There are four nutrient stores in the plant–soil system:

- within the plants (trees, crops);
- within the labile humus;
- within the stable humus;
- within the soil solution (mineral nutrients).

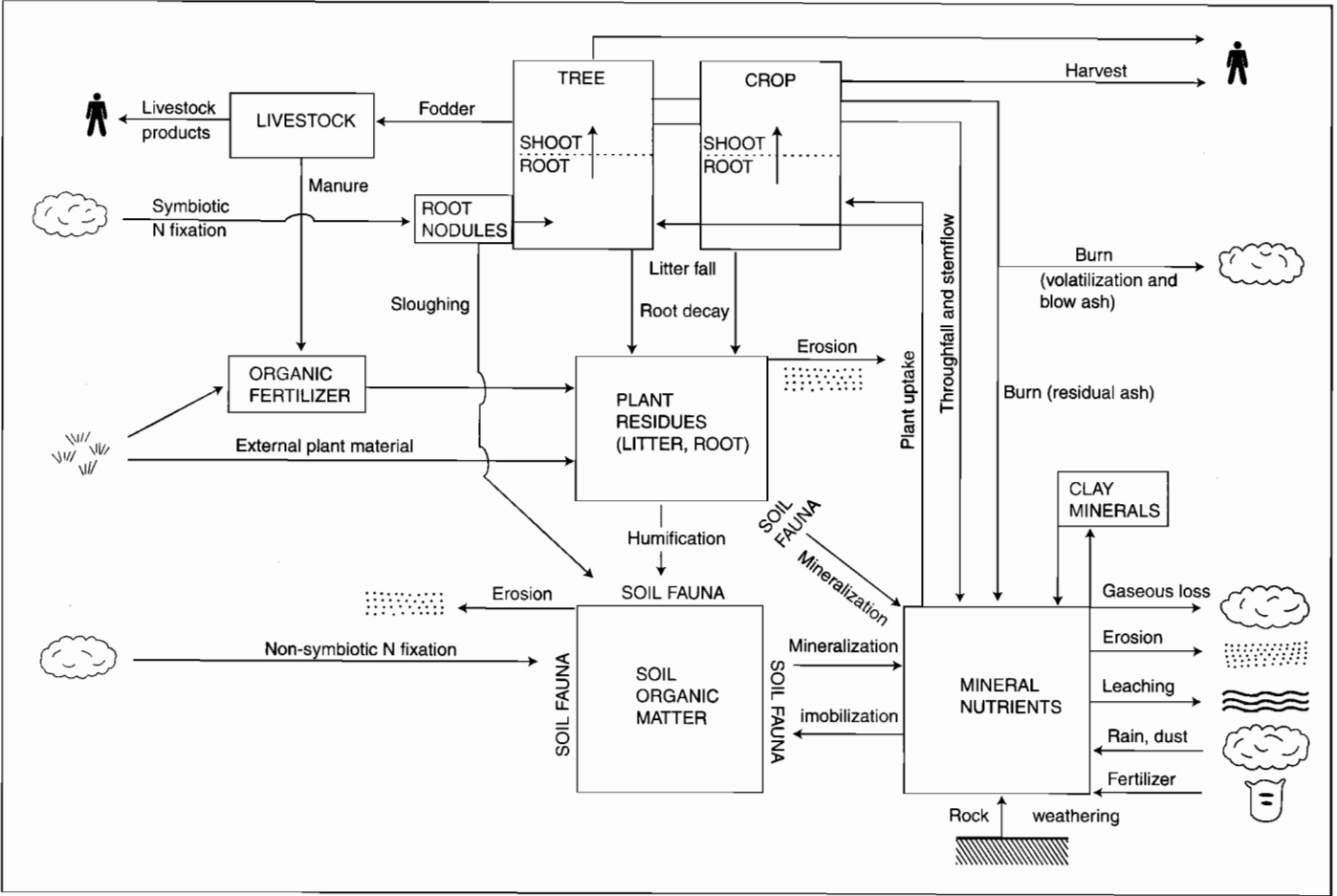


Figure 5. The nutrient cycle (Young 1997)

The *nutrient flows* into the plant–soil system, out of it, and within it are as follows (for both nutrients except where indicated as either N or P):

Gains:	<i>atmospheric deposition: rain and dust</i> <i>fertilizers</i> <i>organic additions</i> <i>non-symbiotic fixation (N)</i> <i>symbiotic fixation (N)</i> <i>deep capture (uptake by roots of trees from below the soil depth taken as the basis for modelling)</i> <i>rock weathering (P)</i>
Losses:	<i>erosion</i> <i>leaching</i> <i>harvest</i> <i>burning (N)</i> <i>gaseous losses: denitrification and volatilisation (N)</i> <i>fixation: net fixation onto clay minerals (P)</i>
Internal flows:	<i>Uptake (soil to plants):</i> <i>Uptake of soil mineral nutrients by plants</i>
Return: (plants to soil):	<i>Mineralisation of litter</i> <i>Humification of litter</i> <i>Throughfall and stemflow</i> <i>Ash from burning</i>
Mineralisation of humus:	<i>Conversion of nutrients from soil organic fractions to mineral form.</i>

The gains, losses and internal flows apply differently to the various stores of nutrients. For example, fertilizers are input directly into the soil mineral fraction, and mineralisation of humus is treated as a transfer (with partial losses) from the plants to the soil organic fraction.

The inputs to SCUAF give estimates of the rates of all of these processes, or allow them to be calculated. The model applies rates to calculate annual changes in the four plant and soil stores of nitrogen and phosphorus.

There is a link between the estimates of erosion, soil carbon, and nutrient cycling. On sloping land, removal of carbon, nitrogen and phosphorus in eroded soil is a major source of loss of these elements from the system. Where erosion of soil exceeds 10 t/ha, this cause of loss of elements frequently dominates the nutrient cycle.

Effects of soil changes on plant growth

While SCUAF is not a total plant growth simulation model, one of its major functions is to estimate the effects of changes in soil properties, relative to their initial condition, on the growth of trees and crops (initial condition refers to the state of the soil at the start of modelling). There are three components to these effects: nutrients, soil carbon, and soil depth.

Nutrients

Nutrients are modelled in the standard manner for soil science, agricultural and forestry research, by comparing plant nutrient requirements with nutrient availability.

<i>Requirements:</i>	Estimated by taking the initial rates of tree and growth, as specified by the user, multiplied by the percentage content of nutrients in each plant part.
<i>Availability:</i>	The nutrients present in the soil mineral fraction (which include fertilizer additions during the current year).
<i>Deficiency:</i>	Requirements minus availability.

In the case of trees, the requirements from the soil may be reduced by deep uptake, the uptake of nutrients by roots extending into weathering rock, or below the soil depth considered in the model (typically the rooting depth of crops).

Requirements and availability are estimated separately for nitrogen and phosphorus. If, for either nutrient, availability is less than requirements, plant growth is reduced proportionally, by using the law of the minimum. For example, if (as kg nutrient/ha):

Plant requirements	N=100	P=10
Availability	N=65	P=20

then nitrogen is the limiting nutrient, and plant growth would be reduced to 65/100 or 65% of its non-nutrient-constrained value. Nitrogen uptake would be 65 kg/ha, but phosphorus uptake would be reduced to $65/100 \times 10$ kg/ha. Where both nutrients are deficient, plant growth is based on the nutrient which causes the greater reduction.

In agroforestry systems, plant nutrient requirements are estimated separately for trees and crops. Correspondingly, nutrient availability is calculated for soil under trees and soil under crops. The model allows a proportion of tree roots to grow into the soil under crops (the proportion being specified by the user), and tree/crop competition for nutrients is calculated on the basis of relative root densities. Thus, trees may obtain some of their nutrients from soil under crops, in effect 'robbing' the crop of part of the nutrient supply which it would have had if the trees were not present.

Soil carbon

The level of soil carbon, and hence organic matter, affects plant growth in two ways: through the release of nutrients by mineralisation of humus, and through its influence on soil physical properties. The former effect operates as a component in nutrient availability.

The organic matter status is the major variable affecting soil physical properties, and these in turn influence plant growth in a number of ways, notably through facilitating the development of root systems, and influencing water-holding capacity. These multiple effects are modelled through two variables, the *carbon feedback factors* for trees and for crops. It is assumed that an increase in soil carbon will improve plant growth, and a decrease will reduce it; the rates of increase or decrease are set by the user.

Soil depth

Erosion removes topsoil, causing a progressive reduction in soil depth. This affects plant growth by reducing the rooting zone and lowering the water-holding capacity. The latter is probably the major effect. The effect of soil depth is modelled by soil depth feedback factors, for trees and for crops, set by the user.

Agroforestry-specific features (Figure 6)

Various SCUAF elements are designed to permit modelling of agroforestry systems. These all arise from the presence of trees and crops on the same land management unit, in a spatial arrangement or a rotation. In modelling agriculture or forestry, with 100% crops or trees, these elements become non-functional.

The agroforestry-specific features are (Figure 6):

- input of the relative areas under trees and under crops;
- separate modelling of soil changes for soil-under-trees and soil-under-crops;
- an adjustment to the rate of erosion to take account of the specific effects of trees, the *tree proportionality factor* (see p.25);
- an input which permits above-ground biomass transfer from the trees to the soil under crops—litter by wind, prunings by human agency;
- an input which permits a proportion of the roots of trees to grow into the soil under crops, and abstract nutrients from it;
- provision for additions (manure, fertilizer) to be applied differentially to soil under trees and under crops (normally, all will be given to the crops);
- the existence of a *cutyear* (see p.12), in which the trees are felled or coppiced, etc., and there is an additional harvest.

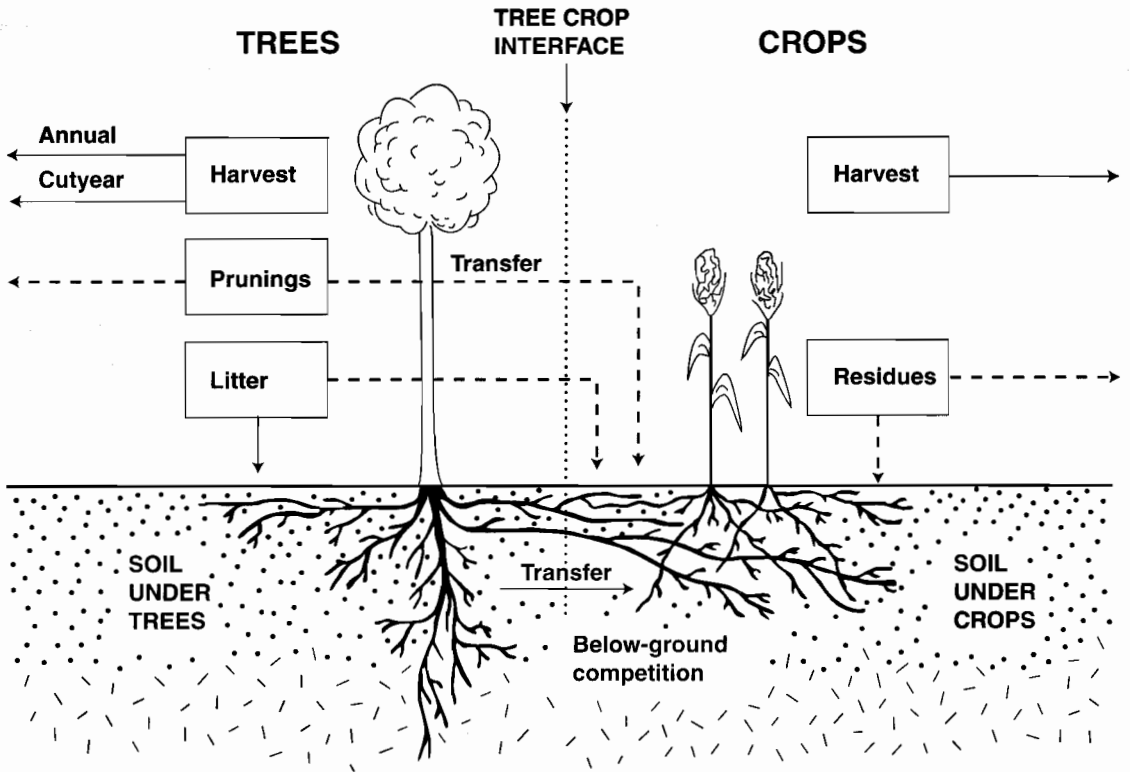


Figure 6. Agroforestry specific features of SCUAF (Young 1997)

The system of default values

All variables in SCUAF are given default values. These are set by the environmental conditions: climate, soil and slope. Examples are:

- the default rates of leaching are higher for humid climates than for dry, and higher for sandy than for clayey soils;
- the slope factor for erosion varies with slope class, and becomes zero if the slope class is 'flat';
- phosphorus immobilisation onto clay minerals becomes higher in strongly acid soils.

Some variables are affected by more than one aspect of the environment, e.g. leaching is affected by climate and by soil texture. Others are the same for all environmental conditions, e.g. by default, roots are always initially set at 40% of above-ground biomass. The dependence of default values on environmental variables is shown in Table 1.

Table 1. Dependency of SCUAF variables on environmental conditions

Environment	Variables affected
Climate	Initial soil conditions, rainfall and cover factors in erosion rates of plant growth, humus decomposition constants, atmospheric input of nutrients
Slope	Slope factor in erosion
Soil drainage	Leaching of nutrients
Soil parent material	Supply of phosphorus by rock weathering
Soil texture	Initial soil conditions, soil factor in erosion, leaching of nutrients
Soil reaction	Phosphorus fixation onto clay minerals
Initial soil organic matter status	Initial soil carbon, organic nitrogen, and organic phosphorus; hence initial soil fertility

The intended uses of the default values are:

- to prevent the model malfunctioning because of missing values;
- in education, exploratory use and demonstration, to provide quickly a set of values which are of the right order of magnitude for the environment selected;
- in research, to fill in missing values where field observations have not been taken.

As soon as a user has altered the default value of any variable, this becomes its new value in the current model, and the default value is never restored.

Some users have misunderstood the intent of the default values, wrongly assuming them to be a precisely calibrated set of quantities appropriate to the environment selected. Default values are intended to be used only for exploratory or conceptual purposes, and in education. For research, SCUAF must be locally calibrated by the user.

User calibration

The construction of SCUAF was based upon a wide range of studies of soil carbon dynamics and nutrient cycling; some of the sources used are listed in the References to Version 2 (Young and Muraya, 1991, p. 123–124). Default values for variables were obtained as follows:

1. Three studies of natural ecosystems were taken, in the forest, savanna and semi-arid zones, and the model adjusted until trees-only gave a steady-state soil.
2. A range of published experimental studies of agroforestry systems was taken, including rotational systems such as shifting cultivation, spatial zoned systems such as hedgerow intercropping, and spatial mixed systems such as perennial crops with shade trees. The model was checked to ensure that the observed results could be simulated, with or without adjustments to the values for processes.

3. Hypothetical situations were taken and the model checked to confirm that, on changing the value of a variable (e.g. rate of plant growth, root fraction), the results for soil changes were in the direction expected.

SCUAF has never been checked against a large body of uniform data extending across a controlled range of environmental conditions. In particular, **values for temperate climates are highly provisional**. Models which have been calibrated against large volumes of data are no doubt more solidly founded for the given range of conditions, although such precision is not likely to extend outside this range.

For research applications, however, SCUAF requires self-calibration, that is, calibration done by the user. The default values should be treated as a fallback—rough approximations for use where more precise data are not available. Users should not expect that the default values will provide an ‘instant’ simulation of their data. The procedure intended is to:

- take a set of experimental data, with estimates of observed soil changes; adjust the default values until the model satisfactorily simulates the observed results.
- use these adjusted, or locally-calibrated, values as the basis for modelling for that area, with its own set of environmental conditions including soil types.

Getting Started

Installation

If any previous version of SCUAF is held, remove it from the hard disk, together with all stored input and output files. If you wish to keep these, either store them on diskette, or place them in a subdirectory with a name other than SCUAF. This must be done, as the presence of earlier input files (of the form FILENAME.SCU) will cause an execution error in Version 4.

SCUAF operates within MS-DOS. The diskette supplied contains two files: SCUAF.EXE and INSTALL.BAT. If installing from such a diskette:

- Exit Windows and enter MS-DOS
- Place the diskette in Drive A:
- Type INSTALL and press ENTER

This will set up the following subdirectories and files:

C:\SCUAF	containing SCUAF.EXE
C:\SCUAF\MODEL	initially empty; will contain stored models
C:\SCUAF\OUTPUT	initially empty; will contain outputs.

If installing without the INSTALL.BAT FILE:

- set up the subdirectory tree as above;
- copy SCUAF.EXE into C:\SCUAF.

To obtain SCUAF's graphical outputs the graphics driver file EGAVGA.BGI must be installed on your computer.

Starting a model

To start modelling, move to subdirectory C:\SCUAF, type SCUAF and press ENTER. Ignore the initial error message and press RETURN.

The sequence of actions to obtain a SCUAF model is indicated by screen prompts. On first entering the model, the user is asked if they wish to 'Start a new model' or 'Retrieve an existing model'. If they elect to start a new model, the initial sequence is:

1. Documentation: the user must assign a FILENAME of up to eight characters; the remainder of documentation is annotation and does not affect the functioning of the model.
2. Physical environment: the user chooses a set of broad classes of environmental conditions, e.g. climate, soil texture. This determines the default values.
3. Main menu: the user is now in the main menu, and should select input menu.

4. **INPUTS:** from the input menu, the user should work through inputs 1–11, entering values (amending the default values) as appropriate. On completing this, exit from the input menu, and select output menu from the main menu.
5. **OUTPUTS:** from the output menu, outputs can be obtained in any order, following the screen prompts.
6. The user is now free to move at will between the input and output menus, and between any items on these, altering one or more inputs and obtaining the new outputs. They can also return to documentation and assign a new FILENAME. A change to the physical environment, however, can be made only by starting a new model.

To close a session, return to the main menu and enter 99—Exit from SCUAF.

Precautions

Execution errors ('crashes') may be encountered. They result in forced exit from the model and loss of non-stored data. To help to avoid such errors:

- Ensure that no files of the form FILENAME.SCU from earlier versions of SCUAF are present in the subdirectory C:\SCUAF\MODEL
- When obtaining outputs from the printer, do not use the keyboard until printing is complete.

In earlier versions, if soil degradation became so severe that plant growth was reduced to zero, this caused an error. In Version 4, a warning message appears: 'PLANT GROWTH REDUCED TO ZERO: CONTINUE?' to which the reply can be Y(es) or N(o).

Other precautions are:

- After inputting a set of data, give the model a FILENAME and save the data.
- Do not over-write outputs into the same file; if the input data are changed, assign a new FILENAME.

Description of the Model

Units

The unit of time is the year. The unit of area is the hectare.

The unit for input of the land use system is fraction of area, e.g. 0.4 if trees cover 40% of the area considered. Although it is convenient in discussion to refer to areas as percentages, they are entered as fractions.

Most of the other SCUAF inputs, as well as the internal calculation, are in terms of:

<i>Unit</i>	<i>Scientific abbreviation</i>	<i>Screen prompt</i>
kilograms per hectare	kg ha ⁻¹	kg/ha
kilogrammes per hectare per year	kg ha ⁻¹ yr ⁻¹	kg/ha/yr

The kilograms may refer to plant dry matter (DM), and plant or soil carbon (C), nitrogen (N) or phosphorus (P), e.g. kg DM/ha/year.

Exceptions are made for inputs which in soil science are conventionally expressed in other units, e.g. soil horizon percentages. Soil depth is expressed in centimetres.

In the following description, some computer programming conventions are employed, including brackets within brackets. Variable names are given in CAPITALS. A slash '/' means 'divided by'.

Inputs (see screen input menu)

The inputs to SCUAF are largely self-explanatory from the screen prompts. The following is an outline, together with—in bold type—notes on points to which users should give special attention. Also noted are some calculations carried out locally within the input modules and which convert inputs into the units employed in modelling.

There is no range-checking in SCUAF. Users must check that values of variables are of the right order of magnitude, particularly by avoiding use of the wrong units (e.g. percentages for fractions, tonnes for kilograms).

Documentation

The FILENAME is used to identify a model and all of its outputs. It must be a word of up to eight characters, commencing with a letter, e.g. MACHAK01.

Model input data are stored in subdirectory C:\SCUAF\MODEL with the extension .SCU, e.g. MACHAK01.SCU.

Outputs are stored in subdirectory C:\SCUAF\OUTPUT with extensions as indicated on the output menu, e.g. soil mineral nitrogen as MACHAK01.SMN.

Whenever the user changes one or more input variables, a new FILENAME should be given. This can conveniently be done by changing the run number at the end of the name, e.g. MACHAK02, MACHAK03. If this is not done, outputs from the amended model will overwrite those of the previous model.

All the other Documentation inputs are annotations for the convenience of the user, and do not affect the functioning of the model. NOTES can conveniently indicate variants to a basic model, e.g. for MACHAK02, NOTES could read 'As MACHAK01 but with prunings harvested'.

Physical environment

The user sets classes for CLIMATE, SLOPE, SOIL DRAINAGE, SOIL PARENT MATERIAL, SOIL TEXTURE, SOIL REACTION and SOIL ORGANIC MATTER STATUS. These are broad and generalised classes, defined in the screen prompts. The physical environment variables are used to set the default values. After this, they have no further function in the modelling. In order to prevent unintended resetting of values, the user cannot return to input to Physical Environment without starting a new model.

Having assigned a filename under Documentation, and set the default values by means of Physical Environment, the user can now proceed successively through inputs 1–11, **altering the default values to correspond to observed local conditions, or to the user's preferred estimates.**

1. Land use system

The land use system is specified as a sequence of PERIODS (maximum 20), each lasting one or more years. For each period, the AREAS of land under TREES and under CROPS are specified as fractions, e.g. 20% TREES as 0.2. If the length of a period is one year, the user is asked if it is a CUTYEAR (see p.12). After completion of the last period specified, the first period recommences automatically during the simulation.

This method allows specification of a wide variety of land use systems: spatial, rotational, and combinations. Examples are given in Table 2.

Table 2. Examples of the description of land use systems in SCUAF

Land use system	Period	Years	Fraction of land under trees	Fraction of land under crops	Is it a Cutyear?	
Agriculture: annual cropping	1	1	0.0	1.0	No	
Plantation forestry: 20 year rotation	1	19	1.0	0.0	—	
	2	1	1.0	0.0	Yes	
Agroforestry: shifting cultivation ¹	1	9	1.0	0.0	—	
	2	1	1.0	0.0	Yes	
	3	3	0.0	1.0	—	
Agroforestry: hedgerow intercropping (hedgerows 1 m wide, alleys 4 m wide, hedgerows replanted every 10 years)	1	9	0.2	0.8	—	
	2	1	0.2	0.8	Yes	
Agriculture: perennial cropping (replanted every 20 years, with fallow year) ²	1	18	0.0	1.0	—	
	(or	1.0	0.0	0.0)		
	2	1	0.0	1.0	Yes	
Agroforestry: multistrata system ³	1	20	0.6	0.4	—	
	or	(1	20	1.0	0.4)	—
	3	1	1.0	0.0	No	
Agroforestry: silvopastoral system ⁴	1	20	0.1	0.9	—	
Agroforestry: managed fallow	Similar to shifting cultivation, but with shorter period of tree fallow, faster tree growth, and no burning in Cutyear.					
Agroforestry: contour hedgerow system	As for hedgerow intercropping, but with SLOPE CLASS set to 'Moderate' or 'Steep'.					
Agriculture: intercropping	Specify fraction of land under TREES as 0 and under CROPS as 1.0; select NUMBER OF CROPS=2; different growth rates, fractions harvested, etc may be assigned to each crop.					

¹ Cutyear includes LOSSES by burning

² It does not matter if a woody crop (e.g. tea) is treated as TREES or CROPS, provided the user is consistent. If the perennial crop were treated as CROPS, then a grass fallow could be treated as 'TREES' with the WOOD component at zero.

³ It is possible for areas under TREES and CROPS to add up to more than 1.0, i.e. to have crops growing beneath the canopy of trees. However, care is needed with the inputs and whilst modelling and outputs are believed to be adaptable to this practice, they should be inspected for consistency.

⁴ Treating grass as CROPS.

An example of the flexibility of the period–area method is shown by the description of the taungya system, which might be:

Periods 1–3	3 periods of each of 1 year, with progressively changing AREAS of TREES and CROPS
Period 4	A 16-year period of TREES only
Period 5	A 1-year period of TREES only, which is a CUTYEAR.

This sequence then repeats with Period 1, replanting of trees with crops. The user can specify two TREES or two CROPS, with their respective areas, each with different characteristics (e.g. rates of growth, whether or not N-fixing, proportions harvested). These can be single species or groups of species. **This method can also be employed where there are two growing seasons per year.** Effectively, because simulation is based on a time unit of a year, the model does not 'know' if two crops are being grown simultaneously (as intercropping) or sequentially.

The plants that are called TREES in the modelling need not be trees, nor do the CROPS need to be herbaceous crops. Either or both plants modelled can be trees, shrubs, crops or grasses, provided the user modifies the default values to assign the appropriate proportions of PLANT PARTS.

If a land use system cannot be adequately specified by the period–area method combined with other inputs, there is a fallback: run the model with one set of inputs up to a given year, obtain the outputs, and **re-input these as the initial values in a new model**. In Version 4, this must be done for plantation forestry with a thinning (partial harvest) followed by felling (complete harvest).

2. Additions

Additions refer to materials brought into the land use system from outside. These may be ORGANIC ADDITIONS (grass or leaf mulch, farmyard manure) or FERTILIZERS. Either of these can be applied to the CROP only, or to the whole system.

3. Removals

Removals refer to materials taken out of the land use system. These are normally HARVEST, which may be of any above-ground plant part: the LEAF, FRUIT or WOOD of TREES or CROPS. Thus, the normal crop harvest is CROP FRUIT, removal of crop residues is harvest of CROP LEAF, removal of the woody parts of tree prunings is TREE WOOD. HARVEST includes harvest of prunings.

If there is a CUTYEAR, additional plant parts may be harvested from the standing biomass, typically all or most of the TREE WOOD.

4. Prunings and transfers

PRUNINGS refers to any matter cut from the plant. PRUNINGS may be harvested or remain on the soil, this being set by the input of HARVEST. TRANSFERS is an input specific to agroforestry systems. It refers to plant material transferred from trees to the soil under crops. TRANSFERS of LITTER are by wind and rainwash, TRANSFERS of PRUNINGS by human agency, for purposes of mulching, erosion protection and fertility improvement of the soil under crops.

5. Plant growth

The user is asked to input a value called the ‘initial’ net primary production (INITIAL NPP), excluding ROOTS, for the TREES and CROPS. INITIAL NPP may represent:

- either* the plant growth expected to occur if there were no nutrient constraints;
- or* the observed plant growth.

INITIAL NPP may not be the same as the modelled plant growth in Year 1. If there are no nutrient deficiencies, then the two will correspond. However, if

there are nutrient deficiencies then the modelled plant growth in Year 1 will be less than the INITIAL NPP. The INITIAL NPP sets an upper limit for plant growth in Year 1, but not in subsequent years.

There is an internal inconsistency, namely that under most environmental conditions, **the default values, which include no fertilisation, lead to a substantial nitrogen deficiency; hence modelled plant growth in Year 1 is less than entered as its 'initial' value.** After consideration, this feature has been retained. It can be avoided either by selecting the soil organic status (under Environment) as 'High' (which doubles soil nitrogen) or by adding fertilizer.

The INITIAL NPP is then apportioned between the above-ground plant parts:

- LEAF: herbaceous matter;
- FRUIT: all reproductive matter, including flowers as well as fruit;
- WOOD: all above-ground woody matter.

Where harvested plant parts are below ground (e.g. potatoes, cassava, groundnuts) it is recommended that these be assigned to FRUIT and thus included in INITIAL NPP, since the output of HARVEST does not include ROOT. For this and other questions on assigning plant material to the four parts, biological correctness is not essential. What matters is that the user should be consistent in the treatment of any such decision throughout the inputs.

Plant growth is entered as kilograms dry matter per hectare, where 'per hectare' refers to a hypothetical hectare completely covered by the plant. Thus, if an existing land use system is being taken as the basis for input of INITIAL NPP, then:

INITIAL NPP = growth of plant on the land use system/area under plant

For example:

- trees cover 20% of the land and crops 80%
- in SCUAF units, AREA UNDER TREES = 0.2, AREA UNDER CROPS = 0.8;
- the measured initial growth on one hectare of this land use system is TREES 1000 kg DM/ha, CROPS 2000 kg DM/ha.

Then the input of INITIAL NPP is:

INITIAL NPP (TREES) = 1000/0.2 = 5000 kg DM/ha

INITIAL NPP (CROPS) = 2000/0.8 = 2500 kg DM/ha

This is a convention for the purpose of standardising the inputs. It does not necessarily mean that if trees were planted over the whole area, their NPP would be 5000 kg DM. In employing experimental results as the basis for inputs of INITIAL NPP, it is important to understand this convention.

The default values for TREES and CROPS are representative for a fast-growing multipurpose tree (such as *Gliricidia sepium*) and a cereal crop (such as maize). **Both the total INITIAL NPP and its assignment between plant parts should be altered by the user for plants of different growth rates and forms.**

If two trees or crops have been selected, rates of growth are requested for TREE 1 and TREE 2, or CROP 1 and CROP 2. This is applicable either for intercropping or for sequential cropping over two growing seasons.

6. Roots

ROOTS refer to all below-ground plant material except that, at the discretion of the user, harvested below-ground parts may be assigned to FRUIT. Observed data on root growth are less common than data on above-ground growth. The default value is that ROOT NPP is 40% of INITIAL NPP (additional to above-ground NPP). This should be altered where observed data, or better estimates, are available. Alteration will frequently be necessary for plants of different structure (e.g. where the CROP is grass), or where harvested parts which are biologically roots have been assigned to FRUIT.

Specified fractions of TREE ROOTS are assigned to grow:

- in agroforestry systems, laterally into SOIL UNDER CROPS;
- below the SOIL DEPTH CONSIDERED.

Tree roots that grow into soil under crops will compete with crop roots for nutrients in this soil; competition is on the basis of proportional root densities.

Tree roots that grow below the SOIL DEPTH CONSIDERED will obtain their nutrients from outside the plant-soil system. This has the effect of reducing the nutrient requirement of the trees, proportionally to the fraction of roots assigned to this.

Roots are divided into FINE and COARSE ROOTS. For the purpose of modelling, FINE ROOTS are defined not in terms of diameter, but as those roots which die back annually. Coarse roots are assumed to die only after a cutyear, when they decay progressively over three years, in proportions specified by the user. It is probable that a high proportion of roots of less than about 0.2 cm diameter do, in fact, die and regrow annually.

7. Plant composition

The PERCENTAGES of CARBON, NITROGEN and PHOSPHORUS in each of the PLANT PARTS are specified. These values are input as percentages, and the program converts them to fractions. These fractions are multiplied by biomass to obtain the carbon and nutrient contents of the plant parts.

There are two main functions of this input:

- to determine the nutrient requirements of the plants;
- to determine the quantities of carbon and nutrients added, as plant residues, to the soil.

It is recognised that a problem remains in Version 4, namely that the program does not allow for leaf senescence, the withdrawal of nutrients before leaf shedding as litter. The user can partly compensate for this through the litter-to-humus conversion losses.

8. Soil

A primary input consists of the soil conditions at the start of modelling—normally the observed soil conditions. These form the starting point for modelling of soil changes.

The user first selects the SOIL DEPTH CONSIDERED (cm). This forms the lower boundary of the plant–soil system taken as the basis for modelling. Among possibilities which could be chosen are:

- 1 The approximate maximum depth reached by crop roots.
- 2 The rock/soil boundary.
- 3 The lower boundary of the topsoil.
- 4 An arbitrary depth, e.g. 100 cm.

Option 1 is recommended.

The inputs are given as soil properties for a series of soil horizons (maximum 5), giving the depth to each horizon lower boundary. Data are entered in the units conventionally employed in soil science, which the program converts to kg/ha. Nitrogen is entered as organic N. Phosphorus levels are entered for plant-available P, organic P, and total P. The user may select any of the definitions of 'available' P (Bray, Truog, etc.), adjusting the default values as necessary; outputs of mineral P will then be on the same basis.

9. Erosion

Erosion is based on the universal soil loss equation (USLE; Wischmeier and Smith 1978), now revised (RUSLE; Renard et al. 1997):

$$\text{Rate of erosion (kg/ha)} = R \times K \times LS \times C \times 1000$$

where R = RAINFALL FACTOR, K = SOIL FACTOR, LS = SLOPE FACTOR (length, steepness) and C = COVER FACTOR; the factor of 1000 converts tonnes of the original equation to kilograms. The COVER FACTOR is entered separately for the tree and crop components, as C_{tree} and C_{crop} . The values entered for these factors can be those obtained by the methods specified in the sources or as simpler, more approximate estimates.

The default values for the RAINFALL, SOIL and COVER FACTORS are based on the sources cited above, together with FAO estimates intended for mapping erosion potential over large areas (FAO 1979). However, for the SLOPE FACTOR, the values given in the USLE (and accepted in SCUAF Version 2) result in exceedingly high rates of erosion on moderate and steep slopes, often several hundred tonnes per hectare per year. These appear to be unrealistic, hence **in SCUAF Version 4, the default values for the slope factor are considerably less than those given by the original USLE.**

Erosion under a cover of trees is normally much less than under crops. In agroforestry systems, however, the trees may exert an influence that is more than proportional to the area which they cover. This is particularly the case with contour hedgerow systems, but can also apply with scattered trees amid

cropland (Young 1997, Chapter 3). This effect is covered by a concept introduced in SCUAF Version 2, the TREE PROPORTIONALITY FACTOR (TPF) (Young and Muraya 1990, p. 58–59). The equation is:

$$E_{system} = (E_{tree} \times TPF) + (E_{proportional} \times (1 - TPF))$$

$$E_{proportional} = (E_{tree} \times A_{tree}) + (E_{crop} \times A_{crop})$$

where

E_{system} = erosion under the land use system

E_{tree} = erosion under trees only

E_{crop} = erosion under crops only

A_{tree} = fractional area under trees

A_{crop} = fractional area under crops

This equation is formulated with respect to two limiting cases, such that:

- if the trees exert no additional influence, other than that which is proportional to the area they cover, $TPF = 0$;
- if the partial cover of trees reduces erosion to the same rate as under a total cover of trees, $TPF = 1$.

If all trees were planted as a block running up and down the slope, it would be expected that $TPF = 0$.

The tree proportionality factor is specific to a particular spatial arrangement of trees in an agroforestry system. It can be determined experimentally by measuring erosion under trees only, crops only, and the agroforestry system. The large effect of contour hedgerows in reducing erosion suggest that, for this system, the TPF may be as high as 0.9 or more. The default value is 0.8.

10. Processes

This input refers to processes which act within the plant–soil system, in particular to the flows, internal and external, which determine changes in the stores of carbon and nutrients. All processes are input in terms of kg/ha–, kg/ha/yr, or fractions.

Processes cover the flows or cycling of carbon, nitrogen and phosphorus, employing widely-used models of these cycles. Most processes are self-explanatory from the screen prompts, and details of the cycles are given in the simulation description below. With respect to inputs, attention is drawn to the following points.

Carbon cycle: The litter-to-humus CONVERSION LOSS refers to the loss of carbon by oxidation during conversion from litter to humus, through the action of soil meso- and micro-fauna. The ‘active fraction’ of some carbon cycling models is in effect subsumed in SCUAF by this loss. The fractional losses may differ as between above-ground plant residues, root residues, and

organic additions. The default values are based on those suggested by Nye and Greenland (1960), most subsequent estimates being of the same order. **Soil carbon changes in SCUAF are very sensitive to rates of CONVERSION LOSS.**

The user may choose between working with either one or two HUMUS FRACTIONS, LABILE and STABLE HUMUS. The default assumption is two fractions, with 67% of initial humus in stable form. Two approaches are suggested:

- either* 1. Model soil changes for the whole soil profile, with two humus fractions.
- or* 2. Model soil changes for the topsoil only, with one humus fraction.

Alternative 1 is recommended. Alternative 2 rests on the view that most short- and medium-term changes in soils take place within the topsoil, and most of carbon in this belongs to the labile fraction.

Data on the values of most variables in the humus cycle, linked with climate and other environmental conditions, are scanty. Specialised studies (e.g. using labelled carbon) are needed to rectify this.

Nitrogen cycle: The soil inputs in the nitrogen cycle are assumed to follow a course parallel to those for carbon. Hence, the values for litter-to-humus CONVERSION LOSS for carbon are also used to divide plant-derived nitrogen between mineralisation of litter and humification.

It is assumed that, of the nitrogen mineralised in a given year, only a small fraction, default value 0.1, is carried over to the next year.

Four values for rates of nitrogen LEACHING are given. The default assumptions are that leaching under crops is faster than under trees; and fertilizer nitrogen is leached faster than nitrogen of organic origin.

Phosphorus cycle: The phosphorus input to the soil from WEATHERING OF ROCK MINERALS cannot be directly measured, but only estimated as a residual item in phosphorus balance studies. In some published phosphorus cycles it appears to be ignored. Nevertheless, it forms the major input unless fertilizers are added. By default, it is assumed to be faster for mafic (low-silica) than for felsic (high-silica) parent materials.

11. Soil-plant feedback factors

The SOIL CARBON FEEDBACK FACTOR models the effect on plant growth of changes in carbon, and hence on soil physical properties (including water-holding capacity). The SOIL DEPTH FEEDBACK FACTOR models the effect of loss of soil profile depth through erosion, notably because of a reduction of water-holding capacity. Both are represented by proportional factors, the percentage reduction in plant growth brought about by a 1% reduction in soil carbon or soil depth, respectively. The user can change these factors. By default, the effects on trees are less than those on crops.

Supplementary inputs

12. Rainfall and water

A screen prompt, explaining why a water module is not included in SCUAF.

13. Animals

A screen prompt, explaining how an animal (livestock) component can be indirectly modelled. It would be unrealistic to model directly, with a 'conversion factor' from harvest of fodder to production of farmyard manure, since this would take no account of external sources of feed. However, an animal component can be included in SCUAF land use systems indirectly, by the user specifying:

- HARVEST of Fodder (TREE LEAF, or CROP LEAF – crop residues);
- ORGANIC ADDITIONS of farmyard manure.

14. Definitions

This item on the input menu gives screen definitions of two technical terms, the TREE PROPORTIONALITY FACTOR in erosion, and the NUTRIENT RECYCLING PERCENTAGE (see p.40).

Modelling of processes

Outline of the simulation

All soil–plant processes are modelled on the basis of the following annual iteration:

- take conditions at the beginning of the year under consideration, as the basis for:
- modelling processes which take place during the year, leading to:
- conditions at the end of the year;
- obtain outputs for the year;
- switch end of year conditions to beginning of year conditions for the succeeding year.

For Year 1, the beginning of year conditions are the initial conditions specified.

There are two main stages to the simulation, called 'early' and 'late', meaning that they are treated as occurring early and later in the year or growing season.

Early processes: Calculation of plant growth, taking account of nutrient limitations.

Late processes: Effects on the soil of plant residue additions, soil processes (e.g. humification, leaching), and erosion.

The division into early and late processes does not wholly correspond to what happens in reality. It is a matter of modelling convenience, in part to

avoid circularity of cause and effect. In particular, erosion is treated as a 'late' process even though most erosion in fact occurs early in the growing season.

Many of the calculations are performed by means of arrays, including:

Plant arrays:(TREE, CROP)

Element arrays:(CARBON, NITROGEN, PHOSPHORUS)

Nutrient arrays:(NITROGEN, PHOSPHORUS)

Calculation of plant growth

Plant growth for each PLANT, namely TREES and CROPS, has been entered as INITIAL NPP (kg DM/ha). This is converted to ACTUAL NPP in three stages:

i. Adjust for areas under each plant:

$$\text{AREA ADJUSTED NPP} = \text{INITIAL NPP} * \text{AREA UNDER PLANT}$$

ii. Adjust for carbon and depth feedback factors:

$$\text{AREA CARBON DEPTH ADJUSTED NPP} = \text{AREA ADJUSTED NPP} * \\ \text{DEPTH FACTOR} * \text{CARBON FACTOR}$$

where

$$\text{DEPTH FACTOR} = (\text{CURRENT SOIL DEPTH}/\text{INITIAL SOIL DEPTH}) * \text{DEPTH} \\ \text{FEEDBACK FACTOR}$$

and

$$\text{CARBON FACTOR} = (\text{CURRENT SOIL CARBON}/\text{INITIAL SOIL CARBON} * \text{CARBON} \\ \text{FEEDBACK FACTOR}$$

iii. Adjust for nutrient deficiency

Separately for each nutrient (N and P), and separately for AREA UNDER TREES and AREA UNDER CROPS, obtain PLANT REQUIREMENT and NUTRIENT AVAILABILITY

where:

$$\text{PLANT REQUIREMENT} = S_{pp}(\text{CARBON DEPTH ADJUSTED NPP} * \text{NUTRIENT} \\ \text{CONTENT}) - (\text{Nutrients obtained from below SOIL} \\ \text{DEPTH CONSIDERED} + \text{N from SYMBIOTIC FIXATION})$$

where

$$S_{pp} = \text{sum for PLANT PARTS.}$$

$$\text{NUTRIENT AVAILABILITY} = \text{Mineral nutrients carried forward from previous} \\ \text{year} + \text{Net nutrient change}$$

It is assumed that all MINERAL PHOSPHORUS is carried forward from the previous year; but only a small proportion, by default 0.1, of the nitrogen.

Net nutrient change = Change in nutrients of organic origin + Change in fertilizer nutrients

Change in nutrients of organic origin = (Nutrients mineralised from soil + Nutrients mineralised from litter + Nutrients from ATMOSPHERIC INPUTS + Nutrients from THROUGHFALL AND STEMFLOW + N from NON SYMBIOTIC FIXATION) – (LEACHING of nutrients of organic origin + GASEOUS LOSSES of nutrients of organic origin)

Change in fertilizer nutrients = Nutrients in FERTILIZER – (LEACHING of fertilizer nutrients + GASEOUS LOSSES of fertilizer nutrients)

Adjust for roots from TREES ‘robbing’ crops of nutrients:

Nutrient uptake by TREES from SOIL UNDER CROPS = Nutrient availability in soil under crops * (Tree root density in SOIL UNDER CROPS/Crop root density in SOIL UNDER CROPS)

Nutrient availability (Trees) = Nutrient availability in SOIL UNDER TREES + Nutrient uptake by trees from SOIL UNDER CROPS

Nutrient availability (Crops) = Nutrient availability in SOIL UNDER CROPS – Nutrient uptake by trees from SOIL UNDER CROPS

Nutrient constraint = the smaller of:

(NITROGEN REQUIREMENT/NITROGEN AVAILABILITY)

or (PHOSPHORUS REQUIREMENT/PHOSPHORUS AVAILABILITY)

ACTUAL PLANT NPP = AREA CARBON DEPTH ADJUSTED NPP * Nutrient constraint

PLANT NUTRIENT UPTAKE = S_{pp} (ACTUAL PLANT NPP * NUTRIENT CONTENT OF PLANT PARTS)

This has the effect of reducing the uptake of the non limiting nutrient. For example, if N limits ACTUAL PLANT NPP to 75% of AREA CARBON DEPTH ADJUSTED NPP, then UPTAKE of P is reduced to 75%.

Effects of plant growth and land management upon soil conditions

i. The plant section of the model

Subsequent calculations are based on ACTUAL PLANT NPP, which is now known for the PLANTS, their PARTS, and their ELEMENT contents (CARBON and NUTRIENTS). This is used to calculate LITTER, where LITTER means all plant residues, above and below ground, which decompose. For each of the eight PLANT PARTS:

LITTER = ACTUAL PLANT NPP – (STANDING BIOMASS + HARVEST + LOSSES)

HARVEST and LOSSES are summed as annual amounts plus extra amounts in a CUTYEAR. STANDING BIOMASS also differs, by default becoming zero in a CUTYEAR.

Where present, ORGANIC ADDITIONS are now included, being treated in effect as a ninth fraction of LITTER, additional to the LITTER from PLANT PARTS.

There is now an OXIDATION LOSS resulting from the activities of soil fauna:

$$\text{HUMIFICATION} = \text{LITTER} * (1 - \text{fractional LITTER TO HUMUS OXIDATION})$$

The fractional losses differ as between above ground plant parts, roots, and organic additions.

For the carbon cycle, LITTER TO HUMUS OXIDATION is a loss from the plant soil system. For the nitrogen and phosphorus cycles, N and P that is not humified becomes mineralised. Hence in effect, the N and P present in litter is divided into two flows, to SOIL HUMUS and to the MINERAL fraction.

ii. Additions from plant residues to the soil

The outputs from decomposition of plant residues become inputs to the organic and mineral fractions of the soil. HUMIFICATION (of C, N and P) is added to the SOIL ORGANIC MATTER, by default entirely to the labile humus. Mineralised N and P are added to the SOIL MINERAL fractions. These nutrients become available to plants in the following year. **Thus, when land use is changed (e.g. if a tree fallow is planted) there is a lag of one year in the new plant litter becoming available, as in the real world situation.**

In Year 1 there is no LITTER, or nutrients derived from it. Hence, in modelling systems such as shifting cultivation it is preferable to start with a forest fallow before the first cropping period.

iii. Soil erosion, and change over time in factors of erosion

SOIL EROSION (kg soil/ha/yr) is calculated from the factors in the universal soil loss equation (see p. 14). Element losses (C, N and P) are obtained as:

$$\text{ELEMENT LOSS by erosion} = \text{SOIL EROSION} * \text{FRACTION OF ELEMENT IN TOPSOIL} * \text{ENRICHMENT FACTOR for element}$$

As a simplification, it is assumed that erosion losses of N and P come from the LABILE HUMUS. Nutrients in the SOIL MINERAL fraction are assumed to be below the soil surface and thus not affected by erosion. It is also assumed that erosion of carbon comes from LABILE HUMUS.

Two factors of erosion, the SOIL FACTOR and COVER FACTORS (for TREES and CROPS), change over time. If soil carbon increases, the soil's resistance to erosion increases, and hence the SOIL FACTOR decreases. This adjustment is made by an equation based on the soil erodibility nomograph (Wischmeier and Smith 1978, p.11). For each 1% (absolute) increase in soil organic carbon, the SOIL FACTOR decreases by 0.069, and vice versa.

If plant growth increases, the COVER FACTORS will become smaller, and hence erosion will be reduced. This adjustment is made proportionally to plant growth:

$$C_n = C_o * (NPP_o / NPP_n)$$

where C_o and C_n refer to the initial cover factor and the cover factor in Year n, and NPP_o and NPP_n refer to the respective rates of plant growth (tree or crop).

iv. Changes to soil organic fractions

Using results from stages ii and iii above, changes to the soil organic matter are now calculated. Taking the default assumption that all gains to the soil are initially to the labile humus:

$$\text{SOIL LABILE ORGANIC C end of year} = \text{SOIL LABILE ORGANIC C start of year} + \text{HUMIFICATION} - (\text{EROSION} + \text{OXIDATION OF LABILE HUMUS} + \text{TRANSFORMATION to STABLE HUMUS})$$

$$\text{SOIL LABILE ORGANIC (N, P) end of year} = \text{SOIL LABILE ORGANIC (N, P) start of year} + \text{HUMIFICATION} - (\text{EROSION} + \text{MINERALISATION OF LABILE HUMUS} + \text{TRANSFORMATION to STABLE HUMUS})$$

where MINERALISATION OF LABILE HUMUS for N and P are at the same proportional rates as OXIDATION OF LABILE HUMUS for C.

MINERALISATION is treated as net mineralisation, i.e. mineralisation minus immobilisation.

Where all plant additions to the soil are assumed to be to the labile humus, as in the default assumptions, the stable humus is obtained as:

$$\text{SOIL STABLE ORGANIC (C, N, P) end of year} = \text{SOIL STABLE ORGANIC (C, N, P) start of year} + \text{TRANSFORMATION} - \text{MINERALISATION OF STABLE HUMUS}$$

MINERALISATION OF STABLE HUMUS being at the slower rate specified.

v. Changes to soil mineral fractions

The changes to soil mineral N and P are not modelled at this point but at the start of the following year, as an 'early' process. However, there is a difference between the treatment of the two nutrients. SOIL MINERAL P is carried forward to the following year. SOIL MINERAL N, by contrast, is for the most part not carried forward from year to year. If not taken up by plants or lost by leaching, etc., it is assumed to be largely (by default 90%) lost before the next year. Thus, the pool of SOIL MINERAL NITROGEN must be reformed each year.

End-of-year procedures

i. Switching of values

The soil changes obtained as above are recorded as end of year values. These form the basis for the outputs.

At this stage, the final point in the simulation, **all end of year values for Year n are switched to become start of year values for Year n + 1**. The annual modelling sequence is then repeated.

ii. Soil homogenisation if areas under trees or crops change

Soil changes are monitored separately for soil under trees and under crops. However, if at the start of a new PERIOD the areas under TREES or CROPS are changed, it would be difficult to continue to monitor the separate parcels of

soil with different histories of land use. Therefore, when such a change in plant areas occurs, a function 'mix' is used, which averages the properties of SOIL UNDER TREES and SOIL UNDER CROPS. Separate monitoring recommences with the new land use. To some degree this action is the equivalent of mixing and homogenising the soil by ploughing.

Outputs (see screen output menu)

The outputs from SCUAF modelling are, in the first instance, as presented as tables, giving year by year changes. They are largely self explanatory. Output can be to:

<i>Screen</i>	The default output.
<i>Screen and Printer</i>	Obtained by entering '50' on the output menu.
<i>File</i>	All numeric outputs (without their headings) are written to ASCII files in the subdirectory C:\SCUAF\OUTPUT.

File outputs are in the form FILENAME.EXT where FILENAME is the file named assigned in Documentation, and .EXT is a three letter mnemonic code, indicated on the output menu and printed on the output tables.

As already noted, only the most recent output for a given FILENAME and EXTension is stored. Hence, **if the user wishes to change a variable and compare outputs, the FILENAME should be changed**, e.g. from FILENAM1 to FILENAM2.

When output is to the printer, do not use the keyboard until printing is complete, or an execution error will result.

Outputs 1–3: Record of input conditions

1. Documentation

Shows basic information on the model. A printout of the Documentation can be made before any set of outputs, serving for identification.

2. Data

Shows the complete set of input data for a model. **Having completed an input, users are advised to obtain a printout of data and check it carefully.**

3. Land use system

Shows the PERIODS of time for which the land use is defined, the fractions of TREES and CROPS, and whether any year is a CUTYEAR. While land use is input by PERIODS, for output it is listed year by year, corresponding to the tabular numeric outputs. The *File* output of land use can be imported into a spreadsheet and added to other graphical outputs, showing how soil changes correspond with changes in proportions of TREES and CROPS.

The next 15 outputs, numbered 4 to 18, shows annual changes in soil properties, their effects on plant growth, and changes in the plant–soil system. With a few exceptions, the units are kg/ha or kg/ha/yr.

4. Erosion

Shows changes in the variable factors of erosion (SOIL, TREE and CROP COVER FACTORS); losses of SOIL, and of CARBON, NITROGEN and PHOSPHORUS in eroded soil; and change in SOIL DEPTH (taking as the initial condition the SOIL DEPTH CONSIDERED).

Outputs 5–6: the carbon cycle

5. Soil carbon

Shows changes in LABILE, STABLE and TOTAL SOIL CARBON, together with the gains and losses which make up the carbon cycle. In practice it has been found that a decline in soil carbon is nearly always associated with a reduction in plant growth and non-sustainable land use. Thus, **maintenance of SOIL CARBON is generally an indication of sustainable land use.**

6. Plant–soil system carbon

The gains are from the atmosphere, as photosynthesis or NET PRIMARY PRODUCTION, and from ADDITIONS of organic material from outside the system, e.g. imported mulch, or manure. The losses are HARVEST, BURNING, EROSION, and OXIDATION OF HUMUS. Systems with steadily growing trees (natural forest or tree fallow) may show loss of carbon from the soil but an increase of plant–soil system carbon, accumulating in the STANDING BIOMASS.

Outputs 7–9: the nitrogen cycle

7. Soil Organic Nitrogen

Shows changes in ORGANIC NITROGEN in the soil humus and its LABILE and STABLE FRACTIONS, together with the gains and losses which cause these changes. Because the processes involved are similar, changes in organic nitrogen run largely in parallel with changes in carbon, although there may be a gradual change in the C:N ratio.

8. Soil mineral nitrogen

Shows gains and losses to mineral nitrogen in the soil, as available to plants. To a large degree, mineral nitrogen is newly formed annually. If plant growth is nitrogen limited, all of the mineral nitrogen, after losses, is taken up by plants.

9. Plant–soil system nitrogen

An output similar to that of Plant–Soil System Carbon.

Outputs 10–12: the phosphorus cycle

These are similar to the corresponding outputs for the nitrogen cycle, differing with respect to certain processes involved: rock weathering is a source of mineral phosphorus, and net fixation (immobilisation) onto clay minerals a cause of loss. Phosphorus immobilised onto clay minerals is treated as outside the plant–soil system.

Outputs 13–15: soil properties

Soil properties

The changes in soil organic carbon, nitrogen and phosphorus, shown in previous outputs as kg/ha, are converted back into the units conventionally employed in soil profile description and shown as changes in topsoil values. It is assumed that the ratio between amounts in the topsoil and in lower horizons remains constant, i.e.:

$$Te_n = Te_o \times (Se_n / Se_o)$$

where

Te_n = Topsoil content of element in Year n,
as % for C and N, mg / kg for P

Te_o = Initial topsoil content of element

Se_n = Total amount of the element in soil in Year n, as kg / ha

Se_o = Initial total amount of element in soil

This output shows average values for the whole area of the land use system.

14. Tree/crop soil differences

This gives the same outputs as for ‘soil properties’ above, but showing differential changes in SOIL UNDER TREES and SOIL UNDER CROPS. **If the areas under TREES and CROPS are changed, the soil is assumed to be ‘mixed’, and values under TREES and CROPS become the same.**

15. Nutrient deficiency and recycling

The columns for nutrient deficiency show, for nitrogen and phosphorus, the nutrient REQUIREMENTS of the plants, AVAILABILITY from the soil (including additions), and hence the DEFICIT (showing a surplus as zero). **Unless there are fertilizer additions, it will frequently be found that plant growth is limited by nutrient deficiency.**

Under the default values, a substantial nitrogen deficiency occurs at the start of a model run. This can be reduced or removed if, under the input of ‘physical environment’, a ‘high’ level of INITIAL SOIL ORGANIC MATTER is selected.

The NUTRIENT RECYCLING PERCENTAGE (NRP) shows the relation between cycling within the plant–soil system, and inputs and outputs of nutrients to

and from the system. It is shown separately for nitrogen and phosphorus. The NRP is formulated so that:

- if there is no internal recycling, NRP = 0%
- if there are no inputs or outputs (a closed system), NRP = 100%

The equation is:

$$\text{NRP}\% = \frac{\text{Internal Recycling}}{\text{Internal Recycling} + \text{Gains} + \text{Losses}} \times 100$$

where

internal recycling = soil-to-plant nutrient uptake + plant-to-soil nutrient return via litter

The NUTRIENT RECYCLING PERCENTAGE is a measure of the efficiency of the land use system in using nutrients, both of organic and fertilizer origin. Natural forest has high values of NRP, whilst monoculture of annual crops has low values. Where based on field data, this output serves to test the agroforestry nutrient cycling hypothesis:

Agroforestry systems can lead to more closed nutrient cycling than agriculture, and hence to more efficient use of nutrients (Young 1997, pp. 20, 117).

Outputs 16–18: plant growth

16. Plant growth

Shows changes in plant growth (NET PRIMARY PRODUCTION) as brought about by soil changes. The soil changes comprise:

- changes in soil carbon;
- changes in soil depth, caused by erosion;
- changes in available nutrients (nitrogen, phosphorus).

The increases or decreases in soil carbon are assumed to affect plant growth through their influence on soil physical properties. Loss of soil depth is assumed to affect growth through reduction in soil water-holding capacity and loss of rooting medium. These effects are applied through the DEPTH and CARBON FEEDBACK FACTORS.

In most simulated SCUAF models, changes in available nutrients affect plant growth in the short term, while changes in carbon have effects over the medium to long term. The effect of depth is very small unless erosion becomes severe. For less severe erosion, its effects on plant growth are largely through loss of nutrients in eroded soil.

SCUAF shows only those effects on plant growth that are brought about by changes in soil properties: depth, carbon, nitrogen and phosphorus. It does not show effects of water deficiency or tree/crop water competition, nor does it cover non-soil influences, e.g. pests and diseases.

17. Standing biomass and carbon

The first part of this output shows changes in the STANDING BIOMASS of the plants, inclusive of COARSE ROOTS, as dry matter (kg/ha). TREES or other perennial plants will progressively increase in biomass unless there is a CUTYEAR.

The second part of the output shows the STANDING BIOMASS converted to carbon, and the TOTAL SOIL CARBON. These are summed to give changes in the total PLANT SOIL SYSTEM CARBON.

18. Harvest

Shows changes in the PLANT PARTS which are harvested, as specified by the inputs. If the whole of a plant part (e.g. CROP FRUIT, TREE WOOD) is harvested, the values shown are the same as those under plant growth. Provision is made for harvest of the six above ground plant parts:

- TREE LEAF, e.g. for fodder;
- TREE FRUIT, i.e. most fruits;
- TREE WOOD, for timber, fuelwood, etc.;
- CROP LEAF, for cases where annual crop residues are considered as a harvest; may also form the main harvest, e.g. as tea;
- CROP FRUIT, the normal harvest of annual crops, and some perennials;
- CROP WOOD, infrequently harvested.

As noted under inputs, it is convenient to treat below-ground harvested parts, e.g. of root crops, as 'FRUIT', even where this is biologically incorrect.

Where two TREES or CROPS have been chosen, these are summed in the output of harvest. The biomass ratios between two trees or two crops remain unchanged during the simulation, hence the separate harvests can be obtained by proportional calculation.

Graphical outputs

The tabular data from outputs 4–18 can be shown in graphical form. Such graphs can be obtained by importing files, stored as tables in ASCII format, into the user's graphics package. The graphs can be annotated by showing changes in the land use system, from input 1 or output 3. These are the principal graphical outputs from SCUAF, showing soil changes over time and their effects on plant growth and harvest.

The second type of graphical output gives snapshot pictures of the plant–soil system in any chosen year, and is implemented directly from within SCUAF. From the output menu, select the graphics menu:

- select either the internal plant–soil cycle or the external plant–soil system balance;
- select the carbon, nitrogen or phosphorus cycle;
- choose the year of the simulated model to which the graphs will refer.

SCUAF uses the widely-available graphics driver file EGAVGA.BGI.

On a HP Laserjet printer, printouts of the graphical outputs can be obtained by entering the command (from the MS-DOS prompt, before loading SCUAF) C:\SCUAF\GRAPHICS LASERJETII.

The internal plant–soil cycle

This shows the stores and flows of C, N or P in the year chosen, as proportional circles and arrows respectively. The data are taken from the following tabular outputs:

Carbon: outputs: 5—Soil carbon, 17—standing biomass, 18—harvest.
 Nitrogen: outputs: 7—organic nitrogen, 8—mineral nitrogen, 17—standing biomass, and 18—harvest.
 Phosphorus: outputs: 10—organic phosphorus, 11—mineral phosphorus, 17—standing biomass, and 18—harvest.

The N and P in standing biomass are not directly found in any tabular output, but obtained by multiplying the standing biomass dry matter values from output 17 by the respective nutrient contents of plant parts.

The element stores and flows shown (for C, N and P unless stated) are:

Stores:	tree (standing biomass)
	crop (standing biomass)
	labile soil humus
	stable soil humus
	mineral fraction (N,P)
Flows:	photosynthesis (C)
	atmospheric fixation (N)
	plant uptake from soil (total, and separately for Trees and Crops)
	harvest
	litter (organic residues) addition to soil (from Trees and Crops)
	humification
	mineralisation from litter (N,P)
	mineralisation from humus (N,P)
	erosion loss
	leaching (N,P)
	oxidation (C) or gaseous losses (N)
	'constant' (= rain and dust + throughfall and stemflow + non-symbiotic fixation (N))
	additions (= organic additions + fertilizers)
	net immobilisation onto clay minerals (P)

The external plant–soil system balance

The plant–soil system is represented as a circle of constant diameter, within which the plant store (trees + crops) and the soil store (labile + stable fractions) are shown as proportional circles. The internal flows are summed

into uptake (soil to plant) and return (plant to soil) (see p.16). The external gains to, and losses from, the plant–soil system are then shown as proportional arrows, using data from outputs 6 (C), 9 (N) or 12 (P).

Also shown in this graphical output are two values:

- the net gain to, or loss from the plant–soil system (kg/ha C, N, or P);
- the nutrient recycling percentage (N or P) (see p. 41).

Miscellaneous

Utilities

The utilities menu is largely self-explanatory:

1. Save current model	Saves all data currently entered in a file FILENAME.SCU, where FILENAME is the current file name.
2. Load a model	Loads a model that has previously been saved. This over-writes any data currently in use.
3. Set default data drive and/or directories	Alters the subdirectories in which data (models) and outputs and/or directories are stored (from the defaults of C:\SCUAF\MODEL and C:\SCUAF\OUTPUT, respectively). This can be used to store a new set of models in different subdirectories if desired.
4. Clear current model	Removes all stored data and replaces them with default values.
5. Delete model files	Enters subdirectory C:\SCUAF\MODEL and gives the opportunity to delete model files, using MS-DOS commands.
6. Delete output files	Enters subdirectory C:\SCUAF\OUTPUT and gives the opportunity to delete stored output files, using MS-DOS commands. All output files from a FILENAME can be deleted by the command DEL FILENAME.*

Differences from previous versions

SCUAF Version 1 (Young et al. 1987) covered:

- soil erosion;
- soil organic matter (represented as carbon);
- consequences for plant growth of changes in soil profile depth and soil carbon.

Version 2 (Young and Muraya 1990) covered, in addition to the above:

- nitrogen cycling;
- consequences for plant growth of changes in soil nitrogen, modelled by a nitrogen feedback factor.

Version 3 was a provisional model, circulated to a small number of users. It has been found to contain errors, and anyone who has it should discard it.

The present Version 4 covers, in addition to the features of Version 2:

- phosphorus cycling;
- consequences for plant growth of changes in the levels of soil nitrogen and phosphorus, modelled on the basis of nutrient requirements, availability, deficiencies, and the limiting nutrient.

Other improvements in Version 4 as compared with Version 2 are:

Inputs:

- provision for transfers of litter or prunings from trees to soil under crops;
- provision for the growth of tree roots into soil under crops;
- a more flexible method for specification of land use systems, allowing for combinations of rotational and spatial agroforestry systems;
- provision to select two crops, or two trees, with different rates of growth;
- the addition of a temperate climate;
- provision to select three initial levels of soil organic matter, corresponding to soils in relatively good, intermediate, and poor condition;
- the default values for the slope and crop cover factors of erosion have been substantially reduced, on the grounds that values taken directly from the universal soil loss equation give unrealistically high rates of erosion for tropical conditions on moderate to steep slopes.

Additional outputs:

- differential changes in soil under trees and under crops;
- nutrient requirements, availability, deficiencies, and recycling percentages;
- graphical outputs of flows of carbon, nitrogen and phosphorus within the plant–soil system, and for the external balance of the system.
- Two features found in Version 2 have been omitted from Version 4. These are:
 - the optional consideration of the effects of rainfall variability (based on the decision that it was not practicable to include a water module);
 - the facility for automatic generation of line graphs of soil changes over time (consequent to the large numbers of graphics packages and software platforms, e.g. versions of Windows, that are now available).

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