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Agroforestry Abstracts

Ecological modelling of agroforestry systems

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Abstract

This review paper begins by considering three uses of models: to describe a system (descriptive models); to generate management recommendations (prescriptive models); and to predict system behaviour and the consequences of management actions (predictive models). Three types of predictive model are considered in more detail: those based on diagrams; those based on qualitative understanding; and those based on mathematical relationships. For the latter type, a representative set of agroforestry-relevant models are reviewed. The modelling elements that are used in their construction and alternatives to conventional programming for their implementation are then discussed. The problems faced in modelling agroforestry systems fall into three categories: gaps in knowledge about particular processes and relationships; deficiencies in how particular aspects of agroforestry systems are modelled; and deficiencies in the modelling environment within which models are constructed, used and communicated to others. The first of these topics was covered in an earlier review paper on ecological interactions in agroforestry (Anderson & Sinclair 1993). In this review, the deficiencies in modelling particular aspects of agroforestry systems are discussed, and then the shortcomings of current modelling environments are considered. Together, these two reviews provide the basis for the formulation of an integrated strategy for modelling and experimentation in agroforestry presented in a third paper (Anderson *et al.* 1993).

I. Introduction

This paper considers the modelling of agroforestry and related systems, thus providing a basis for considering the areas in which the effectiveness of modelling in agroforestry could be improved. The importance of modelling in the strategic aspects of agroforestry research has been recognized in, for example, the working group reports of agroforestry meetings (Huxley 1983; Reifsnyder & Darnhofer 1989). Modelling can provide a way for integrating research knowledge derived from different disciplines in a common framework, it can help to define clear goals for future directed research, and it can be used to enable alternative agroforestry management options to be rapidly explored and evaluated.

This paper concerns modelling that is related to ecological aspects of agroforestry systems at a plot level. While the importance of the socio-economic context within which tree-crop systems operate and the fact that many issues apply at a larger (e.g. catchment) scale are recognized, the ecological interactions in farmers' fields determine the yield and sustainability of agroforestry practices and, therefore, constitute a central element in their development.

II. Types of models

Models have been classified in many ways. For example, Davey *et al.* (1991) classified existing agroforestry models, on the basis of their disciplinary focus, into three types: biological-environmental, economic, and bioeconomic. There is frequently some degree of overlap and fuzziness between the different classifications, and between the classes within one classification. Attempts to classify models frequently confuse as much as they clarify. It is, perhaps, more useful to think of model classifications in relation to pure examples of each class, with many models sharing the attributes of more than one class, rather than to expect that the classification will result in a clear-cut partitioning of all models into discrete groups. One useful classification is into descriptive, predictive and prescriptive types of model.

Descriptive models are primarily intended for structuring and communicating knowledge about the system. An example is a sketch illustrating a typical home garden arrangement.

Prescriptive models are primarily intended for inferring what action a manager of the system should take under given conditions, in order to achieve some goal. An example is an equation for calculating the recommended inter-row spacing from site attributes and crop type.

Predictive models are primarily intended to enable some property of the system to be inferred from explicitly stated information. An example is a model used to predict soil loss from site attributes. Three main types of predictive model are considered here:

(a) diagrammatic predictive models, in which predictions can be made by inspection of a diagram;

(b) qualitative predictive models, which can be used to produce predictions by reasoning with qualitative knowledge; and

(c) quantitative predictive models, by far the most common type, in which the predictions are made by solving mathematical equations.

1. Descriptive models

Studies considering the cycling of energy, biomass, nutrients or water in an ecological system typically result in an inventory of the quantity of the substance in various stores within the system, and information on the flows (or fluxes) between these stores. Examples are given in a series of papers on agroforestry systems including cacao (*Theobroma cacao*) with laurel (*Cordia alliodora*) and poro (*Erythrina poeppigiana*) in Costa Rica (Alpizar *et al.* 1986; Heuveldop *et al.* 1988; Fassbender *et al.* 1988; Imbach *et al.* 1989; Beer *et al.* 1990). Figure 1 is a typical example (Fassbender *et al.* 1988, p. 51). Clearly, the main function of this type of model is to describe the system. However, one could conceivably use even this type of information for making inferences: for example, on the changes that one might expect over some short period of time, or on the relative susceptibility of two such systems to disturbance.

2. Prescriptive models

The role of the prescriptive model is to generate a set of management recommendations given a goal and a set of values characterizing a given system. The management recommendations relate to the decisions that a manager can take. They may be quantitative (e.g. spacing between crop rows, amount of mulch to apply or time to prune the lower branches of trees), or they may be qualitative (e.g. species of hedge to plant in an alley cropping system or the type of erosion control method to apply). Four forms of prescriptive model are considered below.

(a) Prescriptive equations

These consist of an equation (or a set of equations) whose inputs are site conditions, and whose output is a management variable. For example, Young (1989a), uses a simple prescriptive equation (Equation 1) within his model of soil changes under agroforestry (SCUAF):

$W = 100/S$, where W = inter-row spacing (m), and S = slope angle (degrees)

Prescriptive equation models generally have no explanatory component. However, they may be derived mathematically from a mechanistically-based or theoretical model, as in optimum-harvesting models. The goal is usually implicit (for example, to maximize crop yield) rather than an explicit input to

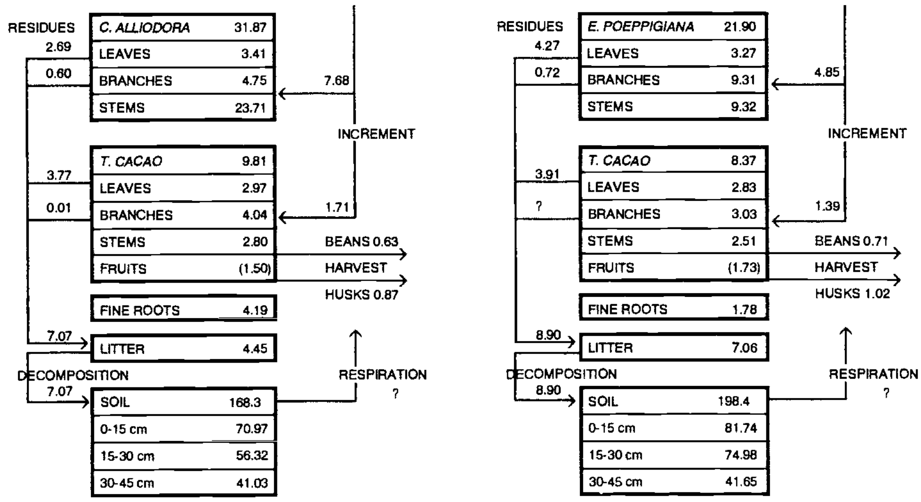


Figure 1. Models for organic matter cycles for agroforestry systems using *Theobroma cacao/Cordia alliodora* and *Theobroma cacao/Erythrina poeppigiana* in Turrialba, Costa Rica (reserves t ha^{-1}, transferences t $ha^{-1}a^{-1}$). Source: Fassbender *et al.* 1988.

the model. Prescriptive equation models have potential for use in delivering the results of the analysis of complex simulation models to managers.

(b) Mathematical programming methods

The most familiar type of programming method is linear programming (LP), but there are a number of related methods, including non-linear programming, dynamic programming, multiple-objective linear programming, and goal programming. These are characterized by having as input:

—parameters characterizing relationships within the system
—constraints
—the objective(s).

The methods use an algorithm which is able to find the optimum combination of inputs to maximize (or minimize) the value for the objective function subject to the constraints.

Figure 2 gives an example of the application of simple linear programming to the problem of deciding on the amounts of land to be used for two agroforestry systems. Dykstra (1984) considers goal programming, a form of multiple-objective linear programming (MOP), to be the most widely used of these techniques in resource management. Given goals and physical constraints, it attempts to minimize deviation from the goals without needing to satisfy the constraints completely. It requires an explicit statement of the relative weighting between goals. Romero & Rehman (1984) give an example in farm planning, to determine the areas to be used for different crops. Mendoza (1987) used the maximization ability of linear programming in a land use planning context in order to generate patterns of land use which are maximally different from one another, while still satisfying various constraints. Mendoza *et al.* (1986, 1987) illustrate the use of various MOP formulations for the planning and evaluation of agroforestry systems, with different opportunities for interactive modification of goals and weights. While mathematical programming techniques have considerable sophistication, they constrain the formulation of the model that can be used, and will not be considered further.

(c) Prescriptive use of predictive models

As noted above, one type of input to a predictive model is management decision variables. A predictive model could, therefore, be embedded in a software system that:

—searches over the range of possible values that the decision variables can take
—determines the values for the output variables for each set of values for the decision variables
—determines the optimum set of values for the decision variables (i.e. that set which maximizes (or minimizes) the values for the output variables).

No examples of the use of predictive agroforestry models based on this approach have been found for the present review. However, the approach has been advocated and used extensively in other areas of resource management (Holling 1978). It is a logical extension of the exploratory, 'what-if' use of management models to evaluate alternative management strategies. The approach, in common with other

The LP formulation of this problem is:
x_1 = ha of *Eucalyptus*-beans
x_2 = ha of *Eucalyptus*-maize
maximize PNV = $551x_1 + 501x_2$

subject to:

$$\begin{aligned} 150x_1 + 125x_2 &\leqslant 900 \text{ labour hours} \\ 280x_1 + 225x_2 &\leqslant 1200 \text{ budget dollars} \\ 15x_1 + 10x_2 &\geqslant 60 \text{ fuelwood m}^3 \\ 250x_1 + 200x_2 &\geqslant 900 \text{ protein kg} \\ x_1 + x_2 &\leqslant 5 \text{ land ha} \end{aligned}$$

Objective function
Total PNV $2483

Optimal production
Eucalyptus-beans 2.6 ha
Eucalyptus-maize 2.1 ha

Figure 2. A simple linear programming problem. PNV=Present Net Value, LP=Linear Programming. Source: Betters 1988.

techniques which are based on exercising a model over a range of conditions, such as sensitivity analysis, treats the model as a black box, embedded in a software system that solves the model repeatedly. It requires no modification to the model itself, save that it must be possible to call it from the higher-level software system. There are numerous search techniques available that facilitate efficient searching for an optimum over parameter space. These differ in their speed of detection of the optimum, and in their susceptibility to getting stuck at local optima.

The prescriptive use of predictive models differs fundamentally from the mathematical programming optimization methods outlined above. In the latter, the form of the underlying model is heavily constrained, whereas in the present context there is in principle no restriction on the form of the model, except that it must be able to execute fast enough to permit enough runs to determine the optimal set of management inputs.

(d) Decision trees and expert systems

Decision trees are branching structures that require the user to answer a question at each node (e.g. on soil type, resources available, etc). The answer takes the user down one branch or another, until arriving at a terminal node, which gives some management recommendation.

Some decision trees have been computerized, and glorified with the name 'expert system'. However, this term is most appropriately restricted to software that has a rule base of expert knowledge (rather more sophisticated than a set of branching points), the ability to reason with this knowledge in ways that mimic the reasoning ability of human experts, and the ability to explain how a recommendation was arrived at. There have been many applications in resource management: over seventy are reviewed by Lambert & Wood (1989). The journal *AI Applications in Natural Resource Management* contains many articles on expert system applications in the resource management area, including pest identification, choice of species for planting, recommendations on fertilizer treatments, and land use planning. Expert systems undoubtedly have considerable potential for delivering expert management advice in a way that is easy to understand, but they are typically based on heuristic (rule-of-thumb) knowledge, and will not be considered further in this review. However, it should be noted that they also have considerable potential for acting as a user interface to a modelling system, to guide in the choice of parameter values, or in model construction.

3. Predictive models

A predictive model enables inferences to be drawn about some aspects of a system given information about other aspects. The most familiar case is when a set of one or more formulae is used to calculate the numeric values for some variables given values for others. However, there are other predictive modelling methods (using diagrams or qualitative knowledge) and in some circumstances these may constitute the most appropriate modelling method.

(a) Predictive modelling using diagrams

Diagrams are a common and powerful modelling tool. They can be used as:

—descriptive models, to communicate ideas about system structure to others
—precursors to the construction of mathematical models ('conceptual modelling')
—predictive models in their own right, permitting the inference of things about the system.

As usual, the distinctions are not absolute: for example, a carbon-flow diagram may be drawn purely for descriptive purposes, may then be used in the design of a mathematical model, and may be used in a predictive mode to infer (in crude terms) the effect of branch pruning. The use of diagrams for predictive modelling is of concern here (while accepting that the same diagrams may also constitute descriptions of systems). Two main diagrammatic approaches are considered:

(i) box-and-arrow diagrams; and
(ii) response curve or response surface diagrams.

(i) Box-and-arrow diagrams

Box-and-arrow diagrams are very common and four types are relevant: program flow charts; flow diagrams; influence diagrams; and cause-effect diagrams. The meaning attached to nodes and arrows varies in each diagram type (Table 1). Program flow charts underlie the implementation of quantitative models, and are not discussed here. Flow diagrams have been discussed under the heading of descriptive models, since that is their main role. Influence and cause-effect diagrams are discussed further below.

Table 1. Meaning of nodes and arrows in different types of box and arrow diagram.

Type of diagram	Meaning of nodule	Meaning of arrow (A-B)
Program flow chart	An operation	Operation B follows A
Flow diagram	Store of some substance	Flow from A to B
Influence diagram	Some (numeric) quantity	A is used to determine B
Cause-effect diagram	Some action or state	A causes B

Influence diagrams

In their pure form, influence diagrams enable inferences to be made for a set of variables which will change as a consequence of a change in a particular variable. When the arrows are labelled with a + or – sign, to indicate a positive or negative influence, it is possible to infer the direction of change, and to detect positive and negative feedback loops (Figure 3). Unfortunately, the meanings attached to the nodes and arrows in diagrams found in the literature are often inexact. First, the nodes on influence diagrams may not have the precise meanings outlined in Table 1. For example, a link from 'soil nutrients' to 'trees' does not indicate which attributes of trees are influenced (although they may be fairly obvious from the context). Second, reasoning with boxes and arrows may become invalid when one or more of the nodes in a chain represents an amount of something: for example, soil loss rate may be shown as having a negative effect on the amount of soil, but a decrease in soil loss rate does not necessarily mean that the amount of soil will increase. These problems restrict the use of influence diagrams for predictive purposes, but they remain useful as tools for conceptual modelling.

Cause-effect diagrams

Cause-effect diagrams are similar to influence diagrams, and it is often possible to convert one to the other. Figure 4 is a simple example showing the causes and consequences of a decline in soil fertility: it enables the inference that (all else being equal) a decline in soil fertility can be caused by, for example, a shortage of land. Like influence diagrams, cause-effect diagrams are an effective way of capturing qualitative understanding about how a system functions. They can thus serve as a bridge between experts (indigenous or scientific) and modellers. When represented on a computer, they constitute a way of modelling in their own right that can be used instead of or as well as mathematically-based models (see section on qualitative modelling below).

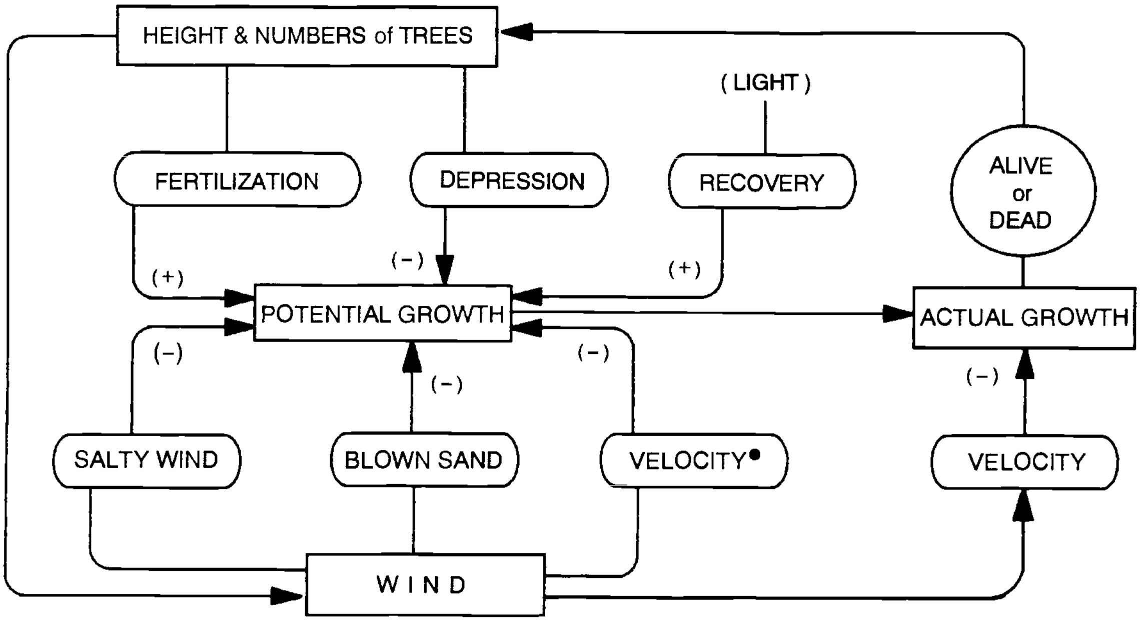


Figure 3. An influence diagram relating forest growth to wind speed. VELOCITY* denotes velocity over a critical value.
Source: redrawn from Matsuzaki 1988.

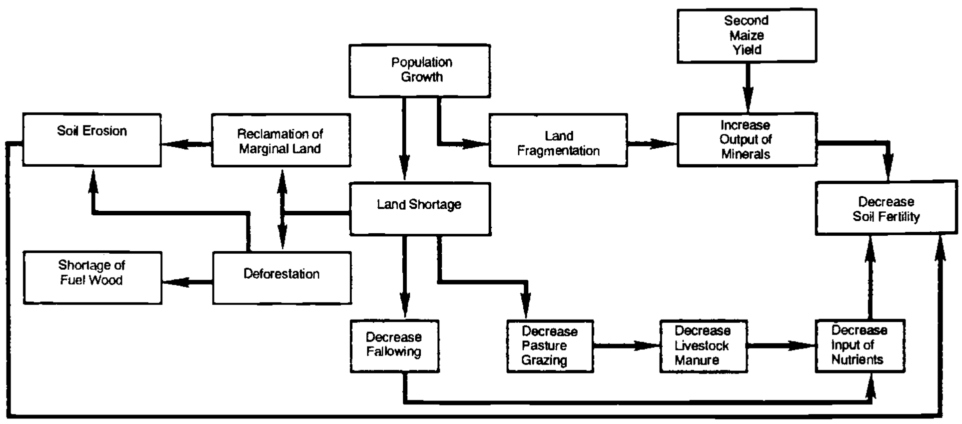


Figure 4. Cycle of land degradation in Kisii District, Kenya.
Source: Duchhart 1989.

(ii) Response curve and response surface diagrams

The other main diagrammatic modelling technique involves the construction of curves (or surfaces) between two or more axes. The curves or surfaces may be derived by some informal reasoning process, or they may be generated from a computer-based model. Six types are described below.

Functional response curves

Ecologists talking to a modeller will frequently express their understanding of particular relationships in terms of a sketched curve, showing the main characteristics of the relationship: whether it passes through the origin, has an asymptote, is linear or non-linear, etc. Figure 5 gives an example with two explanatory variables. Such curves can be used in a predictive way (e.g. 'a unit addition of nutrients will have a smaller effect on fertile soil') even when the axes are not quantified.

Notional response surfaces

Huxley (1986) gives examples of response surfaces showing postulated soil fertility, and crop and tree production, as a function of the tree:crop ratio and time in a hypothetical agroforestry system (Figure 6). These constitute a concise and effective method for capturing expert knowledge, in this example, on

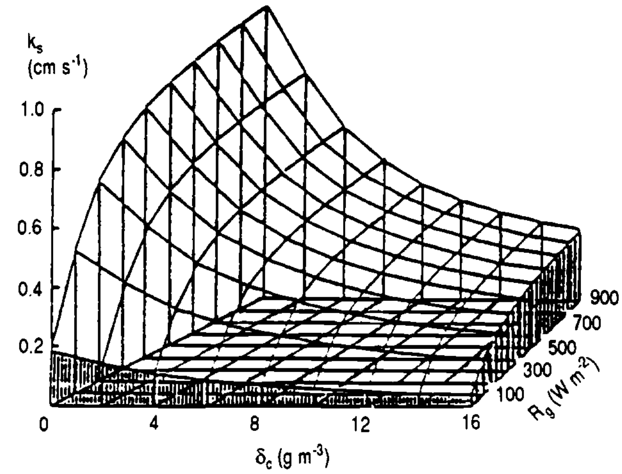


Figure 5. Functional dependence of stomatal conductance (k_s, vertical axis) on solar radiation (Rg) and vapour concentration deficit (δ_c).
Source: Anderson *et al.* 1988.

sustainability and the over-yielding response of tree:crop combinations. If the response surfaces are combined, inferences can be drawn on long-term site productivity. This approach has been repeatedly adopted to capture the complexities of interaction in agroforestry practices (Cannell 1983; Huxley 1985).

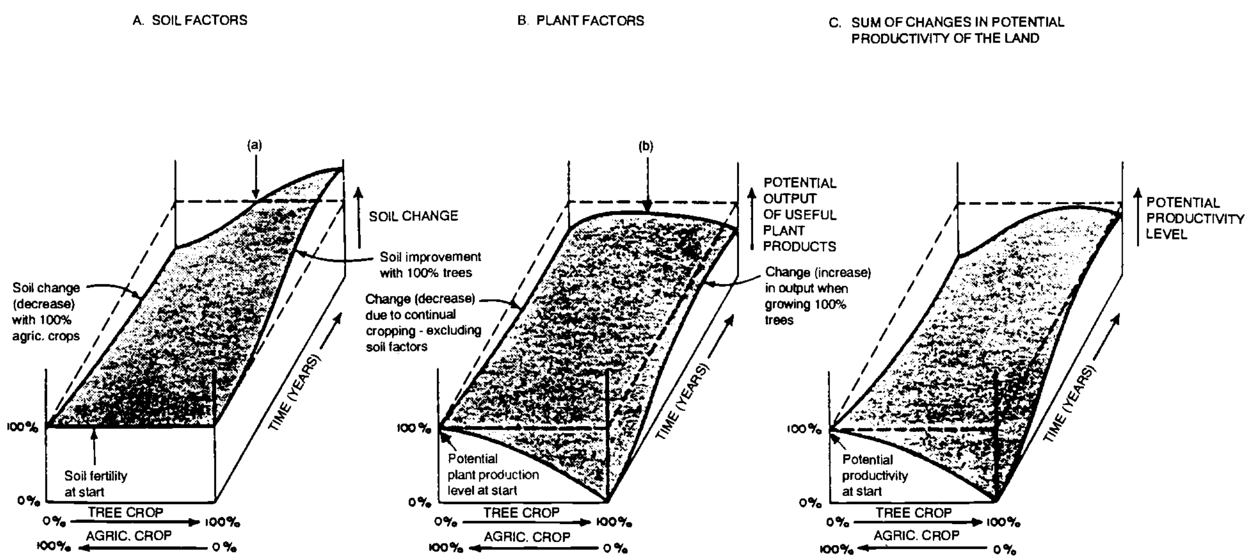


Figure 6. Trends in (A) soil factors, (B) plant factors, and (C) the combined outcome of these on potential land productivity.
Source: Huxley 1986.

Catastrophe theory diagrams

Catastrophe theory applies to situations where a system shows a discontinuous response to a smoothly-changing input. For example, the level of a forest insect pest can suddenly jump in response to a gradual change in forest branch area (Figure 7). Loehle (1989) reviews the ecological applications of this approach, and lists fifteen such applications. A suitable application in agroforestry is in relation to soil erosion: for example, a step increase in the rate of soil erosion as grazing pressure is gradually increased. The approach is useful for purposes of summarizing and analysing system behaviour, but has little explanatory power in itself.

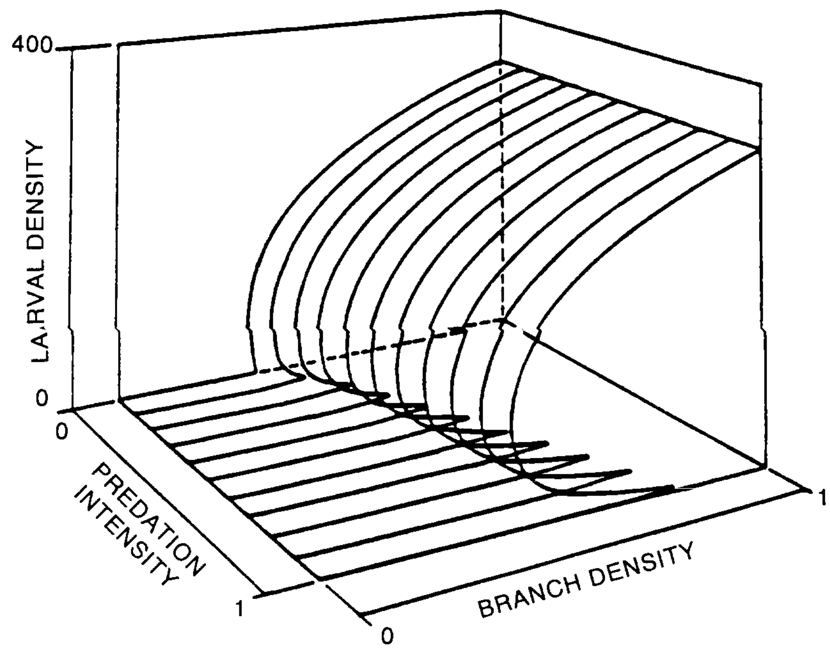


Figure 7. Spruce budworm larval density for different intensities of predation and different branch densities. At a given intensity of predation, the larval density will increase catastrophically as the forest grows.
Source: Holling 1978.

Management nomograms

Management nomograms were developed to enable a manager to investigate the effect of changing management inputs on a set of model outputs, without having to run the model on a computer (Holling 1978). A conventional computer-based simulation model is run many times, for different combinations of the two management inputs. The value (final, mean or total) of each output is plotted against the two inputs, and displayed as a set of contour diagrams. A piece of clear plastic with cross-hairs is moved over the set of contour diagrams, enabling the manager to see which combination of input values results in the best set of outputs (Figure 8). This approach has considerable merit for enabling a manager to explore alternatives, but the limitation to two management variables is restrictive.

Isocline diagrams

Isocline diagrams are used to explore the interaction between two species (typically two competing species or predator-prey). The axes may be the abundance of two species, as in standard two-species competition theory, or may represent resource availability (Tilman 1988). Tilman presents diagrams with two curves ('isoclines'): one curve shows all the combinations of two resources that result in a zero rate of change of one species, and the other the same for another species (see Figure 15 in Anderson & Sinclair 1993). The region on one side of an isocline shows the combination of axis values for which one species increases, while the other region shows the combination for which it decreases. Conventionally, the diagram is constructed by algebraic analysis of a pair of differential equations describing the interaction between the two species. Inspection of the diagram can then reveal whether the two species will reach an equilibrium, whether one will exclude the other, or whether they will oscillate. The utility of the tool for analysis of this type is greatly enhanced by modifying the curves to reflect biological understanding (e.g. that the prey species has a refuge): this can be done purely graphically, and there is no need to translate the biological insight into a mathematical form in order to do this. The approach has obvious application in agroforestry, to reflect the interaction between the tree and crop components. McMurtrie & Wolf (1983) used this approach to analyse the competitive relationships between trees and grass. Tilman (1988) undertook a detailed analysis of competition mediated by nutrient availability. The attraction of the approach lies in the simplicity with which ecological understanding can be expressed graphically, and used to infer the outcome of competition.

Yield-set diagrams

Vandermeer (1989) has developed a diagrammatic technique for analysing the possible positive or negative relationships between two crops grown together (Figure 9). However, the approach is predicated

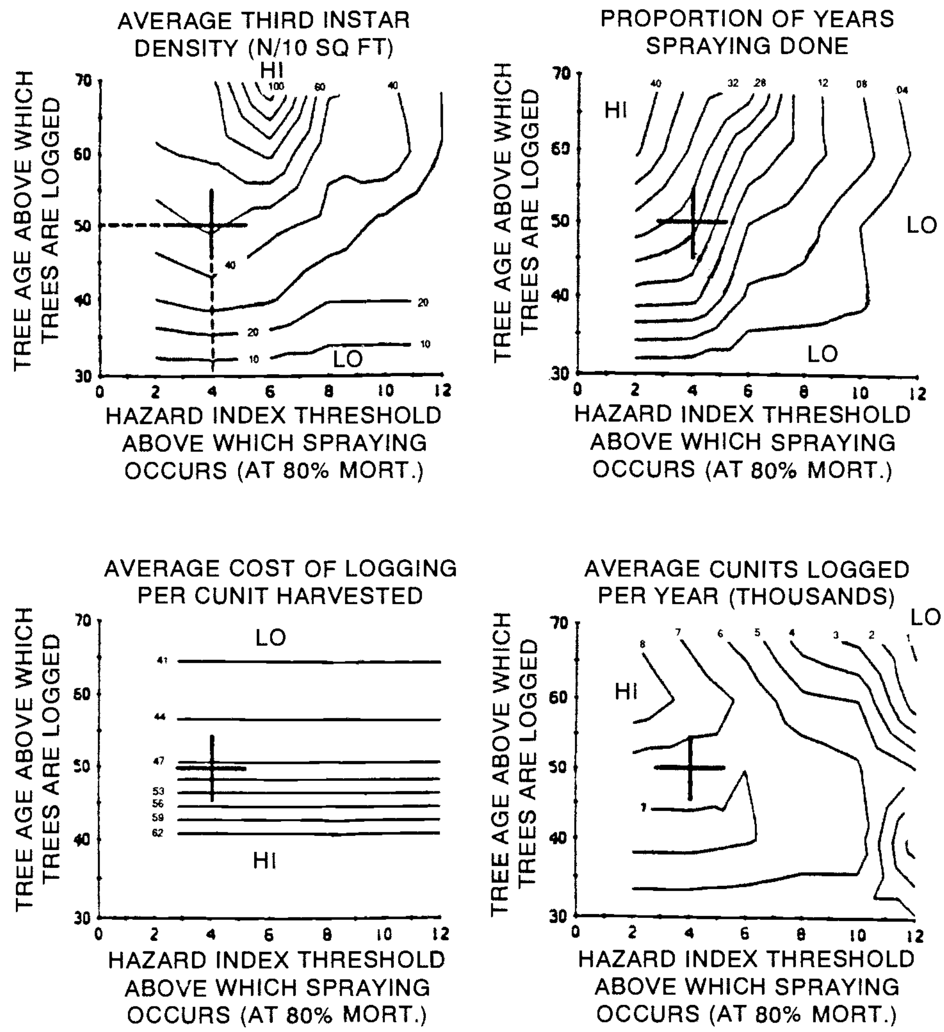


Figure 8. A management nomogram for exploring the effect of varying logging age and pest spraying threshold on a set of four objective functions.
Source: Holling 1978.

on a knowledge of all possible yield combinations (e.g. for every conceivable planting arrangement), and as such has limited utility for capturing knowledge or hypotheses about how the two crops interact.

(b) Qualitative predictive modelling

As a predictive tool, qualitative modelling allows prediction of qualitative rather than quantitative outcomes. For example:

X will change;
X will increase;
X will change from 'medium' to 'high'; and
X will have a higher value under these conditions than under those.

Given the fact that most people's knowledge about how systems function is qualitative (and it is very common to hear experts reason qualitatively about system behaviour) it is surprising that there are very few computer-based approaches for qualitative modelling, in contrast with the very large number of one-off and generic programs for quantitative modelling. There is an established discipline of qualitative reasoning within artificial intelligence, and a number of approaches have been developed (Kleer & Brown 1984; Forbus 1984; Kuipers 1986). However, these are reasonably obscure to the outsider, and have not been widely adopted. The following discussion has been restricted to those approaches that could be applied fairly readily to agroforestry systems. However, there is considerable potential in qualitative modelling approaches, and this may frequently be a more appropriate way of addressing modelling goals than the construction of quantitative models requiring mathematical formulae and extensive parameterization.

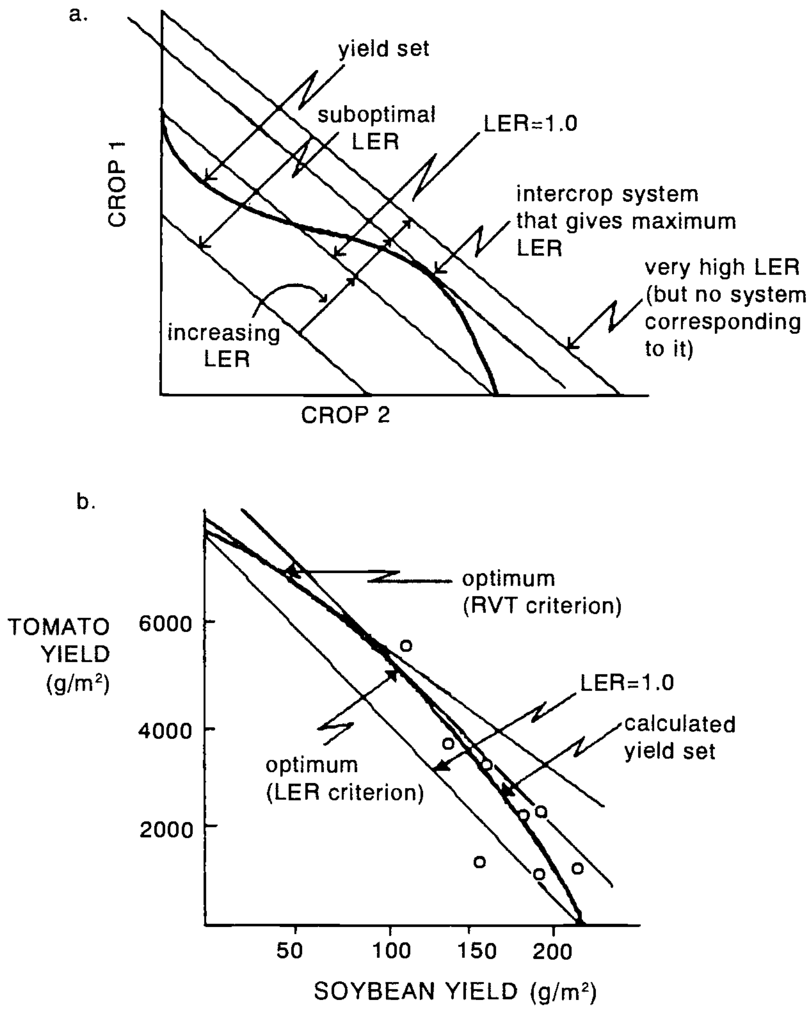


Figure 9. Illustration for finding the optimal intercrop using: (a) the yield set and various values of LER, some suboptimal, one supraoptimal, and one optimal; and (b) a calculated yield set with experimental values (circles) and optimal solutions. LER=Land Equivalent Ratioi, RYT=Relative Yield Total.
Source: Vandermeer 1989.

(i) Reasoning with influence relationships

It is a simple matter to represent the relationships in an influence diagram on a computer (optionally, an indication of positive or negative influence could be included), and to follow through influence chains. For example, Barton (1988) wrote a Prolog program (SIRWIN) to do this, incorporating additional features such as the ability to explain a link in terms of a lower-level set of influences. Such programs can identify, for example, all the tree attributes influenced by a decrease in soil moisture and detect feedback loops. Also of interest is the ability to print all the influence chains between two factors, facilitating consensus amongst scientists on what the important links are. Alexander (1963) gives an example of an influence network for an Indian village with 141 nodes and over 2000 links. It includes many entries for agriculture, forest and soils, and is used to determine the closely-interacting subsystems within the village. It would be useful to combine computer-represented influence networks with qualitative functional response curves, since a response curve is simply a way of fleshing-out a particular influence relationship. This would permit much more subtle reasoning about the consequences of some change in the system, without the need to represent relationships mathematically and to parameterize them.

(ii) Reasoning with qualitative variables

Camara *et al.* (1987) describe a qualitative modelling approach to simulating the interactions between phytoplankton, zooplankton and fish. The variables in the model (state and rate variables) can only take the values 'low', 'medium' and 'high', and rules define the change in each variable in terms of those that affect it. For example:

zooplankton biomass (t+1) = high **IF**
zooplankton biomass (t) = medium **AND**

zooplankton predation rate (t) = low **AND**
zooplankton intrinsic increase (t) = high.

Similarly, Guerrin (1991) presents a modelling method based on the idea that variables can take values only on a five-point scale (very low, low, medium, high, very high), and develops a qualitative calculus for reasoning with changes in such a system. This calculus is roughly the qualitative equivalent to methods for solving differential equation models. It is applied to biological aspects of hydrology, incorporating physiochemical aspects, decomposition, primary production and secondary producers.

(iii) Causal reasoning

A number of causal reasoning systems have been developed for student tutoring purposes. For example, the WHY tutoring system (Stevens & Collins 1977) is able to hold a conversation with a student on rainfall and erosion processes.

(c) Quantitative predictive models

The great majority of agroforestry-relevant models involve the numerical calculation of the response of a system given certain inputs, using a set of mathematical functions. The term 'quantitative predictive model' is used here to include these, and also:

—mathematical models which are analysed algebraically, rather than numerically
—models including some table look-up operation
—models using values generated from some (pseudo)random number generator.

(i) Analytical-equation models

Some models consist of a set of one or more algebraic formulae (loosely called 'equations'), that enable the model output to be obtained by substituting values on the right-hand side, and performing the necessary calculations. Empirical equations are those derived by some statistical curve-fitting method, e.g. typical yield-table models for tree stands, where top height, for example, is related to age and yield class by a polynomial equation (Edwards & Christie 1981). The parameters (coefficients) in these models have no biological or physical meaning. Mechanistic models, on the other hand, incorporate some theory of the underlying mechanism. A simple example is:

reproductive rate = fecundity × number of females

A more sophisticated example is the Penman-Monteith formula for potential evapotranspiration (Monteith 1981). Parameters in these equations generally have biological or physical meaning.

(ii) Simulation models

There is a frequent requirement to know how some variable of interest (e.g. tree height or crop biomass) changes over time. This is typically handled by a repetitive process of working out the change that is expected over some (short) time interval, then adding this change onto the variable of interest. Such models have one or more variables whose values are determined by a process of addition or subtraction of changes from one point in time to the next: these variables are called state variables, and correspond to amounts of something, e.g. tree volume, animal population size, soil water content. The state variables change through the effect of one or more processes: thus, soil water changes through the addition of water from the process of precipitation, and the loss of water from the process of evaporation. Models of this type are frequently specified in terms of differential equations (continuous change), but are still solved on a computer by some process of numerical integration. Simulation models almost invariably contain within them analytical equations: for example, evaporation as a function of soil water and radiation.

This simple view of modelling (into which many agroforestry-relevant models fit) can be extended by:

—introducing some element of randomness (e.g. into pest dispersal patterns)
—subdividing the structure of the model (disaggregation, e.g. dividing the soil into layers)
—allowing the component structure of the model to change dynamically, through the creation and deletion of individuals.

III. Models relevant to agroforestry

1. Problems in reviewing models relevant to agroforestry

Agroforestry is an interdiscipinary subject area within which many models and modelling paradigms are relevant and have been applied, creating problems in attempting to review relevant models.

(a) The number of modelling paradigms

There are a large number of modelling paradigms within which the models are constructed. Steppler & Raintree (1983) emphasize the importance of paradigms for the development of agroforestry, but also the dynamic nature of the rise, acceptance and fall of particular paradigms. In modelling, there is the additional problem of multiple paradigms co-existing, with individuals or groups gravitating to one or the other and deciding, quite understandably, not to spend their time developing a deep understanding of others. In agroforestry modelling, the 'compartment-flow-influence' paradigm is dominant, but there are many others such as those based on matrix algebra, probability theory, chaos, fractals or object-orientated programming.

(b) The number of models

There are many relevant models within a particular paradigm. This is especially true in agroforestry, with its links to many areas of ecology. Dale *et al.* (1985) refer to there being 'several hundred' single-tree forest growth models, and there are probably greater numbers in other areas, such as crop growth and water dynamics.

(c) The number of assumptions and relationships

Many models embody a large number of assumptions and relationships. In a conventional scientific paper, the results can usually be summarized in a few sentences. In a paper describing a model, the 'result' is often a large and complex construction, each element of which can be scrutinized in depth (if indeed all the elements are included in the paper). Some seventy agroforestry-relevant processes that have been modelled are listed in Table 2 (see Section IV.3), and for many of these (e.g. light interception) a wide variety of possible approaches have been taken.

(d) The number of objectives

Finally, a model can only be evaluated with respect to its objectives. These will include the outputs required, but may also reference the inputs that can be varied, the data available, the accuracy required, the simulation running time, the programming time, the type of user and the computer available. Reynolds & Acock's (1985) review of plant growth models focused on the specific objective of plant response to increasing CO_2. In contrast, there are many possible objectives in the modelling of agroforestry systems.

(e) Model validation

The term 'validation' is used here to refer to the process of developing confidence in models. This conventionally relates to the correspondence between model output and a set of independently-determined data. For example, do the rates of photosynthesis calculated by a model at different levels of radiation correspond to those obtained by measurement at the same levels? Strong validation requires that the parameters in the model are independently determined from the measurements used for validation. In physical, physiological or uniform systems, it is relatively easy to obtain the necessary replication of data to a reasonable accuracy to permit strong validation. For example, IBSNAT (International Benchmark Sites for Agrotechnology Transfer) have a rigorous specification of the experimental design needed for validating their suite of crop growth models (Harrison *et al.* 1990). The size and heterogeneity of agroforestry systems, however, means that there may be sparse opportunity to obtain replicate data sets, the data that are obtained may be noisy, and the time scales long. Therefore, opportunities for strong validation of complete agroforestry system models can be expected to remain infrequent. Validation of parts of whole models, close scrutiny of model assumptions by people not concerned in their development, and the assessment of model performance when applied to one-off field studies, are more likely to be feasible.

2. Examples of models relevant to agroforestry

It is clear from the preceding discussion that it would have been neither possible nor productive to evaluate all models relevant to agroforestry and so the approach adopted has been to summarize a set of twenty representative models covering various aspects of agroforestry, thereby illustrating the various modelling approaches that have been adopted and characterizing the tasks involved in agroforestry modelling. Models are grouped according to subject and a brief description of each group is presented. Reference to these and other models are made in the subsequent analysis of the basic 'constructs' that have been used in developing relevant models and the software used for their implementation presented in Sections IV and V. The particular problems involved in agroforestry modelling are then drawn out in Section VI.

(a) Agroforestry and intercrōpping models

There are few agroforestry models as such. Of these, most are interested in two-species yields, and incorporate very simple interactions between the two components. Details are given below of four relevant models. In SCUAF, the primary interest is in soil fertility, with tree and crop growth being handled very simply. Most of the models are dynamic, based on the compartment-flow paradigm (carbon, nutrients, water), although BEAM is non-dynamic.

SCUAF: Soil changes under agroforestry

Reference: Young & Muraya (1991).
Purpose: To predict the effects on soils of specified agroforestry systems in given environments.
Inputs: Climate zone, soil class, slope.
Outputs: Soil erosion (mass, nutrients, organic matter), soil fertility, cycling of N & P.
Time base: 1-year steps, for 20 years.
Substructure: Trees: leaf, fruit, roots, wood. Crop: leaf, fruit, roots.
State variables: C, N & P for tree, crop and soil components (see Figure 10).
Implementation: Pascal program.
Comments: Model type involves compartments, flows and subsidiary equations. The model is biologically/physically based, but with growth rates supplied rather than calculated, and with simple use of multipliers to capture interactions.

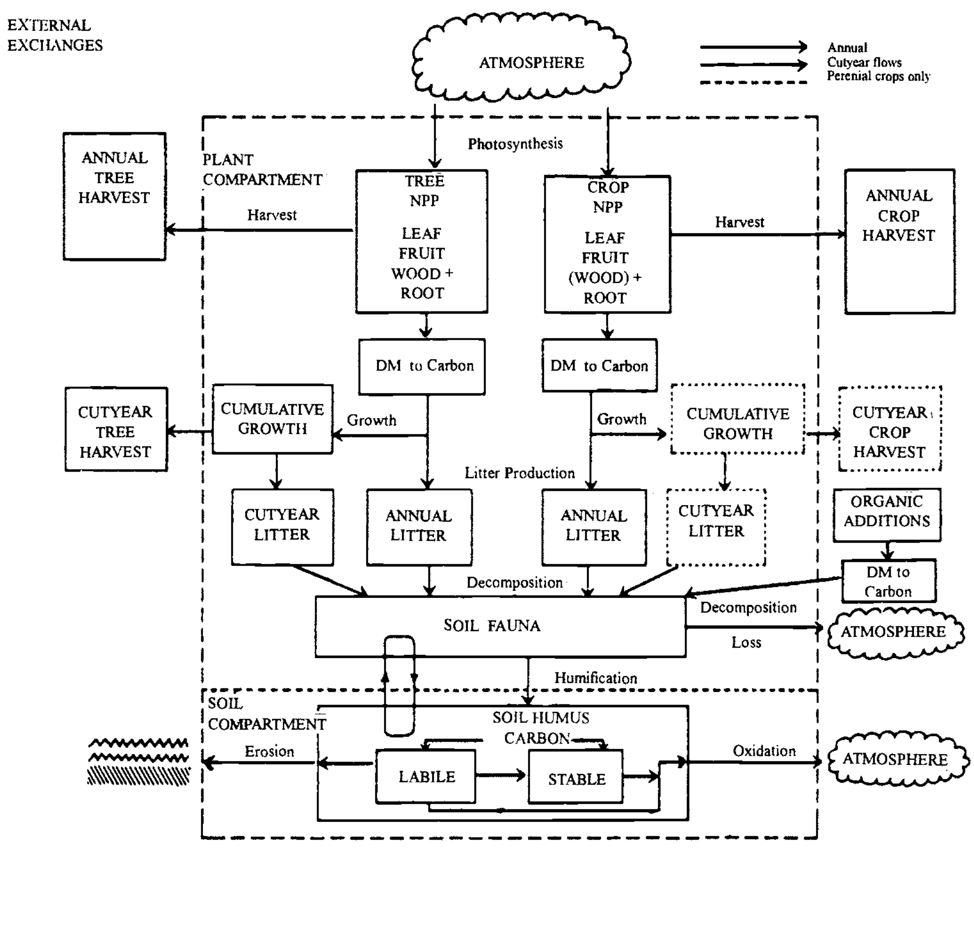


Figure 10. Structure of the SCUAF carbon model.
Source: Young 1989a.

BEAM: Maize/leucaena alley cropping model

Reference: Thomas *et al.* (1991).
Purpose: To predict maize and leucaena yield, and economic return.
Type: Equations (no state variables).
Inputs: Maize maximum and normal yield, leucaena dry- and wet-season growth rates, field layout.
Outputs: Maize and leucaena production, economic revenue.
Substructure: Maize rows (number of rows worked out from spacing inputs).
Implementation: Spreadsheet.

Ash/grassland inter-cropping model

Reference: Doyle *et al.* (1986).
Purpose: To study the effect of site, tree density, planting configuration and N availability on biological and economic yields.
Inputs: Tree density, N availability.
Outputs: Wood and grass production, sheep stocking rates.
Time base: Continuous time, for 1 year.
Substructure: None.
Implementation: The model is written as a series of first order differential equations, which can be easily used with simulation languages , such as CSMP and ACSL.
Comments: See Figure 11. Agroforestry mix is specified in terms of the proportion of the land occupied by each component. Biological basis (includes photosynthesis, etc.). Light is assumed to penetrate vertically.

CROPSYS: Maize/soybean multiple-cropping model

Reference: Caldwell & Hansen (1990).
Purpose: To explore management options for maize-soybean inter-cropping systems.
Inputs: As for IBSNAT models CERES-maize (see below) and SOYGRO, plus competition parameters, and management options for mixed-row, strip and relay inter-cropping.
Outputs: Maize and soybean yields, return in terms of 'maize equivalents'.
Comments: Integration of CERES-maize and SOYGRO (removing duplication, etc.), plus the addition of competition functions: light, water, nutrients (for example, light handled by determining the degree of shading of soybean by maize). It is not stated, but presumably the model is non-spatial, with the inputs on the field layout being used to determine either average light levels, or to simulate the shaded and unshaded soybean separately. The issues involved in integrating two crop models are similar to those needed for integrating tree-crop models.

(b) Forest dynamics models

There are a large number of models of forest dynamics. The great majority operate at a plot/stand level, and apply to uniform, even-aged plantations. Many use empirical yield equations; many (gap models) represent competitive effects within small plots (*circa* 0.1 ha), often with trees represented individually. The plot/stand approach is of limited relevance for agroforestry modelling, since it does not lend itself to the edge effects and wide spacings found in many agroforestry systems. Few models consider the growth of trees at wide spacings (see Anderson 1991). Details are given below of three models.

ALLOCATE: a model of competition in size-structured stands

Reference: Tilman (1988).
Purpose: To study the effect of environment on plant morphology, and the effect of plant morphology parameters and life history on community dynamics after disturbance.
Inputs: N per unit biomass. C allocation parameters to leaf, stem, root. Photosynthesis parameters. Death rate. Seed size. N supply rate.
Outputs: Root, stem, leaf biomasses. Amount of limiting N.
Time base: Daily for 140 days.
Substructure: Species and daily cohorts.
Comments: Non-spatial competition for light and N. Crown is a single monolayer of leaves. All allocation to vegetative structures until tree reaches maximum height, then all to seeds.

FORMIX: simulation model of natural tropical forest dynamics

Reference: Bossel & Krieger (1991).
Purpose: To evaluate long-term stand development and regeneration following logging.
Inputs: Light, felling decisions, physiological parameters.
Outputs : Biomass and tree number by canopy layer class.
Time base: Annual for *circa* 500 years.
Spatial basis: 20×20 m grid squares.

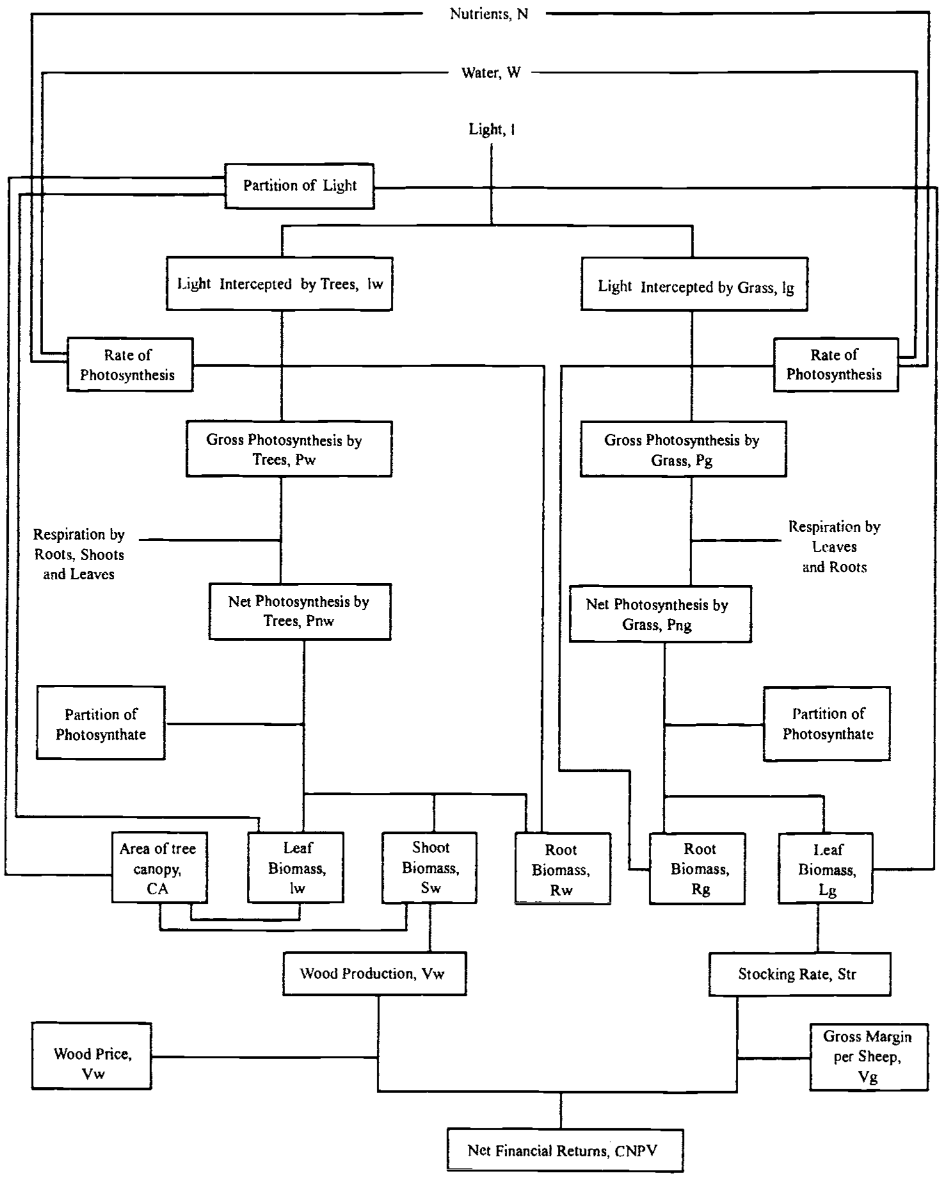


Figure 11. Structure of the Doyle *et al.* ash/pasture model.
Source: redrawn from Doyle 1991.

Substructure: Six canopy-layer classes: seedlings....emergents.
Comments: No species differentiation. Very similar to classic gap models but individual trees not represented.

Mitchell Douglas fir model

Reference: Mitchell (1975).
Purpose: To explore alternative management strategies for an even-aged plantation.
Inputs: Site quality, felling decisions.
Outputs: Standing and harvested volume.
Time base: Annual.
Spatial basis: Coordinate space.
Substructure: Individual trees, branches at each annual node.
Comments: Competition simply implemented by stopping horizontal growth of crown when it touches a neighbour, tree growth then a function of crown volume.

(c) Light interception models

The problem of light interception by plant canopies has attracted a very large amount of attention, possibly because it is seen as a relatively clean, physical problem (Myeni *et al.* 1989). Almost all of this is based in some way on the 'turbid medium' analogy (leaf density forms a sort of soup within a given volume), rather than on a representation of the individual leaf surfaces. As with forest dynamics, most of the work is based on an assumption of horizontal homogeneity, though there are several models that handle individual tree crowns (see review in Anderson & Sinclair 1993), such as MAESTRO, for which details are given below.

MAESTRO: light interception by a tree within an array of trees

Reference: Wang & Jarvis (1990).
Purpose: To predict absorption of radiation by a crown surrounded by the crowns of other trees.
Inputs: Site location, slope, bearing. Soil temperature, reflectance. Leaf transmittances and reflectances, density distribution. Physiological parameters. Tree coordinates, crown dimensions. Weather data.
Outputs: Radiation flux density at any point in the stand, hourly and daily amounts absorbed. Photosynthesis and transpiration.
Time base: Hourly for one growing season.
Substructure: Individual trees.
Implementation: Fortran program.

(d) Crop growth models

There has been a large amount of work in the development of crop models, characterized by an emphasis on the processes (both above and below ground) that drive crop growth, including the phenological aspects. Many of the models are formulated within the compartment-flow paradigm, principally for carbon but also for water and nutrients. Details are given below of three models.

PARCH: integrated modelling of semi-arid agriculture (crop component)

Reference: Bradley & Crout (1992).
Purpose: To simulate crop growth in response to soil water status.
Inputs: Weather data (daily temperature, rain, sunshine hours, evaporation, relative humidity). Cultivar parameters (phenological thermal time periods, grain parameters). Soil water. Partitioning parameters.
Outputs: Crop yield.
Time base: Daily for growing season.
Spatial basis: Two-dimensional: vertical soil layers and one horizontal slicing.
Substructure: None (for crop).
Implementation: Microsoft QuickBASIC on PC-compatibles.
Comments: Resource-capture model: growth determined by most limiting of potential growth from light and water.

SORKAM: Sorghum growth and development

Reference: Rosenthal *et al.* (1989).
Purpose: To simulate the growth and yield of sorghum.
Inputs: Radiation, soil water. Crop parameters.
Outputs: Sorghum yield.
Substructure: None.
Comments: Radiation → potential dry matter production. LAI → potential transpiration. Evaporation → soil water → actual transpiration → actual DM production.

CERES-maize: Maize growth and development

Reference: Godwin *et al.* (1989).
Purpose: To simulate the growth and yield of maize.
Inputs: Daily weather data. Cultivar parameters (phenological thermal time periods, grain parameters etc.). Soil water (from soil water balance sub-model, see comments below).
Outputs: Maize yield.
Time base: Daily for growing season.
Substructure: None.
Comments: Part of the IBSNAT suite of crop growth models (twelve crops targetted in all) that work to a specified minimum data set for inputs and validation and involve considerable biological detail in their treatment of soil water balance (common submodel) and uptake, light interception, plant growth and development, and nitrogen dynamics (Harrison *et al.* 1990).

(e) Water dynamics models

A large amount of work has been done on the mathematical modelling of water fluxes both above and below ground. See also Teklehaimanot & Jarvis (1991) to see how models for one process (evaporation of intercepted rain water) can be adapted for an agroforestry context. Details are given below of two models.

PARCH: Integrated modelling of semi-arid agriculture (water component)

Reference: Bradley & Crout (1992).
Purpose: To simulate soil water dynamics in vertical and horizontal dimensions.
Inputs: Soil properties. Slope. Temperature, solar radiation, etc.
Outputs: Runoff, soil water content.
Spatial basis: Two-dimensional: vertical soil layers and one horizontal slicing.
Comments: Uses simple gradient-flow approach for flux between layers and for evaporation from soil surface.

Ritchie two-stage model for soil water evaporation

Reference: Ritchie (1972).
Purpose: To calculate the rate of evaporation of water from the soil surface.
Inputs: Temperature, radiation, crop leaf area index, soil hydraulic properties. (Vapour pressure deficit, wind speed).
Outputs: Rate of evaporation.
Comments: Stage 1: surface is sufficiently wet for evaporation to proceed at potential rate (governed by radiation). Stage 2: soil is drier, evaporation governed by transport of water from below.

(f) Pest models

Generally, insect pest models represent life stages (egg, larva, etc.), and often have a cohort (age class) structure, as in the first two below. The spatial representation of dispersal is less common, although Holling (1978) describes the spatial dynamics of the spruce budworm; the approach could easily be scaled down for within-plot dispersal. Details are given below of three models.

PAROPSIS: Population dynamics of a defoliating beetle

Reference: Stafford-Smith & Landsberg (1991).
Purpose: To integrate the effect of climate and management practices on the population dynamics of the defoliating beetle: *Paropsis*.
Inputs: Daily temperature, foliar N, mean temperature at which tree growth starts, classification of years as wet or dry.
Outputs: Beetle population size.
Time base: Weekly time step, for several years.
Substructure: Cohort structure (1-week age class?).

Brown planthopper on rice

Reference: Holt *et al.* (1987).
Purpose: To investigate the effect of control measures on the population dynamics of the brown planthopper.
Inputs: Climatic factors, crop factors and population parameters of the planthopper and of its spider predators, including immigration/emigration rates.
Outputs: Population size over time.
Time base: Daily for one rice growing season.
Spatial basis: Uses subplots, but no interaction between them.
Substructure: Daily age-class cohort structure.

Rice pest-loss model

Reference: Teng (1987).
Purpose: To predict reduction in grain yield.
Inputs: Percentage damage on flag leaf at maximum tillering.
Outputs: Percentage unfilled grains.
Comments: Simple, single-equation empirical model.

(g) Bio-socio-economic models

Two very different examples are given here. The first models patterns of land use in swidden agriculture, based on fallow periods and walking times from the village. The second shows how the compartment-flow modelling approach can be extended to incorporate social (population size) and economic (wealth) factors. See also the BEAM model above.

Modelling swidden cultivation

Reference: Wilkie & Finn (1988).
Purpose: To examine the effect of changing populations and swidden agriculture on forest structure.

Inputs: Forest succession data, travelling time.
Outputs: Forest structure (spatial pattern).
Time base: Annual.
Spatial basis: 0.5 ha grid square.
Comments: "A cell is eligible for cultivation if it is in the usufruct, it is older than the fallow period, and it has the shortest travel time from the village."

IRUC: Integrated Resource Use and Conservation

Reference: Grossman (1986).
Purpose: To determine sustainable resource policies.
Inputs: Population size, land for forestry, litter needed for brick production, wealth, efficiency of energy use, etc.
Outputs: Food, wood and brick production, wealth, conservation of agricultural and forest land.
Comments: An extension of the compartment-flow approach to socio-economic factors.

(h) Economic models

These have minimal biological interest: the user generally has to provide yield data rather than having them calculated. They are included here because of the possibility of integrating these models with biologically-based yield models. Details are given below of two models.

MULBUD: Economics of agroforestry

Reference: Etherington (1991).
Purpose: Economic appraisal of land use systems over long time horizons.
Inputs: Crop production rates, labour inputs, prices.
Outputs: Discounted revenue.

FARMTREE: Economics of agroforestry

Reference: Loane (1991).
Purpose: Economic appraisal of land use systems.
Inputs: Species, spacing, harvest age, slope, rainfall, labour costs. Yield data, weedkiller costs. Effect of tree crowns on pasture loss.
Outputs: Discounted revenue.
Comments: Does not use extensive yield table data, unlike most plantation forestry models.

IV. Modelling constructs

In the previous section, a range of agroforestry-relevant models were presented, treating each model as a unit. However, models are generally complex structures, that can only be understood by analysing the way they are put together. For example, consider a pest/crop model that uses a daily age-class representation of the pest population, with the age-specific fecundity being a function of leaf nitrogen. Such information may be presented, in this way, as part of the characterization of the model, but it becomes clumsy and long-winded to do this directly for a number of models. It is more useful, for comparative puposes, to represent the same information in a nested fashion as follows:

—the model *contains* a pest and a crop component
—the pest component *is represented* as an age-class structured population
—the population *changes through the process* of reproduction
—reproduction *depends* on pest fecundity
—pest age-specific fecundity *depends* on crop leaf nitrogen.

In this section, models relevant to agroforestry are analysed by consideration of several key constructs which are used in their specification. This approach cuts across some of the more usual dimensions of analysis (e.g. the empirical/ mechanistic distinction, or the use of biological topics). The constructs considered are:

—model variables
—processes
—compartment-flow constructs
—the influence relationship
—disaggregation
—submodels.

The distinctions between these constructs are not absolute (for example, one type of influence leads on to the concept of disaggregation), but they nonetheless provide a framework for a useful consideration of model structures.

1. Model variables and parameters

Models can be characterized in terms of the variables they contain:

—state variables (amounts, e.g. leaf nitrogen, soil organic matter)
—rate variables (processes, e.g. rate of photosynthesis)
—intermediate variables (those calculated from others and neither of the above)
—parameters (coefficients read in at the start of the simulation)
—exogenous input variables (e.g. temperature, monthly rainfall)
—management inputs (e.g. pruning level).

Many agroforestry-relevant models are based on the compartment-flow paradigm. Therefore, they can be characterized in terms of their state and rate variables (for compartments and flows respectively). It greatly helps model comprehension when a list of model variables is included in a description. For example, Makela & Hari (1986) list the name, description and units for all state, rate and intermediate variables, and also the values and source for parameters. Many model descriptions, however, do not do this. In practice, there is little standardization on consistent naming and definitions for variables. However, the IBSNAT (Harrison *et al.* 1990) and TSBF (Anderson & Ingram 1989) programmes have pointed the way by publishing explicit guidelines on determining site characteristics. Frequently, compound variable names are used, e.g. tree leaf nitrogen. Again, there are no standard conventions.

2. Compartment-flow constructs

Many aspects of agroforestry systems can be intuitively conceptualized in terms of storages and flows. For example, storages of carbon, water or nutrients in trees, crop plants and soil, and flows between these various stores. This paradigm is formally referred to as System Dynamics (Forrester 1968). The common use of this paradigm lends itself well to graphical display, as a flow diagram. Many model descriptions include this when it is appropriate (e.g. Thornley & Verberne 1989; Young 1989b). Connor (1983) stresses the utility of this form of diagrammatic 'language' for communicating model structure. However, there are instances where System Dynamics diagrams are used in an informal way to convey model structure when in fact the model is not based on the compartments shown, e.g. Holt *et al.* (1987).

3. Processes

There is frequently an equivalence in the literature between a flow (or flux) in a compartment-flow model, and the use of the term 'process' in relation to the physical or biological system. For example, the process of transpiration may be represented as a flux of water from the crop to the atmosphere. Table 2 lists some seventy processes mentioned in the agroforestry literature. It is restricted to the physical/biological part of the system, and excludes management processes (e.g. pruning or harvesting). It also excludes things with process-like names that cannot be thought of in rate terms, e.g. 'shading'. There is some redundancy in this list; for example, growth would probably not be used in a model that included photosynthesis, respiration and allocation. The list serves both to help the modeller and to illustrate the magnitude of the modelling task. It can help by focusing the modeller's attention on the need to prioritize the processes for a model with given objectives. While not every model will need all of them, for certain objectives, the inclusion of most of these processes could be justified, and for most of the processes several alternative modelling approaches already exist. However, the equivalence between the notion of process and the notion of flow in a compartment modelling sense does provide a valuable framework within which to design a model.

4. The concept of influence

The point has already been made that it is extremely common to find statements of the form 'X influences Y', or equivalent forms, in the agroforestry literature. In fact, a large proportion of agroforestry knowledge can be represented in statements of this form, particularly when made conditional, for example, on certain species, soils, or climatic conditions. There are three major forms in which the informal notion of 'X influences Y' translates into modelling terms:

—as a functional relationship (Y is calculated from X)
—as a statement about dynamics (infiltration influences soil water content)
—as a statement implying the need to disaggregate a model component (insect age influences its fecundity).

Table 2. Processes mentioned in the agroforestry literature.

Origin/Source	Related processes
Solar radiation	interception, transmission, reflection
Organic – above ground	photosynthesis, respiration (leaf/branch/stem; maintenance/growth), translocation, allocation, competition, growth, branching, elongation, age senescence, stress senescence, phenological aging, pollination, seed formation/dispersal/germination, reproduction, mortality, litter fall
Organic – below ground	decomposition, humification, bacterial oxidation, root growth/death, root respiration (maintenance/growth), detritivory, wind erosion, soil erosion
Pests	reproduction, mortality, active/passive movement, predation of, parasitism of, herbivory, granivory, disease introduction
Diseases	spread, germination, infection, growth, reproduction
Water	precipitation, irrigation, evaporation from canopy/soil surface, throughflow, transpiration, infiltration, percolation, capillary rise, runoff
Nutrients	fixation, root-to-root transfer, uptake, translocation, fertilizing, rain/dry deposition, litter fall, mineralization, leaching, water/wind erosion
Soil physics	water/wind erosion, making porous
Soil toxicities	acidification, alkalinization, salinization, allelopathy

The discussion here is restricted to the first of these, since it is directly relevant to the issue of characterizing models. The other two are more relevant to the question of designing models from informal descriptions.

The statement 'solar radiation influences evaporation of water from the soil surface' translates in modelling terms into a function in which evaporation is determined by solar radiation. This is usually done algebraically, with an assignment statement in the program being used to calculate evaporation using (amongst other terms) solar radiation. However, the function make also take the form of interpolation on a set of tabulated values, or by straight table look-up, as in the case of the slope-length component of the USLE (universal soil loss equation) erosion model (Wischmeier & Smith 1978). It may also appear in the form of a conditional statement: 'If the soil type is S, then Y = 2*X, otherwise Y = 3*X', indicating that Y is a function of (is influenced by) both X and S. Figure 12 summarizes the factors influencing photosynthesis, conductance and partitioning for a number of models of plant dynamics illustrating the value of using influence relationships for model summary and comparison.

Some authors include influence diagrams in their model descriptions (e.g. RESCAP, Figure 13). Alternatively, the information may be conveyed as an interaction matrix, or as a set of functional dependency statements, as in the description of the GRASSMAN model (Scanlan *et al.* 1991), where the model calculations are summarized as:

(1) potential pasture production = f(rainfall, soils, vegetation community)
(2) actual pasture production = f(potential growth, tree basal area, pasture condition)
(3) pasture condition = f(pasture utilization, previous season's growth)
(4) beef production = f(potential liveweight gain, pasture utilization, stocking rate)
(5) tree growth = f(imposed management, vegetation community)
(6) gross margin = f(beef production, fixed costs, variable costs)

Apart from some ambiguity (is 'potential pasture production' in (1) the same as 'potential growth' in 2?), this summary provides a useful characterization of the model at a certain level, without cluttering up the description with details of how the calculations were performed.

There are several points to note:

First, 'X is used to calculate Y' says nothing about the empirical, mechanistic or theoretical basis of the relationship. It is for this reason that the notion of 'influence' can be developed as a unifying concept in modelling, separate from the issue of whether models (or parts of them) should be empirical or mechanistic. Individual relationships can still be classified as empirical or mechanistic, but even here there is a fuzzy area of overlap. For example, fitting a polynomial to data on the growth response of a crop to varying nutrient levels is certainly empirical, but fitting a rectangular

			Photosynthesis						Conductance			Partitioning					Other					
	System	Acronym	Leaf Nitrogen	Conductance	Temperature	Irradiance	Carbon Dioxide	CH20 Inhibition	Carbon Dioxide	Humidity	Leaf Water Potential	Substrate Avail.	Water Status	Temperature	Nutrient Status	Plant Age	Architecture	Senescence	Carbon Storage	C/N Storage	Leaf Expan. Rate	Litterfall
Crop Species Models	Soybean	GLYCIM	●	●	●	●	●	●			●	●	●	●	●	●	●	●	●	●	●	
		SOYMOD	●	●	●	●	●	●			●	●		●	●	●	●	●	●	●	●	
		SOYGRO	●		●	●		●						●				●	●	●	●	
		SOY			●	●						●			●	●		●			●	
	Cotton	GOSSYM			●	●	●					●	●	●	●	●	●	●	●		●	
		COTCROP				●						●	●	●	●	●	●	●	●	●	●	
	Sorghum	SORGF			●	●						●		●		●	●				●	
	Sugar Beet	SUBGRO			●	●						●	●					●	●		●	
	Alfalfa	SIMED			●	●		●					●	●		●		●	●			
	Corn	CORNF				●							●	●		●	●	●				
		CORNGRO			●	●		●													●	
	Potato	MASHED			●	●		●						●				●	●			
	Lettuce	LETTUCE			●	●	●							●				●	●		●	
	Wheat	TAMW											●	●		●	●	●			●	
		WHEATIES			●	●																
	Rye/Clover	RYE1				●												●			●	
		RYE2			●	●								●				●			●	
		CLOVER			●	●															●	
	Weed	SETSIM			●	●		●				●	●	●		●			●		●	
	General	ARID CROP				●							●	●		●			●		●	
		BACROS		●	●	●		●	●	●	●	●	●	●				●	●		●	
		ELCROS			●	●						●		●		●		●			●	
		GROW1		●	●	●	●	●		●	●	●	●	●		●			●		●	
		CROP1		●	●	●					●		●					●			●	
		CROP2		●	●	●				●	●		●						●			
Native Species Models	Grassland	ELM	●		●	●						●	●	●	●	●		●	●	●	●	●
		ELMAGE	●		●	●						●	●	●	●	●	●	●	●	●	●	●
		MATADOR	●	●	●	●				●	●							●	●		●	●
		BASGRAS	●			●									●				●	●		
		GRASS1			●	●							●	●				●				●
		GRASS2	●									●			●		●	●	●	●	●	●
		GRASS3	●		●	●						●	●		●			●			●	●
		GRASS4			●	●										●		●				●
	Forest	TEEM			●	●						●	●			●		●	●			●
		CERES		●	●	●	●	●			●	●	●			●			●			●
		CONIFER		●	●	●					●	●	●	●				●	●		●	●
		DOUGLA				●											●					●
		FORSIM1			●	●																●
		FORSIM2																			●	●
	Arid-system	LARREA		●	●	●	●	●				●						●	●			●
		MEDECS		●	●	●				●	●	●	●		●			●	●			●
		SHRUB											●	●		●		●	●			●
	Tundra	NECS			●	●	●	●				●		●	●				●	●	●	●
		ARTUS			●	●						●	●	●	●			●	●		●	●
		ARTUS-CO_2			●	●	●	●	●			●	●	●	●			●	●		●	●
	Saltmarsh	SPARTINA	●		●	●																

Figure 12. Checklist of features in a sample of plant growth models.
Source: redrawn from Reynolds & Acock 1985.

hyperbola could be viewed as either mechanistic (appeal to enzyme kinetics) or empirical (an algebraic form that happens to have the right shape). In the area of light interception and photosynthesis, it is doubtful whether the widespread use of the Beer-Lambert law for radiation penetration combined with some leaf-based light-response curve is really a mechanistic treatment of these processes, since the canopy is not a murky soup, and leaves are exposed to a complex combination of sunlight, penumbra and diffuse light.

Second, equations in a model do not always translate back to the conventional notion of 'influence'. Sometimes, the equation is a mathematical definition (e.g. area = πr^2). Sometimes, it describes a handy (usually empirical) relationship, with no notion of causality (e.g. tree volume = f(diameter)). This risks turning into a semantic quagmire, and there would seem to be no harm, in a modelling context, in equating 'X influences Y' with 'X is used in determining a value for Y'.

Third, it is of course very common to find that several factors influence a particular factor. Sometimes, as in the case of evaporation, there is theory to help combine the factors in a meaningful manner (e.g. the Penman-Monteith equation). Often, however, relevant theory is not available, and some other more or less arbitrary way of combining factors is adopted (e.g. the law of

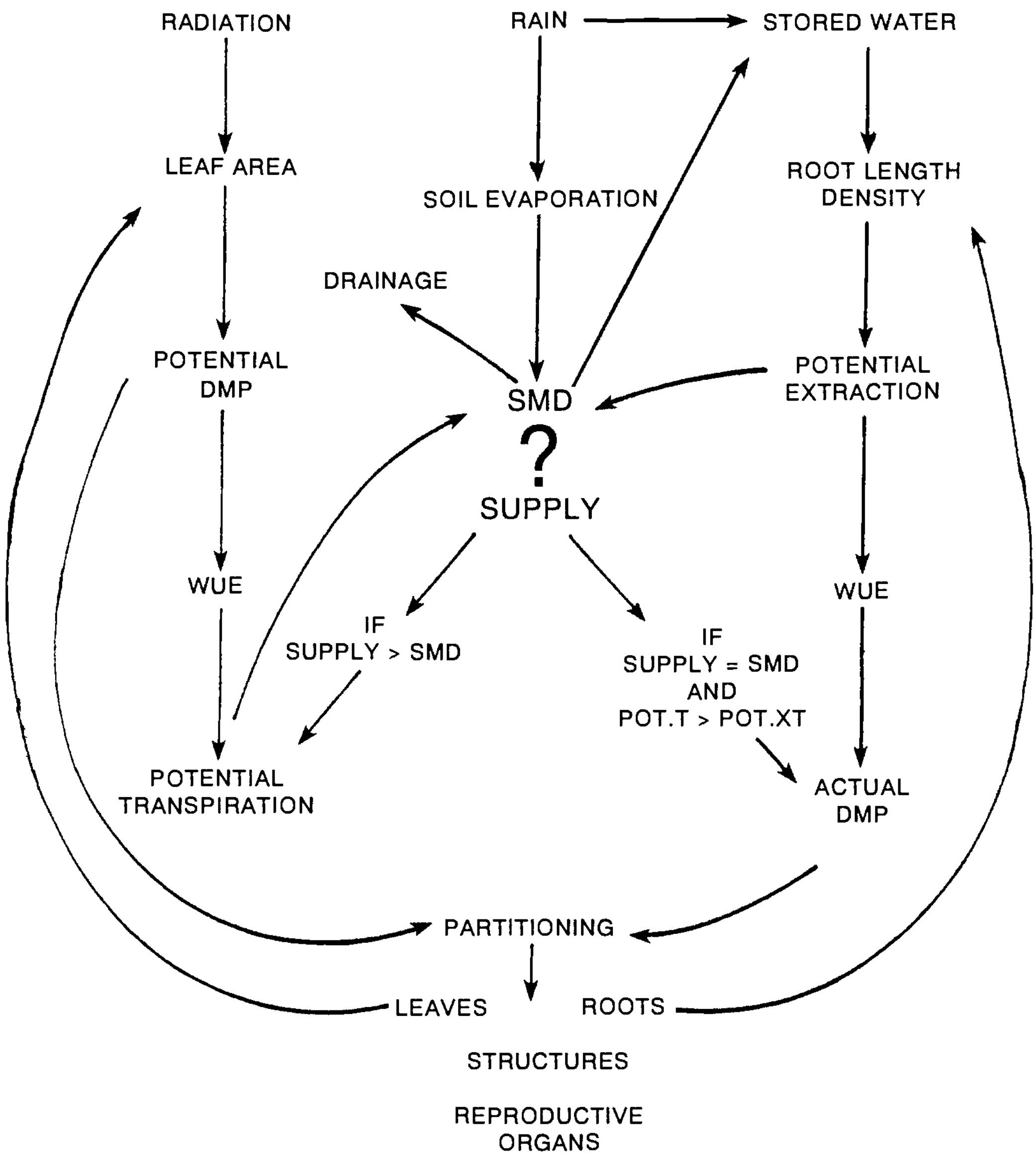


Figure 13. Summary influence diagram for the RESCAP model. WUE=Water Use Efficiency, DMP=Dry Matter Production, SMD=Soil Moisture Deficit, POT.T=Water Loss through Transpiration, POT.XT=Water Extracted by the Root System.
Source: Monteith *et al.* 1992.

the minimum; multiplicative or additive combination). O'Neill *et al.* (1989) analysed several candidate approaches for the particular problem of multiple nutrient limitations.

5. The concept of disaggregation

Disaggregation refers to the inclusion of substructure in model components. Examples of disaggregation include dividing soil into vertical layers and horizontal grid squares, the tree component into individual trees, and a pest population into age classes. The term usually refers to a repetitive set of elements, as in the above examples. It can be extended to refer to the splitting up of a component into its component parts. The disaggregation used in a model is an important part of the process of characterizing the model.

Most existing agroforestry and intercropping models appear to have little disaggregation. In contrast, many models of potential relevance to agroforestry (trees, pests) have a significant degree of disaggregation. Moreover, the nature of agroforestry, with its horizontal heterogeneity, vertical layering of canopies and soils, and mixture of species, suggests that there are rich possibilities for incorporating a much greater degree of substructure in representing model components.

The disaggregation used in a model invariably has major implications for the programming implementation of the model. For example, representing soil water as a single value requires only a simple program variable; disaggregating it into soil layers requires the use of a one-dimensional array, with associated subscripting and looping whenever soil water is used in calculations. This simple choice thus has implications that ramify throughout the program, resulting in a marked reluctance of modellers to vary the degree of disaggregation used in the model.

Table 3. Classification of disaggregation of model components

Unit of disaggregation	Examples
(a) Static substructure The number of elements in the disaggregation is set throughout the simulation run.	
Layers	Soil water and root biomass (PARCH, Figure 14). Soil water and nutrients, CERES-Maize (Goodwin *et al.* 1989). Stand photosynthesis and transpiration (Jarvis *et al.* 1985).
Horizontal space	Land segments in one dimension (PARCH: soil water, crop biomass. Figure 15). Grid squares for modelling the spread of an insect pest (Figure 15). Grid squares for spatial forest modelling (Figure 16).
Individual objects	Maize rows (BEAM, Thomas *et al.* 1991). This is an interesting example, because the number of rows is calculated in the program from the field layout inputs, rather than being specified directly by the user. Trees. There are a large number of individual-tree stand modules, Dale (1986) mentions several hundred. Some of these (concentrating on processes such as light interception, photosynthesis and transpiration) have a fixed number of trees (e.g. MAESTRO, Wang & Jarvis 1990). Shoots may be represented individually (Figure 17).
Classes for grouping individuals	Age classes: Stafford-Smith & Landsberg (1991) use daily cohorts in the PAROPSIS model and Tilman (1988) uses daily age classes in the ALLOCATE forest dynamics model. Life stages: Bossell & Krieger (1991) use life stages which they equate with layers in the canopy.
Architectural structure	Light interception models based on ray-tracing methods.
(b) Dynamic substructure The number of elements making up the disaggregation varies dynamically during the course of the simulation.	
Individuals in a population	Trees and animals.
Architectural structure	Tree branching patterns (Mitchell 1975; Prusinkiewicz & Hanan 1989, see Figure 18) and root branching patterns.

A brief classification of the types of disaggregation that have been used for components in agroforestry-relevant models, illustrated with reference to particular models, is outlined in Table 3. However, it sometimes requires careful reading of a paper to know just how a model component was represented. For example, Bossell & Krieger (1991) include a diagram which suggests that they modelled individual trees when they did not (Figure 16), while Holt *et al.* (1987) use a compartment-flow diagram for the life stages of the brown planthopper, when in fact the population was modelled using daily age classes. Average individuals are sometimes used in models of forest dynamics (e.g. Mohren 1987) and probabilistic methods may be used rather than detailed representation of many separate components. Oker-Blom (1986), for example, uses a probabilistic approach to calculate canopy light interception by individual leaves.

6. The concept of submodels

The concept of the submodel enables a complex model to be built from a number of simpler models, or conversely, to be split up into a number of discrete but inter-linked units. The relevance of this concept to

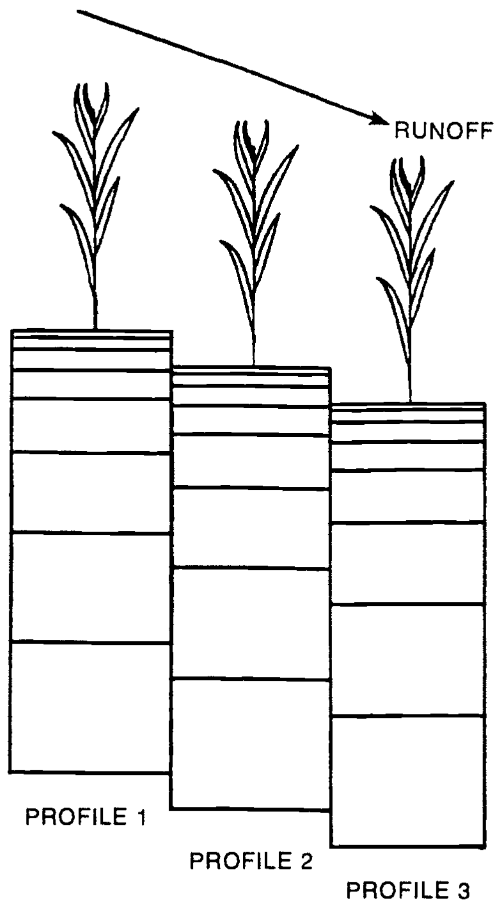


Figure 14. Horizontal and vertical disaggregation in the PARCH model.
Source: Bradley & Crout 1992.

characterizing models is that it permits models to be described at a number of levels, from the general to the very detailed. Many authors use some sort of submodel notation in constructing and presenting their model (e.g. Figure 19). Bossel (1986) describes how the WOODS model was constructed from nested submodels for trees, pasture, shrubs and light.

The concept of a submodel at the modelling level is frequently related to the concept of a subroutine (procedure) at the programming level. There are, however, a number of potential problems in translating submodels directly into subroutines, and these are discussed below as the utility of submodelling approaches in agroforestry-relevant models is considered.

The MAESTRO model (Wang & Jarvis 1990) calculates the absorption of solar radiation, photosynthesis and transpiration of a single tree standing in an array of trees. The paper describing it explicitly refers to seven submodels, corresponding to subroutines in the main program: sun position; radiation partitioning; crown structure; radiation absorption; leaf conductances; transpiration; and photosynthesis. The description of each submodel clearly and explicitly lists its inputs and outputs. However, the Fortran implementation of MAESTRO makes extensive use of COMMON blocks for transferring information between subroutines, and this reduces the clean modularity that a submodelling approach offers.

Several models have been developed by combining two or more existing models, often with considerable modification. For example, the PARCH model (Bradley & Crout 1992) combines a crop growth model, derived from the RESCAP model of Monteith (1992), and a soil water balance model. The CROPSYS model developed by IBSNAT for simulating maize/soybean intercropping (Caldwell & Hansen 1990) combines modified forms of the CERES-maize and the SOYGRO models, along with functions to simulate the additional aspects of competition for light, water and nutrients. Thornley (1992) outlines the forest growth and the soil submodels in the ITE Edinburgh Forest Model. These examples seem to use a rather more natural interpretation of 'submodel', as referring to a subcomponent or process, than the reference to a 'crown structure' submodel in MAESTRO.

It is clear that describing a model in terms of its submodels is a useful way of characterizing the model. If the submodel is already well known, then there is a benefit in parsimony as well. The approach can be seen as a hierarchical extension to the concept of influence, with each submodel being described in terms of the set of outputs calculated from a set of inputs (as opposed to the single output implied by the simple influence approach). Thus, for example, the 'sun position' submodel in MAESTRO can be

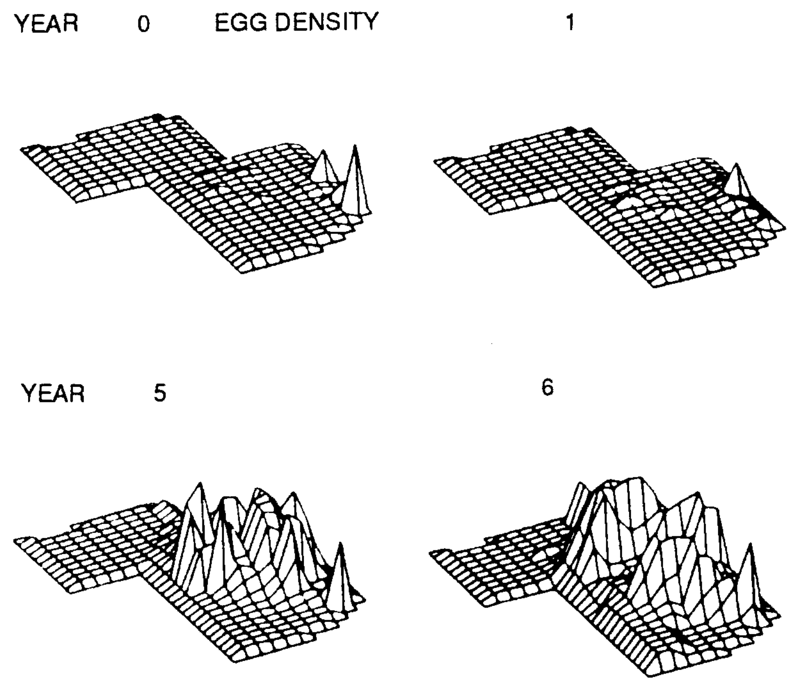


Figure 15. Grid-square modelling of an insect pest: changes in spruce budworm larval density during the course of a simulation.
Source: Holling 1978.

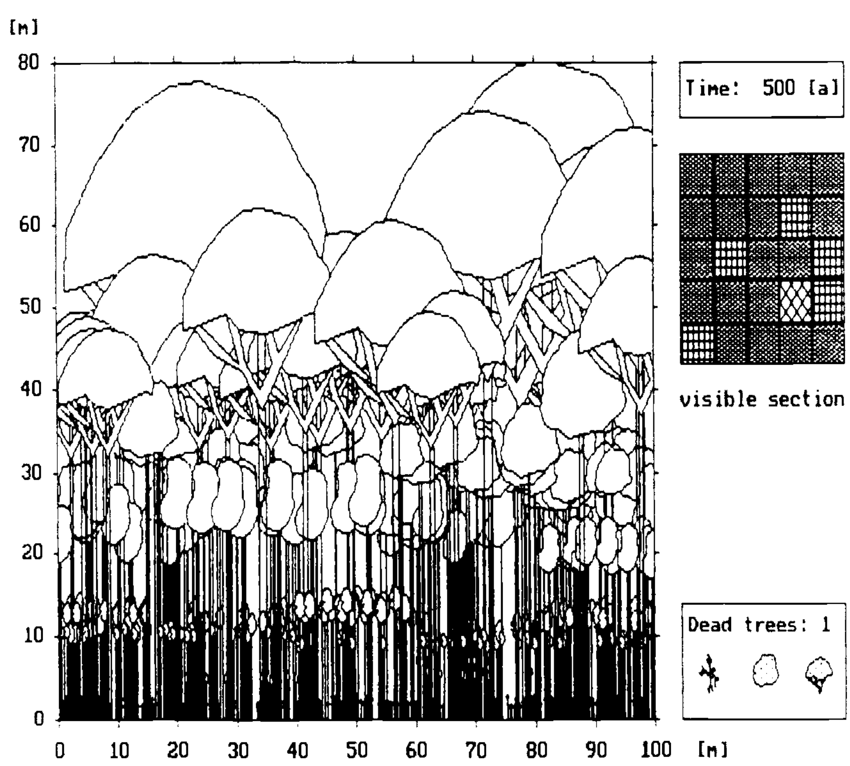


Figure 16. Grid-square and canopy-layer disaggregation in a tropical forest model.
Source: Bossel & Krieger 1991.

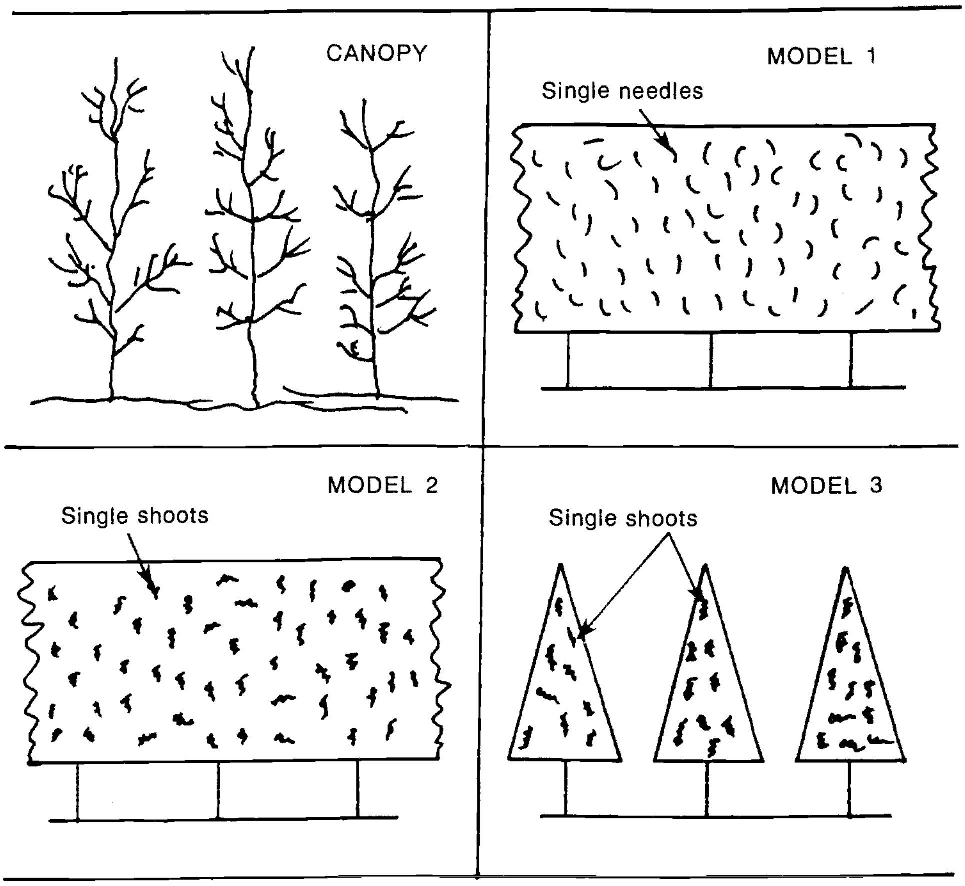


Figure 17. Choices of the disaggregation of forest canopy.
Source: redrawn from Kellomäki *et al.* 1985.

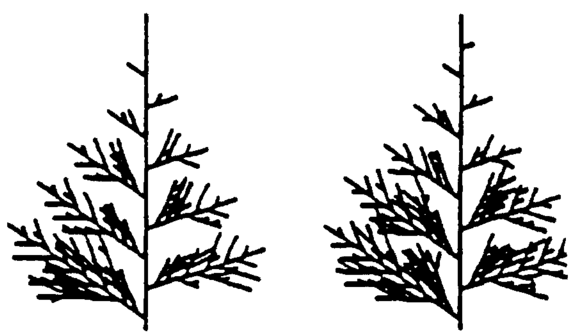


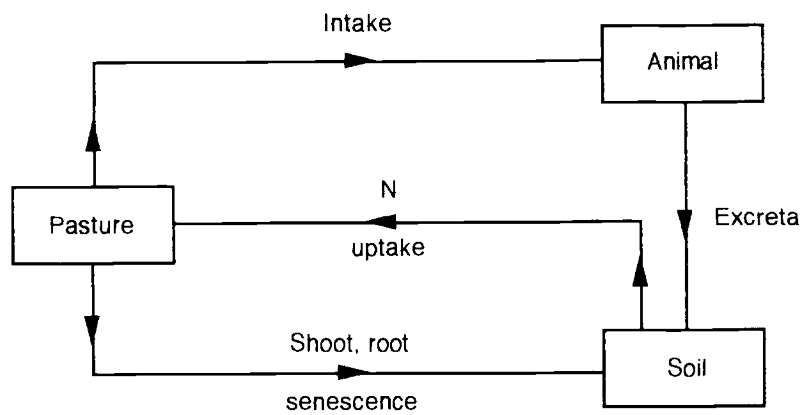
Figure 18. Fractal-grammar generation of tree branching structure.
Source: Prunsinkiewicz & Hanan 1989.

characterized as:

(zenith angle, azimuth angle, daylength) = f(time, day of the year, latitude, longitude)

However, it is often not clear whether the description of a model in terms of submodels corresponds precisely to the implementation of the model, or whether it is merely a presentational device. There are also programming issues involved in implementing a submodelling approach, and again it is often not clear from the model description (including the program flowchart) how these have been handled. For example, the norm in modelling is to determine all the rates of change first, then update the state variables. A 'submodel = subroutine' approach encourages the programmer to update the state variables in one submodel before calculating the rates of change in the other submodels but this is in general incorrect, and can introduce significant biases into the model.

a)



b)

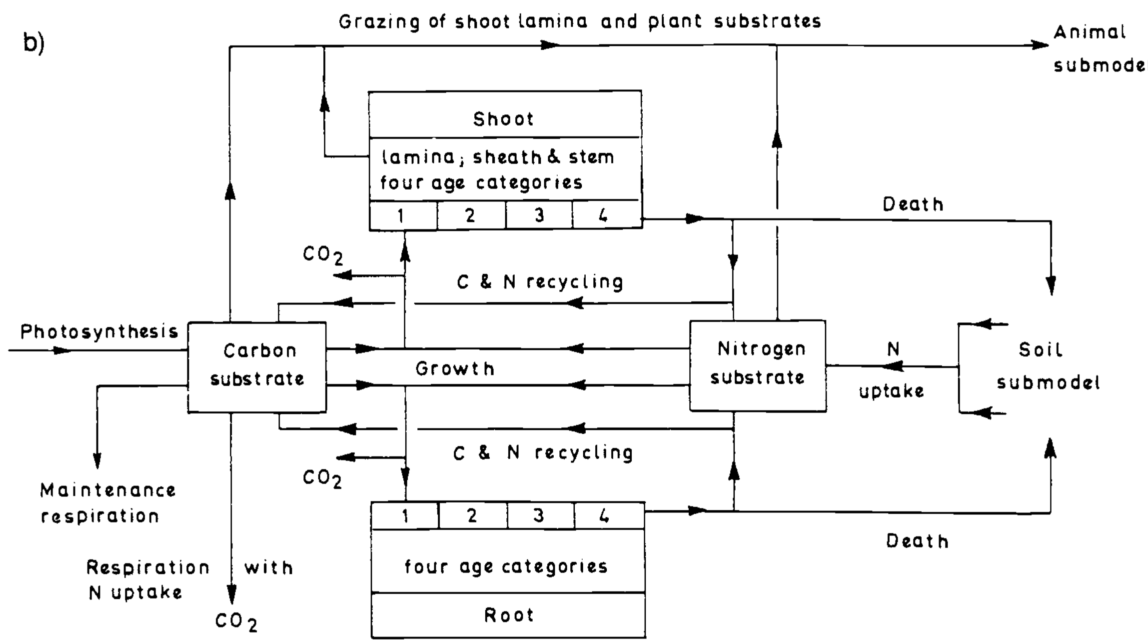


Figure 19. Submodel structure for the Hurley pasture model: (a) shows an overview of the model structure, comprised of three submodels; (b) shows the structure of the pasture submodel.
Source: Thornley & Verberne 1989.

V. Software tools for modelling

The vast majority of ecological simulation models are implemented in a conventional procedural programming language (usually Fortran, BASIC or Pascal). These have significant disadvantages, including the length of time required to implement a model and the opaqueness of the model to others, as discussed in Section VI. It is, therefore, appropriate to consider the use of other software tools for implementing models.

1. Spreadsheets

Spreadsheets have been promoted as a desirable tool with which to implement models, including agroforestry models. Thomas *et al.* (1991, p. 27) state that spreadsheets make it easy for the user of a model to vary a parameter value, and observe its effect on the output of the model. They also claim that "A spreadsheet is transparent. There is no black box which prevents a user from changing the formulas (*sic*) which underly any calculation within it." In contrast, Warner (1991, p. 5) claims that "It is now possible to use a wide range of software packages, particularly spreadsheets, to make the complex arithmetical and logical calculations of a model transparent to the user — the user can concentrate on providing the necessary input and analysing the output generated by the model." Although both these examples use the word 'transparent', in the first case this is equated with being able to see the model structure, while in the latter case it means the opposite — and both are claimed as advantages.

To a certain extent, both views are right. A spreadsheet can be used to allow the user to work at the level of inputs and outputs alone, but also to provide access to the formulae used to calculate the values in each cell. However, spreadsheets have a number of significant disadvantages when it comes to modelling, including the difficulty of seeing the structure of the whole model, and the lack of an effective equivalent to the array data structure in a conventional programming language.

2. Model-simulation environments

A number of workers have recognized that the implementation of a model can be distinct from the software needed to interact with the model to, for example, obtain parameter values, plot output, undertake sensitivity analysis, etc. In principle, it is fairly straightforward to design and implement generic software of this type, since a high proportion of models can be characterized in terms of: a fairly small set of parameters and initial values for state variables; the data files containing values for driving variables (forcing functions, exogenous variables); and the outputs they produce. The advantages of adopting this approach are potentially very large, since a large proportion of a conventional modelling program can be devoted to file handling and user interface issues. For example, approximately two-thirds of the Pascal implementation of SCUAF is concerned with such housekeeping and interface tasks.

In practice, there are a number of model-simulation environments in use, but these tend to be in-house constructions, developed for the convenience of the modellers within one institution by one keen individual, and few appear to be in use by other institutions. One significant development is DSSAT (Decision Support System for Agrotechnology Transfer), developed within the USAID-funded IBSNAT project (Anon. 1989; Jones & Jagtap 1990). IBSNAT has produced detailed models for a number of key crops, each one as a stand-alone program. Several of these have been adapted to fit within the DSSAT software, which is described as "a microcomputer software package which provides easy access to weather, crop and soil databases, and uses this information to drive crop models which simulate alternative outcomes of alternative management practices specified by the user." (Anon. 1989). It is not clear to what extent DSSAT is independent of particular models (i.e. whether additional models can be added without any change to DSSAT itself), and many of the features of DSSAT are very specific to crop modelling (for example, in the graphical display of results), so it is a long way from being an example of generic model-simulation software. Nevertheless, it does illustrate the benefits that can be obtained by embedding a number of models within a common environment.

3. Simulation languages

Simulation languages not only provide a model-simulation environment (in the sense used above), but also a language for specifying model structure. This avoids the need to implement the model in a conventional programming language (though routines written in one of these languages may be incorporated if required). The majority of simulation languages are for modelling discrete-event systems (e.g. queuing and scheduling problems in factories), in which time advances directly to the next scheduled event. Despite the fact that the operation of an agroforestry system can be viewed in an event-driven manner (based on phenological stages, the timing of management interventions, etc.), no application of this modelling paradigm in agroforestry was found for the present review.

There are three main simulation languages suitable for implementing typical agroforestry-relevant models. Two are designed for models based on differential equations (CSMP, ACSL), while Dynamo is primarily intended for difference-equation models (though the distinction can be weakened by appropriate choice of time step and integration method). In addition, a number of software packages are becoming available for personal computers that have similar characteristics, enabling the model equations to be entered into a text window, and supporting the processes involved in using the model (Kirchener 1989).

CSMP (Continuous Systems Modelling Program) has been used as a common implementation for the wide range of ecological, crop and soil models developed in Wageningen (Wit & Goudriaan 1974; Wit & Keulen 1972). ACSL (Advanced Computer Simulation Language) has perhaps attracted a wider following, and replaced CSMP as the front runner. It has been used to implement a number of major simulation models, including a very large bio-socio-economic model (Freeman & Benyon 1983) and the ITE Edinburgh Forest Model (Thornley 1992). Both languages enable differential and subsidiary equations to be entered in any order, and provide access to a range of methods for numerical integration.

In summary, simulation languages:

—remove the need for the programmer to enter equations in the order of evaluation (though one can argue that that is in fact quite a useful discipline, and aids model comprehension)

—remove the need to program methods for numerical integration (although most existing agroforestry models probably use a very simple method in any case)

—help the programmer by providing some useful built-in functions (e.g. ramp functions)
—provide some facilities of a model-simulation environment (see above).

4. Diagram-based modelling packages

It is common for a modeller to use diagrams when communicating the structure of the model to others. The two commonest conventions are:

—the compartment-flow (System Dynamics) diagram (Forrester 1968)
—the submodel/function diagram (Figure 19).

Diagram-based modelling packages exploit these conventions to enable a model to be constructed using these diagrammatic conventions, rather than simply using them for communication.

(a) Compartment-flow modelling packages

Stella is a modelling package developed for the Apple Macintosh within the System Dynamics paradigm. It provides a tool-kit of modelling symbols (compartment, flow, variable, influence arrow), allowing a diagram to be built up by placing these symbols on the screen, labelling them, and linking them together (Figure 20). This diagram is a partial specification of the model: the specification is complete when equations are provided enabling each flow and variable to be calculated, and when initial values are entered for the compartments. Once constructed, a model can be run, with the results being displayed as graphs or as an animation of the amount in each compartment.

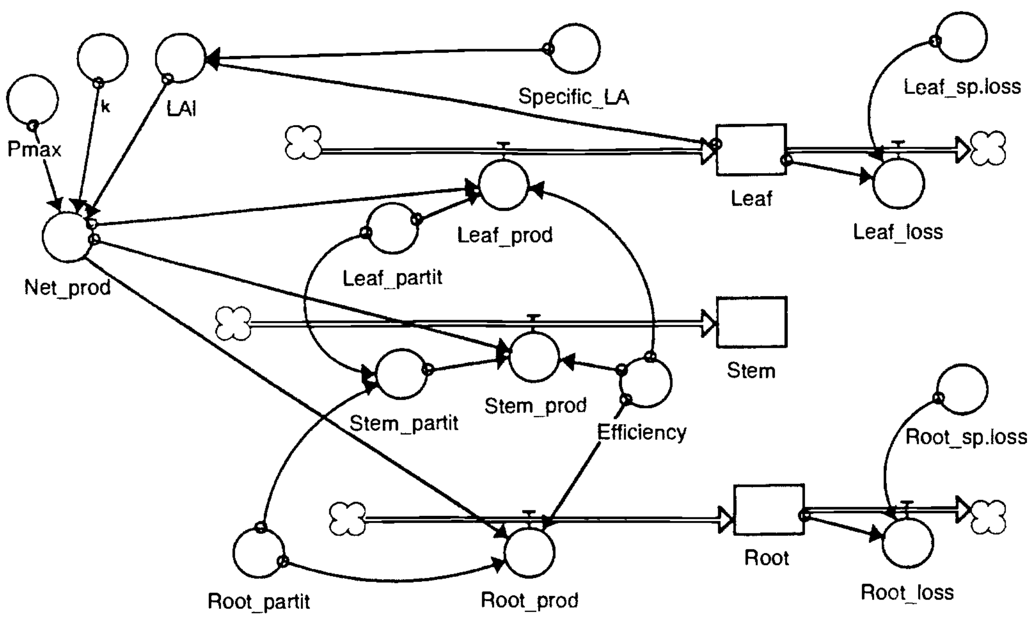


Figure 20. On-screen appearance of a forest model implement in Stella.

Stella is excellent as a teaching tool, although students need to be aware that the compartment-flow diagram is merely a cosmetic interface to underlying differential equations, and that the physical properties of real compartments (e.g. finite capacity, cannot become negative) are not captured. It is also useful for rapid conceptual modelling, say in a short workshop. Ecological papers are appearing that have made use of Stella (e.g. Boyce *et al.* 1991), but it has marked deficiencies which make it unsuitable, in general, as a research tool. These include the absence of any facilities to support disaggregation, and only limited support for model-simulation activities.

(b) Submodel/function diagrams

The use of influence diagrams and submodels as ways of characterizing models has already been discussed. It is quite common for descriptions of models to be presented in these terms. Modelling software based on these ideas enables diagrams to be constructed in which the main symbols represent simple functions or more complex submodels. There are a number of software packages of this form developed in an engineering systems analysis context, but these tend to be based on low-level functions (e.g. a multiplier, an integrator), or use domain-specific modelling elements (discussed below).

Examples of general submodelling packages include:

Extend (for the Apple Macintosh) which supports the creation of a library of submodels, which can be selectively retrieved and linked together. However, the individual submodels have to be programmed in a special-purpose programming language, and the system appears to have no ability to nest submodels in an hierarchical manner.

SIMPLEX-II, described as "a model construction and experimentation environment" (Langer & Schmidt 1987). This supports the notion of a 'model bank', containing models (submodels) which can be combined to make a new model, can be used repeatedly within one model (e.g. two crops could be modelled with the same submodel, using different parameter values), and can be nested to any depth (Figure 21). The environment supports various forms of experimentation with the model, interaction with the model during simulation, and graphical display of results.

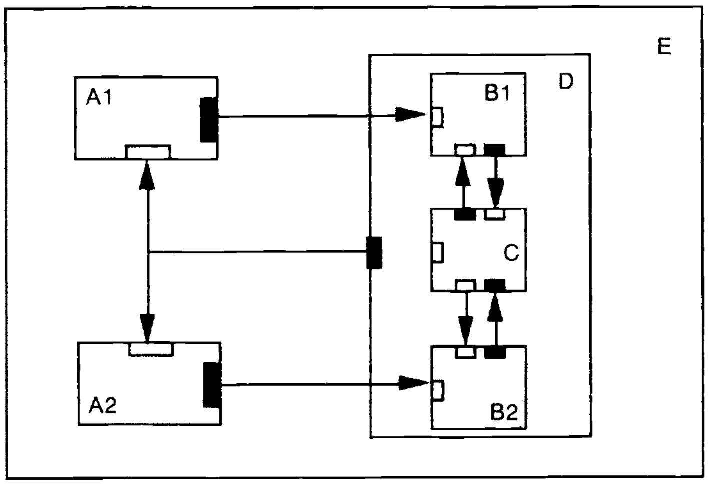


Figure 21. Illustrating the hierarchically-organized nature of a number of interacting submodels using Simplex-II.
Source: redrawn from Eschenbacker & Schmidt 1987.

(c) Domain-specific modelling software

There are numerous examples of software developed within the context of chemical, electrical and electronic engineering which support model construction using elements appropriate to the domain. For example: valves, pipes and tanks in chemical engineering; generators, transformers and motors in electrical engineering; and integrated circuits in electronics (Figure 22).

The possibility exists of adopting a similar approach in agroforestry, since an agroforestry system can be thought of as a number of linked components. This could be a useful way of delivering modelling capabilities to workers who wanted to explore alternative agroforestry system designs (and possibly alternative model formulations), without having to work at a generic modelling level. However, it must be recognized that there is a world of difference between modelling with engineered components (whose input-output properties are well known), and modelling with ecological components where there is often uncertainty about how copmonents function and the way they should be modelled.

VI. Future Needs for Agroforestry Modelling

Previous sections have considered the current state of agroforestry modelling and concluded that:

Some graphical modelling methods have value for focusing on the key features of interaction between two species, for delivering the results of a model in summary form, and as a first step in developing mathematical models.

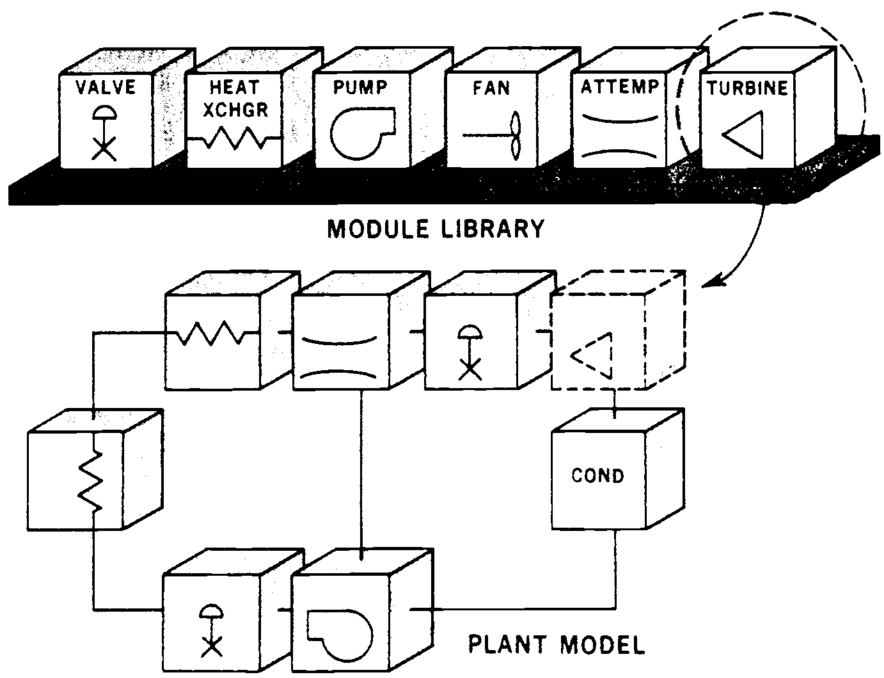


Figure 22. Illustrating the construction of a model using MMS: a domain-specific modular modelling package for electrical engineering.
Source: Anon. 1986.

Qualitative modelling is virtually non-existent in agroforestry, but has considerable potential, without the heavy demands for parameterization of mathematical models.

Most agroforestry-relevant models currently fit closely into the System Dynamics (compartment-flow-influence) paradigm. However, there are a large number of other modelling paradigms of potential relevance, such as object-orientated modelling, which have rarely been used.

Most agroforestry models have little disaggregation, but many models in relevant areas (light interception, pest populations, hydrology) are considerably disaggregated.

Even admittedly-simplified models such as SCUAF are actually quite complex structures.

Agroforestry models tend to be programmed in a conventional programming language (BASIC, Fortran, Pascal). Some are implemented in spreadsheets. Some models relevant to agroforestry are implemented in simulation languages (CSMP, ACSL). There is little use of model-simulation environments or diagrammatic modelling packages.

The programs implementing reasonably complex models are long (thousands of lines) and take a long time to implement (at least months).

When programs are implemented in a conventional programming language, considerable effort may go into peripheral aspects, such as input of data, display of results, and run control.

Model structure is communicated to others through published papers and (less frequently) program listings.

In this section the factors that are likely to diminish the future effectiveness of agroforestry modelling are addressed. The problems faced in modelling agroforestry systems fall into three categories:

—gaps in knowledge about particular processes and relationships
—deficiencies in how particular aspects of agroforestry systems are modelled
—deficiencies in the modelling environment within which models are constructed, used and communicated to others.

The first of these topics was covered in an earlier review paper on ecological interactions in agroforestry (Anderson & Sinclair 1993). In the last section of this review, the deficiencies in modelling particular aspects of agroforestry systems are discussed, and the shortcomings of current modelling environments are considered. Together with the conclusions of the earlier review, these considerations have provided the basis for the formulation of an integrated strategy for modelling and experimentation in agroforestry published in a third paper (Anderson *et al.* 1993).

1. Problems in modelling particular aspects of agroforestry systems

As stated before, models are designed to address certain objectives, and can only be evaluated in relation to those objectives. Anderson & Sinclair (1993) identified over-yielding, reduced variability, and sustainability as the three overriding ecological issues in agroforestry. Most agroforestry models will therefore relate to one or more of these issues. However, within this framework, a particular model may be intended to answer a much more specific question, such as the role of soil fauna in decomposition, the effect of tree planting patterns on light interception by crops, or the effect of different soil conservation or water harvesting measures on rates of erosion. It follows that what is an important modelling feature for one model may be irrelevant for another and that it is impossible to generalize on the modelling features that all models will require. The following discussion, therefore, refers to problems that are important for a significant subset of all agroforestry modelling.

(a) The modelling of spatial geometry

Agroforestry practices are principally classified on the basis of the components involved and their spatial configuration (Figure 23). Agroforestry systems in general are characterized by the great diversity of patterns of spatial heterogeneity involved. Some are regular, on a row or grid basis; others are irregular, in terms of patches of land or scattered trees. This spatial heterogeneity will principally act through light, water and nutrients, but will often be mediated through other aspects (soil organic matter and fauna), and could include other agents (e.g. pest dispersal patterns, allelopathy, soil chemistry). Very few models appear to be designed to handle the types of positive or negative edge effects at the tree/crop interface (Figure 24).

The modelling of spatial heterogeneity in agroforestry-relevant models has been very limited. It may be based on a crude partitioning of an area into the proportion with trees and the proportion with crops or pasture (e.g. Doyle *et al.* 1986), with no geometric representation at all. Light interception models that have been used in agroforestry have investigated light interception by single trees or hedges in a simple 'shadow-casting' manner (Jackson & Palmer 1989; Quesada *et al.* 1989), although a number of general radiative transfer models are available for single tree crowns at various levels of sophistication (e.g. Wang & Jarvis 1990; Mann *et al.* 1979; Charles-Edwards & Thornley 1973). Underground effects (e.g. root plates) have rarely been modelled.

Methods for representing the branching pattern of trees and root systems are being developed, and have obvious application both in terms of adaptive responses to light regimes, physical abrasion, etc. at the canopy level, and patterns of nutrient competition at the root level. The combination of the three dimensional modelling of branching structure with ray tracing algorithms could provide effective light interception models. Grid-square spatial disaggregation of an area is rare (largely restricted to so-called gap models of forest dynamics and hydrological models), and there appear to be no instances of more sophisticated methods, such as hexagons or polygons on a within-plot basis. There is a need for tools to facilitate the inclusion of spatial aspects in agroforestry models.

(b) The representation of individual objects

There appear to be very few examples of agroforestry-relevant models that include an explicit representation of individual objetcs, such as tree crowns or crop plants. Those that have been made do not exploit the object-oriented paradigm, which is specifically intended for the representation and dynamic creation and deletion of individual objects. Papers demonstrating the approach have appeared for large mammals (Folse *et al.* 1989), host-parasitoid systems (Baveco & Lingeman 1992) and plants (Sequeira *et al.* 1991), and these justify the view that this modelling paradigm could be a very natural way of modelling agroforestry objects such as individual trees, crop plants, hedgerows, or pest animals. There is a need to explore the value of this approach.

(c) Probabilistic methods

An alternative approach to the representation of individuals is to reason in a probabilistic way about the behaviour of a population of individuals, as Oker-Blom (1986) has shown for leaves and shoots in tree canopies. The approach has considerable promise for overcoming the averaging problems of aggregated models while not making the huge computational demands of highly disaggregated models.

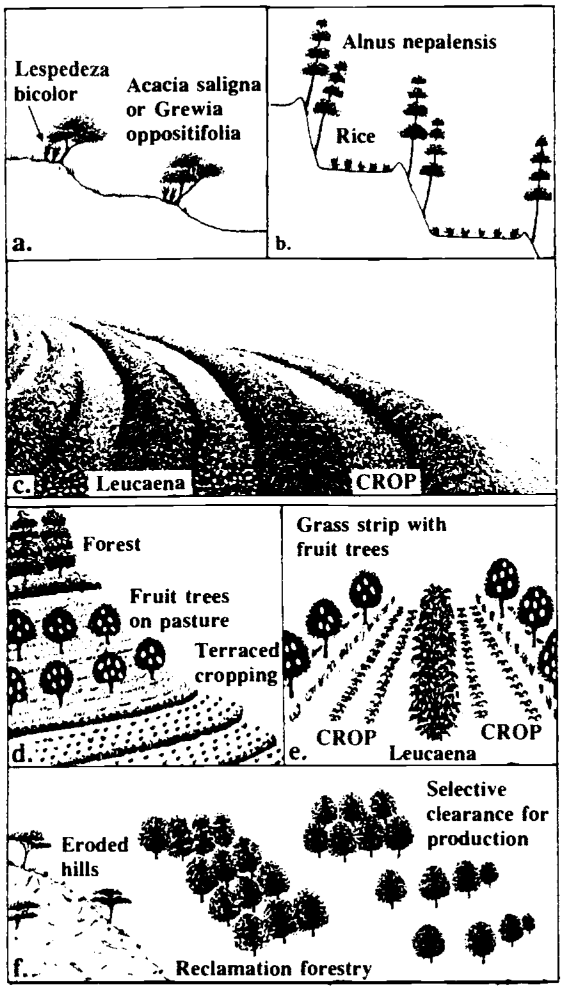


Figure 23. Examples of agroforestry patterns for erosion control: (a) trees on terrace risers, Ethiopia (after a recommendation for trials in Carlowitz 1986); (b) trees on risers of irrigated terraces, Nepal; (c) hedgerow intercropping with *Leucaena* laid out on a slope (after a photograph in Kang *et al.* 1984); (d) model for land use as an alternative to shifting cultivation, north-east hills region, India; (e) plan view of suggested land use on slopes, combining barrier hedges with trees on grass barrier strips, Philippines (after Celestino 1985); (f) possible development of reclamation forestry into productive use by selective clearance of contour strips (based on Poulsen 1984; Young 1985).
Source: Young 1989a.

(d) Combining the effect of multiple influencing factors

Informal analysis of the factors influencing some process frequently lead to a list of several such factors. Rarely is a theoretical basis available for combining the influence of these factors (e.g. the Penman-Monteith formula). The only alternative is to use some fairly arbitrary method, such as the notion of limiting factors (e.g. nutrients), or multiplicative/additive combination. There is a need to develop guidelines on the appropriate choice of method, and to facilitate the rapid exploration of alternative methods.

(e) The degree of disaggregation

Quite apart from the need for spatial disaggregation, the modeller needs to choose an appropriate degree of disaggregation more generally. For example, for pest populations, what degree of lumping of species, and use of age classes, is appropriate? Some studies have explored this issue from a theoretical point-of-view (e.g. Iwasa *et al.* 1987), or by simulation with a particular system. There is a need to produce definite guidelines on this aspect.

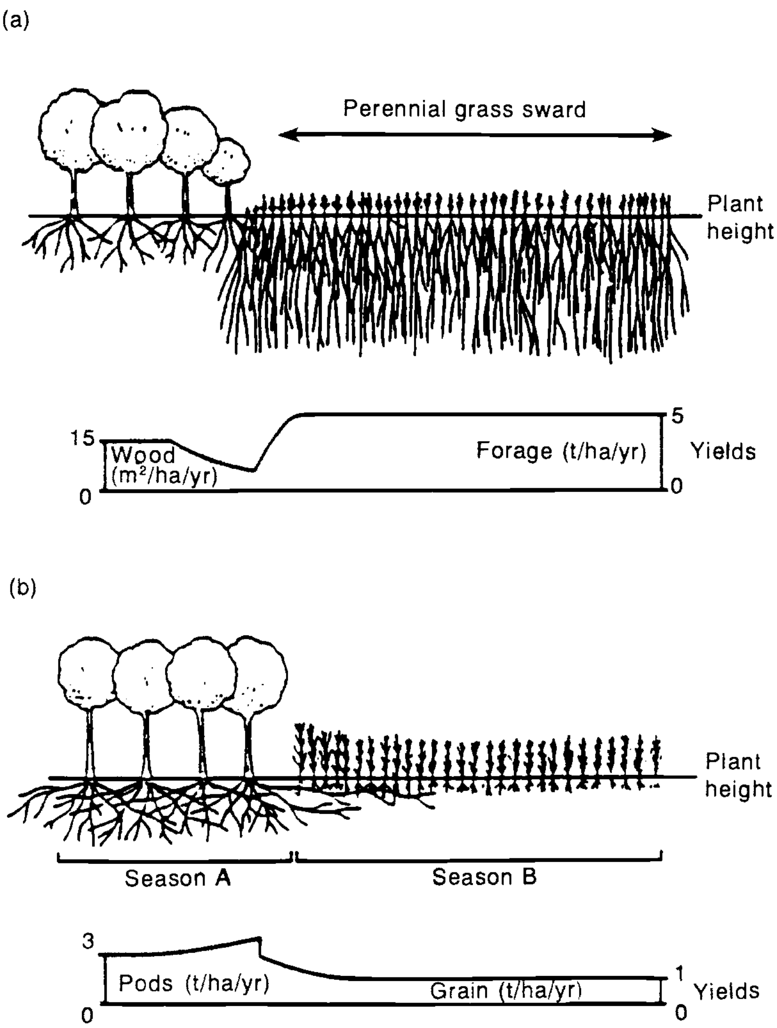


Figure 24. Section across the tree-crop interface, showing (a) inhibition of tree growth by a deep-rooting perennial, and (b) facilitation of the *Acacia albida*/grain crop interface.
Source: Cannell 1991.

(f) Scaling across levels of organization

Scaling refers to the manner in which understanding obtained at one level of organization is applied at a higher level (see Jarvis & McNaughton 1986). It has a number of aspects which are currently poorly understood, including the change in the nature of some relationship (e.g. a curvilinear leaf light response curve becoming linear at the stand level), and the problem of how to undertake temporal or spatial averaging of inputs into non-linear response curves. An example is the importance of sun-flecks and penumbra in photosynthesis. Complications arise here both spatially (an inner-canopy leaf may in fact be in unobstructed light), and temporally, giving rise to the problem of complicated responses to transients (Anderson 1991). The non-linearity of the light-response curve means that calculations based on mean light levels using the turbid medium approach will, in general, consistently over-estimate photosynthesis compared with those that capture the full-light/penumbra/shade distinction.

2. Shortcomings of current modelling environments

(a) The cost of model development

Reynolds & Acock (1985) give estimates of the cost of developing and implementing a single crop growth model. At 1985 prices, the total came to an estimated $1 200 000 including $150 000 for the literature search and $150 000 for programming. The programming costs are not surprising when one considers the size of typical agroforestry-relevant models. SCUAF (Young & Muraya 1991) is implemented as a Pascal program of about 7000 lines and MAESTRO (Wang & Jarvis 1990) as a Fortran program of around 3000 lines. By any standard, this represents a considerable programming effort. Clearly, it must be desirable to devise ways of reducing these costs.

(b) Modification of models

The ability to modify models relates to the extent to which models can be altered to reflect a changing awareness of the importance of various factors in addressing the objectives of the model or be adapted to slightly different objectives than those for which they were designed. The ease of modification has a direct bearing on the extent to which models can be used and shared amongst researchers, and, therefore, on the efficienct use of the original development costs. Modification can apply at a variety of levels, and becomes increasingly difficult as one moves through the levels. At the lowest level, it can involve a change to the value of some numeric constant that happens to be built into the program, as opposed to being input from a data file by the user. This is easy to do, though it does require the ability to edit the program source file. Modifying an equation in the model is somewhat more difficult, and is certainly a programming task. It may have implications for other parts of the program, such as the need to alter the parameter read-in section. At higher levels, adding or removing processes or components is a reasonably major re-programming activity, while changing the substructural representation of some component (such as representing the soil in layers) may have implications that permeate through the whole program, and take weeks to implement. The consequences of the difficulties of modification are that models are often not altered, with model assumptions becoming ossified in the program implementation, or else they are modified in certain restricted ways involving a considerable investment in programming time.

(c) Comprehension of models

It is often difficult for people not involved in the development of a model to fully comprehend it. The ability of others to comprehend a model has had very little investigation, though Uschold (1990) explores the use of a formal, logic-based method for this task. At the heart of the problem is the fact that models are communicated through published descriptions, but implemented as computer programs. This opens the door to three dangers.

Incompleteness: the published description is rarely a complete description of the implemented model, simply because of space limitations in print.

Ambiguity: the precise form of the model may not be clear from the published description. For example, Holt *et al.* (1987) describe a model of brown planthopper dynamics: the text implies that they used daily age classes, while a figure implies that each life stage (encompassing several days) is represented by a single state variable.

Inconsistency: the published description may be out-of-step with the (current) implementation of the model. This is almost inevitable, given the fact that the published description is at best merely a snapshot of the model at a particular point in time.

(d) Duplication of programming effort

There is considerable duplication of programming effort between different modelling groups, and relatively little re-useability of implemented code. This applies to two main areas:

Duplication of programming effort for particular submodels. It is rare for the program source code to be published for submodels (although Nikolov & Zeller (1992) provide an example of where it was done). For simple submodels, an algorithm may be published, which then has to be translated into a programming language, while it appears rare for the program source code to be exchanged for more complex submodels.

Duplication of programming effort for model support tasks. Most model-implementing programs include the model-support tasks as part of the complete program: handling input, display of model results, interaction with the user during a run, etc. There is considerable potential to reduce this duplication by, for example, recognizing the distinction between the implementation of the model itself and the environment within which the model is used. Note that this problem is much less acute in the case of models implemented within spreadsheets, simulation languages, or modelling packages, since these tend to provide generic features for interacting with the model. Conversely, the graphical features of modern computers open up the possibility of generating realistic images of the dynamic state of actual trees, crops and soil profiles, creating a potential demand for generic agroforestry display software.

(e) The difference between models as research tools and their use in decision-support

There is a large gap between using a model in research, and its delivery as a decision-support tool. Not all agroforestry modelling has to be justified in terms of an applied role in decision-support but there can be little doubt that agroforestry decision-support systems will incorporate models. These models will need to be packaged in a way that enables people with little formal scientific training or computer literacy, such as extension workers, to use them. There is little software at present for packaging scientific models for this role. That which exists tends to be very specific to one domain.

(f) Criteria for model formulation

There is a need to develop criteria for model formulation in terms of the degree of explanatory content of agroforestry models and the balance between their flexibility and their application to particular situations. Consideration needs to be given to the 'empirical vs. mechanistic' choice. The conventional view is that empirical (statistical, curve-fit) models are very site specific, while mechanistic (process-based) models can be applied to a range of sites. However, it is not immediately obvious that a six-parameter polynomial regression model relating crop biomass to time of year and soil moisture is any more (or less) site-specific than a mechanistic model of the same problem that also has six parameters. It may be easier to determine the parameter values in the latter model, but that is quite distinct from the greater generality claimed for mechanistic models. Criteria also need to be developed and agreed on what constitutes an appropriate agroforestry model. Lip service is paid to the need to meet objectives, but what does this mean in practice? One danger is attempting to incorporate everything that is known about how the system functions. While this contradicts the view that models should be a simplification of reality designed to meet certain objectives, it is implicit in, for example, the recommendations for 'comprehensive' agroforestry models (Working Group 2 report in Reifsnyder & Darnhofer 1989) or in tabulations of important factors in agroforestry (e.g. Young 1989b).

(g) Model integration

It is difficult to integrate existing models of parts of agroforestry systems into larger models. This review of agroforestry-relevant models has demonstrated that there has been a tremendous amount of modelling of the individual components of agroforestry systems (light interception, crop growth, soil moisture dynamics, pest dynamics, etc.), contrasting dramatically with the few agroforestry system models. Those whole system models that do exist tend to treat the physical and biological processes in a simple way. There would be considerable utility in integrating models of component processes as submodels in larger agroforestry models where mechanistic detail is required. Currently, such integration is a major programming activity. For example, Caldwell & Hansen (1990) discuss the problems involved in integrating CERES-maize and SOYGRO to produce the CROPSYS inter-cropping model, and that involved two similar models produced within a common programme (IBSNAT). These problems are compounded when the individual (sub)models have been programmed in different languages in different programming styles.

In addition to the programming difficulties of combining diverse models, there are also more fundamental modelling issues. For example, consider the problem of combining a crop growth model with a tree growth model. The crop growth model probably assumes horizontal spatial homogeneity, but when combined with the trees, edge effects may need to be captured at the tree/crop interface. The crop model may in principle include all the factors that are thought relevant (e.g. the effect of light, water and nutrients on crop growth), but not in a way that captures the spatial heterogeneity that is required to represent interactions in agroforestry.

VII. Conclusion

The complexity and interdisciplinary nature of agroforestry creates major problems that hamper the construction, use and dissemination of relevant models, and thereby restrict both the cost effectiveness and scientific rigour of modelling in agroforestry. Cost effectiveness is affected by the time taken to implement individual models, the lack of re-useability of model components, and the failure to maintain completed models as a resource. The scientific rigour of the modelling process is reduced by the difficulty of comprehending other people's models, the lack of correspondence between model description and implementation, and the virtual impossibility of exploring alternative but equally plausible model formulations. Many of these problems stem from the use of conventional programming languages for model implementation. The effectiveness of agroforestry modelling could, therefore, be increased by the development of a modelling environment that enabled interactive construction and modification of models by researchers, as already exists in other disciplines, such as computer-aided design in architecture and engineering. Appropriate software for agroforestry would need to include facilities for compartment-flow modelling, the development, modification and linkage of submodels, and spatial disaggregation. The specifications for an appropriate modelling environment and its central role in an integrated strategy for modelling and experimentation in agroforestry are set out by Anderson *et al.* (1993).

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