3 Models of Below-ground Interactions: Their Validity, Applicability and Beneficiaries

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Key questions

1. What lessons can be learnt from modelling mixed-species and monocrop systems?
2. What models are currently available in the public domain?
3. How valid and reliable are existing models for complex agroecosystems?
4. Who is likely to use and benefit from explicit models and what contribution can they make?

3.1 Introduction

We all use models, to such an extent that we may not even think of them as models at all. Each one of us carries around in our mind a mental model of the way we perceive the world to work – this model is an abstraction of what we call 'reality', although philosophers would argue whether an objective reality even exists. We are also surrounded by visual models, such as maps or pictures, and are likely to use abstract arithmetical or algebraic models in our daily activities. As children, we probably played with models of cars or people. Computer simulation models are just another type of model, consisting of abstract mathematical representations of processes occurring in nature. The feature common to all these different types of models is their ability to provide a way of understanding the world around us, allowing us to interact with it.

Since the 1960s, many simulation models have been constructed that describe the way different crops grow and develop in relation to their physical environment. The ways in which these models have been applied in relation to tropical agriculture have recently been reviewed by Matthews and Stephens (2002). So far, greatest use has been made of such models by the research community as tools for organizing knowledge gained in experimentation. Simulation models are often also put forward as potential tools for decision support; certainly previous experience has shown that their use in this way has had major impacts in the areas of irrigation scheduling and pest management, in that they have changed the growers' way of thinking (see Cox, 1996). However, the original aim that underlies their use as operational decision support systems (DSSs) has not always been achieved – as soon as farm-

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ers learn the optimal management regime for their crops, they have no further use for an operational DSS. Models also have a useful role to play as tools in education, both as aids to learning the principles of crop and soil management, and also in helping students to develop a 'systems' way of thinking, to enable them to appreciate that their speciality is part of a larger system (Graves *et al.*, 2002).

The number of models that describe processes in mixed-species cropping systems is substantially lower than the number of models that describe monocrop systems, partly because of their increased complexity, and partly because modelling efforts have focused on developed agriculture where monocrops are the norm. The productivity of mixed-species systems is the result of the many interactions between the different plant species in the system and their environment. If our aim is to increase the productivity or stability of such systems, it is logical to, first, understand and quantify these interactions, particularly those for water and nutrients and, secondly, to use this understanding to make changes to a particular system to achieve our aims. For example, agroforestry is not beneficial in all situations, and competition between trees and crops can result in reduced crop yields. Moreover, the long growing period of trees means that it is time-consuming, and hence expensive, to find out whether a particular system is likely to be successful or not. Models provide a way of evaluating the likelihood of success of these changes, both before the real system is interfered with and within a reasonable timeframe.

In other chapters of this book, the current state of our knowledge of below-ground interactions in mixed-species production systems has been described and, in some cases (e.g. Chapter 10), this knowledge has been incorporated into simulation models. Drawing on lessons learnt from the modelling of both mixed-species and monocrop systems, in this chapter we discuss some of these models and consider how valid and reliable they are, who is likely to use and benefit from them, and what contribution such models can make.

3.2 Models Incorporating Below-ground Interactions

Various models that incorporate simultaneous below-ground interactions between different plant species, and whose descriptions have been published in the literature, are given in Table 3.1. We have purposely not included models in which the below-ground interactions are temporal in nature (e.g. crop rotations), as any two or more crop models with soils components could, in principle, be run sequentially in order to simulate these types of system. Instead, we have focused on models that have addressed direct below-ground interactions between two or more species. The list is not intended to be exhaustive, but is rather intended to show some of the types of models available. These are discussed below.

3.2.1 SCUAF

SCUAF (Soil Changes Under AgroForestry v4.0, Young *et al.*, 1998) is a nutrient-cycling model with an annual timestep, and is used to predict medium-term changes (10–20 years) in soil properties under specified agriculture, agroforestry and forestry systems within given environments. The model includes soil erosion, soil organic matter, and nitrogen and phosphorus cycling processes, as well as competition for nutrients between trees and crops. Although plant growth is included, this is specified by the user as an input in the form of annual increments in biomass. Water uptake and use is not simulated, due to the low resolution of the timestep. An example of this model's use is the analysis made of the economics of hedgerow intercropping in the Philippines (Nelson *et al.*, 1997).

3.2.2 WaNuLCAS

WaNuLCAS (Water, Nutrient, Light Capture in Agroforestry Systems; van Noordwijk and Lusiana, 2000) simulates tree–soil–crop interactions in a range of agroforestry systems in which trees and crops overlap in

Table 3.1. List of some models incorporating simultaneous interspecific below-ground interactions.

Model name	Reference	Scale (subplot, plot, farm, region, country)	Time-step	Dimensionality (1, 2, 3)	Strengths	Known limitations	Target users	Examples of applications
SCUAF	(Young *et al.*, 1998)	Plot	Yearly	1	Simplicity and ease of use; includes SOM, N and P dynamics	Simplistic simulation of plant growth	Researchers	Bioeconomic modelling (Nelson *et al.*, 1997)
WaNuLCAS	(van Noordwijk and Lusiana, 2000)	Plot, landscape	Daily	1, 2	Multispecies systems, interactive competition for H_2O, N and P	Complex; tree canopy development; no nitrification module	Researchers	Safety-net or filter efficiencies (Cadisch *et al.*, 1997, and Chapter 10, this volume)
HyPAR	(Mobbs *et al.*, 1998)	Plot	Daily	1, 2, 3	3-D simulation of light interception, below-ground competition		Researchers	Characteristics of successful agroforestry systems (Cannell *et al.*, 1998)
HyCAS	(Matthews and Lawson, 1997)	Plot	Daily	1	Includes SOM, N and P dynamics; compatible with DSSAT databases	Homogenous canopy, not validated, not user friendly	Researchers	MSc projects (Cranfield University)
COMP8	(Smethurst and Comerford, 1993b)	Root/plot	Variable	2	Includes P and K		Researchers/ forest industry	Tree/weed competition (Smethurst *et al.*, 1993)
WIMISA	(Mayus *et al.*, 1998a)	Plot	Daily	2	2-D compartments of soil water calculations	Does not include nutrient limitations or soil erosion; LAI development and microclimate needs improving	Researchers	Tree–crop interactions in windbreaks in Sahel (Mayus *et al.*, 1998b)
APSIM	(McCown *et al.*, 1996)	Plot	Daily	2	Modularity due to object-oriented techniques; components well tested	Mixed-species model not validated; source code not available	Researchers, extension agents, consultants, farmers	Cropping systems, agroforestry, windbreaks (Huth *et al.*, 2002)

Continued

Table 3.1. *Continued.*

Model name	Reference	Scale (subplot, plot, farm, region, country)	Time-step	Dimensionality (1, 2, 3)	Strengths	Known limitations	Target users	Examples of applications
CropSys	(Caldwell and Hansen, 1993)	Plot, farm	Daily	1 (canopies are 2-D)	Individual crop models well tested; compatible with DSSAT databases	Maximum of two species; not well validated	Researchers, educators	
ALMANAC	(Kiniry *et al.*, 1992)	Plot	Daily	1	Process-based, but designed for practical applications	Two species are simulated sequentially in each time step	Researchers	Crop–weed interactions (Debaeke *et al.*, 1997)
GAPS	(Rossiter and Riha, 1999)	Plot	Daily, some processes <daily	1	Modularity due to object-oriented techniques	Not widely tested	Researchers, educators	

SOM, soil organic matter; LAI, leaf area Index; DSSAT, Decision Support System for Agrotechnology Transfer.

space and/or time. It runs on a daily timestep, and has a four-layer soil profile and four spatial zones. Within each of these layers and zones, the water, nitrogen and phosphorus balance is calculated, including uptake by a crop (or weeds) and up to three different types of trees. The model is written in the STELLA modelling environment, making it easier for users to modify parameters and add extra model components than would be the case for models developed in traditional programming languages. WANULCAS has been used both for teaching and research (e.g. Cadisch *et al.*, 1997; see also Chapters 9 and 10, this volume).

3.2.3 HYPAR

HYPAR (Mobbs *et al.*, 1998) is a combination of the Hybrid tree model (Friend *et al.*, 1997) and the PARCH crop model (Bradley and Crout, 1994), and can be used to simulate tree–crop interactions in agroforestry systems under a range of soil, climate and management conditions. The model operates on a daily timestep, and simulates the biomass production and partitioning of both the tree and the crop; water uptake and use (vertical redistribution of soil water, infiltration, drainage and soil water evaporation); and competition for nitrogen between the two species. The current version (v3.0) includes routines to represent disaggregated canopy light interception and 3-D competition for water and nutrients between the roots of trees and crops (Chapter 10, this volume). An example of its use is the analysis of the rainfall requirements for successful agroforestry systems made by Cannell *et al.* (1998).

3.2.4 HYCAS

The HYCAS model (Matthews and Lawson, 1997) simulates competition for resources (light, water, nitrogen and phosphorus) in tree–cassava agroforestry systems on a daily timestep. The model is based on two other models, the HYBRID tree model (Friend *et al.*, 1997) and the sole-crop GUMCAS cassava model (Matthews and Hunt, 1994), which are integrated in a way similar to that used to integrate the two different models used in the HYPAR model. The use of the GUMCAS model structure as a base provides compatibility with the DSSAT (Decision Support System for Agrotechnology Transfer) standard format for input and output files (Hunt *et al.*, 1994), and hence access to the large database of weather and soils data compiled by the IBSNAT project (International Benchmark Sites Network for Agrotechnology Transfer; Tsuji and Balas, 1993) and by other modelling groups. To our knowledge, apart from its use during initial testing and verification, the HYCAS model has not been used for any specific application.

3.2.5 COMP8

COMP8 (Smethurst and Comerford, 1993b) simulates, based on solute transport theory, nutrient uptake by both competing and single root systems. The model calculates the volume of soil allocated to each root system and the concentrations of solute at the root surfaces. It also allows each root system to have a different absorbing power, as experimental evidence has indicated that uptake per unit surface area of root varies between species (Smethurst and Comerford, 1993a). The model was used as a research tool to study competition for P and K between pine trees and various weeds (e.g. Smethurst *et al.*, 1993), but does not seem to have been used since then.

3.2.6 WIMISA

WIMISA (WIndbreak MIllet SAhel; Mayus *et al.*, 1998a) simulates crop growth as influenced by trees growing as windbreaks. The model is two-dimensional, and simulates the growth of a number of crop rows as a function of the local incident solar radiation and soil water. Soil water flow is simulated in two dimensions, to account for horizontal gradients due to different water extraction by trees and crop and horizontally varying evapotranspiration. Competition for water is expressed by distributing available soil water between trees and crop in proportion to their uptake rates in a non-competitive situation. Water uptake is calculated on the basis of root length density distribution. The model has been used to analyse experimental data from windbreak/millet experiments in Niger (Mayus *et al.*, 1998b).

3.2.7 APSIM

The APSIM (Agricultural Production Systems Simulator) suite of crop simulation models began life as a collection of point-based models for sole crops and pastures (McCown *et al.*, 1996). Some initial attempts were made to link these individual crop models together, in order to study competition for light and soil resources in intercropped plant species (Carberry *et al.*, 1996). More recently, a tree stand module has been added (Huth *et al.*, 2001) and, with developments in the intermodule communication procedures that allow the simulation of spatial entities, work has started on linking crop and tree modules together to simulate agroforestry systems (Huth *et al.*, 2002). This has been done using object-oriented programming techniques, with different crop rows and soil compartments being represented by different instances of the same submodel classes. Simple rules for partitioning tree transpiration demand between soil compartments are based on the soil water supply of each compartment, and on the assumption that tree root density decreases proportionally to the square of the distance from the tree. Although the approach gives realistic predictions of the behaviour of each of the components, it has yet to be validated against observed data (Huth *et al.*, 2002).

3.2.8 CropSys

CropSys (Caldwell and Hansen, 1993) is a process-level simulation model that is designed to predict the performance of multiple cropping systems across genotype, soil, weather and management combinations. The central core of the model is a soil module that simulates the basic processes of the water balance and nitrogen balance on a daily timestep continuously for long time periods. Crops come and go, and are represented by crop modules based on the CERES and SOYGRO families of crop models (maize, rice, wheat, barley, sorghum, millet and soybean). Crop processes include light interception and photosynthesis, dry matter partitioning, phenology, root system development, and growth in canopy dimensions and leaf area. When two species share the field at the same time, the model calculates competition for light and competition for water, nitrate and ammonium by soil layer. Input and output files follow the DSSAT standard format definitions. CropSys has been further developed into an object-oriented hierarchical framework called JanuSys (Caldwell and Fernandez, 1998).

3.2.9 ALMANAC

ALMANAC (Agricultural Land Management Alternatives with Numerical Assessment Criteria; Kiniry *et al.*, 1992) is based on the EPIC model (Williams *et al.*, 1984), and simulates plant growth, water balance and nutrient balances for two or more competing species. Competition for soil water and nutrients is based on the current rooting zone of each species and on the demand exerted by each species. If the available water in the rooting zone is less than the potential evapotranspiration, the species planted first has first access to, and will fulfil its needs from, what water is available; the second-planted species can use what remains. Among other things, ALMANAC has been used to investigate maize–soybean intercrops (Kiniry and Williams, 1993) and crop–weed interactions (Debaeke *et al.*, 1997).

3.2.10 GAPS

The GAPS (General-purpose Atmosphere–Plant–Soil Simulator; Rossiter and Riha, 1999) model simulates intercrop competition for light and water between a number of species. It contains a number of different crop modules that are based on existing, published, models, and also a module for fast-growing trees. Communication between modules is handled by a simulation driver. The various crop models within GAPS have different ways of calculating the amount of water extracted from the soil. In the simplest calculation method, the amount of plant-available water in each soil layer is supplied in proportion to the crop's total root length density in that layer. In a second method, the amount of plant-available water is supplied in proportion to an exponential function that decreases with depth; in a third method, the crop equilibrates its leaf and water potentials with the soil water potential and takes up water according to the potential gradient. In each approach, the amount of available water is reduced as it is taken up by each crop in turn. GAPS is used as a research and teaching tool.

3.3 Validity, Reliability and Applicability

3.3.1 Model limitations

The models described above all have limitations that may restrict their usefulness for a particular application, partly because they are, by definition, a simplification of a complex reality, but also because our knowledge of all the processes involved is incomplete. Most models, for example, assume that roots are distributed regularly in some way – a common assumption is that root density declines exponentially with depth. In reality, this is often not the case, as roots preferentially follow cracks in the soil, and dry, infertile or compacted soil zones restrict root growth while compensatory root growth occurs elsewhere. Failure to take into account the clumping of roots will cause an overestimate of the ability of the root system to extract water (Passioura, 1983). Similarly, Comerford *et al.* (1994) found that K uptake was overestimated unless the root spatial pattern was included in the model. The plasticity of the root system shape and size, particularly as it is affected by the presence of roots of other species, is also not incorporated into most models. One root system may restrict the growth of another, through competition for water and nutrients, or through allelopathic influences.

Additionally, not all of the roots in a root system may be active at any one time in terms of water or nutrient uptake. Robertson *et al.* (1993), for example, estimated that only 11% of wheat roots were active in terms of nitrate uptake even when no nitrogen fertilizers were applied. Similarly, water-uptake models based on the consideration of plant and soil water potentials predict that water should be taken up at all depths in proportion to root length density. However, observations show that it is actually often taken up preferentially from the surface layers, even when the soil, at depth, is fully wetted and there are roots present there. It would seem that plants have some mechanism for controlling the activity of different parts of the root system over and above the physical processes that govern water and nutrient uptake.

However, it should be remembered that these limitations do not necessarily prevent a model from being used for a particular purpose, provided that the limitations are taken into account when interpreting its output.

3.3.2 Do models reflect conditions in farmers' fields?

Apart from the limitations of below-ground models that were discussed above, there exists the question of whether models adequately reflect conditions in farmers' fields in developing countries. Most models are developed using data from controlled experiments. Indeed, this is an essential part of the research process – in order to understand the influence of a particular factor, other factors must be held constant. However, the real situation in agroecosystems is more complex, and often involves a large number of factors all interacting together. The challenge for modellers, therefore, is to be able to capture this complexity in their models.

Reviewing the SARP (Systems Analysis for Rice Production) project at the International Rice Research Institute, Mutsaers and Wang (1999) noted that most of the crop simulation models used were originally developed for monocrops grown under highly uniform conditions (resulting from high levels of external inputs) and that the focus was on maximizing yield. As such, they were not well equipped to deal with cropping systems in lesser developed countries (LDCs), the characteristics of which include

- limited control by the farmer of factors determining production (including water);
- management practices that are often aimed at risk reduction rather than yield maximization;
- limited or no use of external inputs;
- high within-farm and within-field soil variability;
- high potential for weed and pest infestation;
- cultivation of mixtures of species.

The modelling of mixed-species systems, particularly in relation to the below-ground interactions described in this book (e.g. WANULCAS, Chapter 10, this volume), goes some way towards addressing the last two characteristics listed. However, the other points made by Mutsaers and Wang (1999) remain valid; most crop models, for example, have been developed for conditions of high-input agriculture. Thus, practices that are common in developed countries (DCs; e.g. fertilization and irrigation) are included in the models, but practices common in LDCs (e.g. green-manure systems) are not. The widely used DSSAT crop models, for instance, recognize a range of different fertilizer types, but lack detailed soil organic matter (SOM) routines, which are crucial when describing low-input systems, in which most nutrients taken up by plants are derived from the decomposition of crop residues or SOM, rather than from applied fertilizers. The soil N transformation submodel in all of the DSSAT models is based on that used in the PAPRAN pasture model (Seligman and van Keulen, 1981), from which it was adapted to work with crop models (Godwin and Jones, 1991). This SOM/residue module assumes only two OM pools, a fresh organic matter pool (e.g. crop residues, etc.) and an older humic pool, but does not differentiate between very old and more recent fractions of this humic pool. Similarly, it does not include the possibility of a litter layer on the soil surface, and cannot, therefore, describe systems in which large amounts of organic material accumulate without physical incorporation into the soil, such as, for example, green manuring or forest systems. For this reason, a new SOM/residue submodel, based on the well-tested CENTURY soil organic matter model (Parton *et al.*, 1988; Kelly *et al.*, 1997), was recently added to the DSSAT models (Gijsman *et al.*, 2002a). Figure 3.1 shows the significant improvement in the ability of the new model to predict changes in soil organic carbon evident in a 40-year dataset from Rothamsted in the UK.

Thus, it is important that the development and use of models for predicting the functioning of agroecosystems in LDCs do not perpetuate a research tradition that may be more relevant in orientation and method to agriculture in DCs, or to richer farmers in LDCs who can afford to use intensive agricultural management practices. Scientists developing and using models for tropical agricultural systems need to make the conceptual links that will make their models relevant to the conditions that occur in the fields of resource-poor farmers.

3.3.3 Long-term processes

In order to assess the degree of sustainability possessed by a particular system, there is a need to quantitatively understand how the processes determining production interact with soil characteristics, environmental conditions and management practices. The main limitation attached to the use of process simulation models for the analysis of long-term trends is that they have not yet been thoroughly validated, particularly over a long enough time-span to judge their long-term behaviour. This is partly due to the shortage of good-quality long-term data, although such experiments do exist in the UK (e.g. Rothamsted, ~ 140 years), the USA and elsewhere, and can give valuable insights into soil fertility issues and the sustainability of crop yields. However, these experiments are the exception rather than

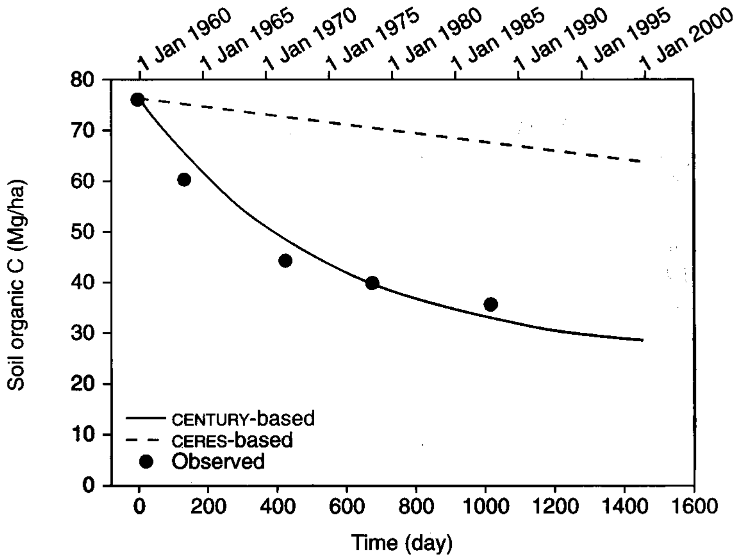

Fig. 3.1. Soil organic carbon content of the 0–23 cm layer of the soil in the Rothamsted Highfield bare-fallow experiment (Jenkinson *et al.*, 1987), as simulated with the CERES-based (dashed line) and CENTURY-based (solid line) SOM/residue modules.

the rule, and, to our knowledge, none have been run in developing countries. They also have their limitations: they are laborious and time consuming, often the many variables needed to validate the models thoroughly have not been measured, and they generally take too long to give results (in relation to the timeframe available for making decisions). Moreover, variability in environmental conditions makes it difficult to extrapolate specific results from one time and place to other environments (van Keulen, 1995). Despite these problems, recent efforts have been made to compare a number of soil organic matter models against data from long-term field experiments (e.g. Smith *et al.*, 1997a).

A second limitation to the use of long-term models for tropical agroecosystems is our incomplete knowledge of many of the biophysical processes underlying these systems, or our inability to incorporate these processes into the models. Most crop models were originally designed to describe crop growth and soil processes over one season, and the relatively simple relationships generally employed are usually adequate for this time period. However, we just do not know whether all of these relationships are sufficient to describe soil changes over much longer time periods. Error propagation within the models may be another potential problem – a small error may be relatively unimportant over a single season, but over several seasons it could accumulate and result in a substantial error at the end of the run. This is clearly demonstrated in the comparison of the CERES-based simulation with data measured over 40 years (Fig. 3.1). So far, little work has been done to investigate the magnitude of such errors.

3.3.4 Spatial variability

Spatial variability is an inherent characteristic of tropical agroecosystems. Specific agronomic practices further increase spatial variability (e.g. by nutrient transfer from grass strips to tree lines in orchards, tropical hedgerow intercropping, or by injection of slurry or fertilizer into the soil). Animals also increase spatial variability – often they have preferences for certain spots (e.g.

shade or near a water source). Many of the management decisions made by small farmers living in heterogeneous environments make use of spatial variability on their farms, such as growing different crops on different patches of land, abandoning part of their land, or focusing their efforts only on those patches with the highest returns to investment of labour or inputs (van Noordwijk *et al.*, 1998e).

Most of our current models are one-dimensional (i.e. vertical) and do not handle spatial variability well, if at all. There is a clear need to develop existing models further, or to construct new ones, in order to address this limitation. Unfortunately, the structure of many existing models does not facilitate transformation to spatially explicit versions, as their linear nature restricts them to being run in sequence many times, in order to simulate each patch of land in turn (e.g. Basso *et al.*, 2000). This makes it difficult to simulate simultaneous interactions between patches of land (e.g. soil, or water flow down a gradient). The easiest course of action in such cases is usually to build a new model from scratch. Conversion of a one-dimensional model to a two- or three-dimensional one would be made much easier by the use of a 'systems dynamics' structure (e.g. Jones *et al.*, 2001), in which the calculation of rates of change of state variables in the model are separated from the integration (or updating) of these variables.

3.3.5 Data requirements

Simulation models describing crop growth generally need input data on weather and soil conditions, crop characteristics, management information, and possibly on the occurrence of pests and diseases. Complex ecosystem models may require even more input data. Some of these data will be the same over large areas, whereas some will vary at much smaller scales. Obtaining such data at a scale which is sufficiently detailed that it represents the actual variability existing in a field or a region can be difficult and time consuming, and may deter potential users of a model, particularly if they want quick answers. For new sites or plant species, such data may not even be available. Thus, there is a need on one hand for databases that can provide inputs for a diverse set of conditions and cropping systems, and on the other there is a need for approaches that facilitate an estimation of parameters from more easily measurable characteristics.

For weather variables, equations have been developed that give estimates of conditions at a given location, based on the location's coordinates and altitude, and interpolation of weather data from several nearby weather stations (Jones and Thornton, 2000). With such methods one can, in principle, obtain reasonable weather data for almost any site on the globe, although, of course, models can never account for all local variation.

For soil parameters, relationships have been developed to estimate parameters that are difficult or laborious to measure, using more easily measured characteristics (for example, soil water release parameters can be estimated using measurements of soil texture, bulk density and soil organic matter). These so-called 'pedotransfer functions' (see also Chapter 9, this volume) exist for many different soil types or regions (e.g. Canada – de Jong, 1982; Australia – Minasny *et al.*, 1999; and the USA – Saxton *et al.*, 1986), but to date have not been developed for many soils in LDCs. Though it is tempting just to use any pedotransfer function for any soil, the estimates given by each can vary widely (Gijsman *et al.*, 2002b); one should thus carefully consider which method is most appropriate for which soil and, if possible, combine it with some actual measurements.

With the compilation of a large dataset, comprising over 2000 entries largely from tropical species, recent advances have been made regarding the quality characterization of organic resources, i.e. cover crops, agroforestry prunings, manure and crop residues (Palm *et al.*, 2001). The compilation of root length densities and rooting depths for agroforestry trees in this book (Chapters 4 and 5) will help fill another knowledge gap.

There is also a need to make input data more 'user-friendly' for users who may not be familiar, in a scientific sense, with a model. For example, rather than requiring specific numerical values of parameters to be input, ranges such as 'high', 'medium' or 'low' could be requested, and the model itself could then convert these into numerical values that it could use. However, some thought needs to be given to reconciling the different perceptions different people have – what one user may call 'high' may be what another calls 'low'. This problem of perception means that some numerical definition may still be necessary. Modellers should also appreciate that the units required are often not intuitively obvious to the end-users, but rather follow the specific model design. Options allowing users to choose their own units could solve this problem.

3.4 Beneficiaries and Target Groups

In the context of research on mixed species production systems in the tropics, the ultimate beneficiaries will, in most cases, be subsistence farmers and/or smallholders. However, it is unlikely that this group will use models directly – it is more likely that such models will be used by, and therefore will be targeted at, researchers, consultants or educationalists in LDCs.

In Fig. 3.2, we have attempted to show, in a simplified form, how models might contribute to the flows of information between the main groups involved in the agricultural systems of LDCs. The uppermost level represents the people involved in developing the models, who are, currently, mainly scientists in DCs or scientists working at the International Agricultural Research Centres (IARCs), although there are an increasing number of models being built by national scientists in LDCs. The second level represents the direct users of the models, i.e. those who actually take a model, run it, and interpret the results. In our classification, these may be consultants (in either DCs or LDCs), and scientists and educationalists in LDCs. The third level represents groups of people who may, potentially, benefit from the models' output, but

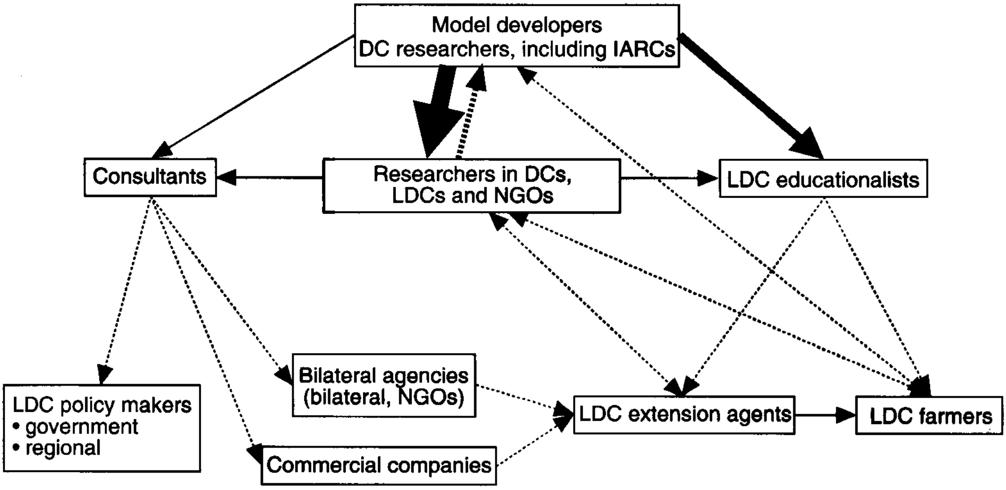

Fig. 3.2. Postulated relationship of simulation models to flows of information between various stakeholders in agricultural development. Solid arrows represent information encapsulated in simulation models themselves, dashed arrows represent flows of information by other means, but arising from the use of models. Thickness of arrow is an estimate of relative information flow rate. Overlap may occur in certain cases, e.g. researchers may also be consultants. IARC, International Agricultural Research Centre; DC, developed country; LDC, lesser developed country; NGO, non-governmental organization. Reproduced from Matthews and Stephens (2002) with permission.

who are unlikely to use the models directly. These include policy makers at various levels, staff in aid agencies or commercial companies, extension personnel and farmers. We recognize that the boundaries between the groups are not clear cut and that, in many cases, the same people may be fulfilling two different roles; model developers, for example, may use their models to fulfil an educational role in graduate classes, or as tools for consultancy work. Similarly, there may well be cases in which people within development agencies or non-governmental organizations (NGOs) use the models directly. Nevertheless, as a workable framework for considering how models may fit into the overall development process, we believe this is a useful starting point. In the following section, we discuss the relevance of simulation models to each group in turn.

3.4.1 Researchers

The ways in which crop–soil models have been applied in a research context have been recently reviewed by Matthews *et al.* (2002a). There is no doubt that, so far, the largest uptake and use of models has been by the research community, both in DCs and LDCs. This is because models are primarily research tools – for most scientists, the incorporation of knowledge into simulation tools is a process taken for granted. For them, models are a way of organizing and utilizing information, which, in turn, can help to identify gaps in their knowledge upon which they can focus further experimental research. There is, however, some concern that much use of models is really just confirming what is already known, rather than adding new knowledge (Matthews and Stephens, 2002). Sinclair and Seligman (2000) make the point that many papers on crop modelling merely calibrate models to local conditions, and have proposed three criteria that should be met if papers on crop modelling are to be published: (i) a clear statement of the scientific objective and a defined domain of relevance; (ii) a mechanistic framework; and (iii) an evaluation of the scientific innovation of the model.

3.4.2 Consultants

It is difficult to know the extent to which agricultural and policy consultants use simulation models as, due to client confidentiality, such work is not generally published. Examples of models in the DSSAT suite (Decision Support System for Agrotechnology Transfer; Tsuji *et al.*, 1994) that are being used in consultancy work in South Africa have been discussed by Stephens and Middleton (2002) and include the following:

- CERES-Maize was used to simulate the production potential and risk associated with maize on two farms for an organization wishing to buy a commercial farm for small-scale farming development. The modelling helped them to decide which farm to buy.
- The DSSAT package was used, on behalf of a fertilizer company, to gauge the optimum level of nitrogen application for a particular field.
- CERES-Maize is used in yield estimation for the Orange Free State Department of Agriculture. These data are then used by the National Crop Estimates Committee (NCEC) to provide information for FAO (Food and Agriculture Organization) and SADAC (Southern African Development Community) early-warning systems.
- A simulation study has been made of the impact of climate change on South African maize production, the results of which will be used by a mitigation team as the basis for plans to minimize the impact of climate change.
- CERES-Maize was used to determine the potential for, and risk of, growing maize on rehabilitated soils. This study was undertaken on behalf of a mining company, which had bought land from farmers on the understanding that, at the end of the opencast mine activities, the land would be returned to farming activities. There are also plans to use the model to help the mining company

monitor whether they are on target in terms of restoring the original potential of the site.

In each case, the modelling work was carried out on behalf of the clients by the modelling consultants – the clients did not use the models themselves.

3.4.3 Educators and trainers

Educators and trainers are also important end-users of simulation models (Graves *et al.*, 2002). They may either use models to help illustrate to their students particular processes (e.g. root growth, water uptake, etc.) and the effects these have at higher levels of analysis, or they may use modelling as part of the process by which students learn systems analysis techniques, in which case the students may build their own models or use existing models to provide information about a component of a larger system, such as an agroforestry system or a farm.

There are several advantages for students. For example, the speed and sensitivity of 'experiments' can be increased, and complex relationships and interactions can be more easily understood. 'What if?' scenarios can be developed to allow students to learn heuristically. Educational institutions can also benefit, through a reduction in the need for expensive laboratories and equipment, and through the more efficient use of instructors' contact time with students. However, there are also disadvantages to the use of simulation models. Students may end up believing that the model is some kind of 'reality', and may fail to learn essential field and laboratory skills. They may also waste time struggling to operate the models, rather than understanding the lessons they can convey. At the institutional level, disadvantages can include the time and costs involved in developing, selecting or adapting appropriate models, and in modifying courses to incorporate their use. Not all institutions may have adequate computer resources, particularly those in LDCs.

3.4.4 Policy shapers and makers

There may also be scope for the use of simulation models to support strategic decisions at a larger scale. However, the extent to which this would be successful will depend on institutional issues and the level of training available to the decision-making staff. In DCs, there tends to be a greater commitment to the acceptance of new knowledge and to the promotion of new practices. This allows technology to be advanced more rapidly (Tollefson, 1996). In the institutions of LDCs there may be resistance to a new technology, especially if it is seen to pose a threat to the existing system. Decision makers who are very busy and who are already dubious about the value of models may find the opportunity cost of learning unacceptable. Spedding (1990) makes the point that policy makers are generally sceptical of systematic methods: 'they are alarmed at the idea of it being publicly known where they are trying to get to, except in the most general terms, in case they never arrive!'.

It should be remembered that the interest of policy makers does not necessarily lie with the best state of an agroecological system, but more with the impact that will be made by the type of interventions they have in mind. Similarly, development and donor agencies are, increasingly, under pressure to demonstrate the value of their proposed intervention for the community and to seek supportive measures from policy makers. However, demand for the assessment of solutions has shifted away from purely biophysical effects and towards the impact such solutions have on people's livelihoods.

3.4.5 Extension staff and NGOs

Extension personnel and NGOs are an important link in the chain that links researchers and farmers. In DCs, the former often provide farmers with a human interface with computerized DSSs. In farming, much advice comes from trusted advisers: substituting such advisers for a computer may be off-putting to many farmers (Knight, 1997). For example, Blokker (1986) found that DSSs designed for direct use by farmers (as distinct from those interpreted by an extension officer) were generally not appreciated by farmers and only had a marginal influence on their decision making.

In LDCs, however, it is less likely that extension personnel will have access to a computer, in which case computerized DSSs would not be appropriate. The information encapsulated in the form of a computer model is not, therefore, likely to flow, in that form, further than research and education groups. However, this does not mean that such information flow need stop at these groups. Information gained from research is more likely to reach extension staff and NGOs in other forms – such as research reports, brochures, posters, training workshops, verbal communications on field days, radio broadcasts, or via informal contacts with research staff.

The influence extension staff and NGOs have on poverty alleviation can be very significant, as they are in direct contact with the farmers being targeted. It is the efficiency and speed with which they are able to transmit information to the farmers that will partly determine whether a particular technique is likely to be adopted or not. They also have another important role to play in the transfer of information in the opposite direction (from farmer to researcher) so that research activities are relevant to the real problems faced by farmers, not just to problems that researchers perceive farmers to have.

Unfortunately, extension services in many LDCs are badly under-equipped in terms of staff, transport and accommodation (Tollefson, 1996), not to mention access to computing facilities. This situation may well change in the future, however, as computer technology becomes cheaper and the skills to operate them become more widespread: computerized DSSs may well then become more relevant to extension staff.

3.4.6 Farmers

It seems unlikely, for three reasons, that, in the short to medium term, there is much potential for the on-farm use of computer-based DSSs by smallholder farmers in LDCs. First, the time when they will achieve the financial ability to purchase and run a computer is a long way off in the case of most subsistence farmers: many do not even have an electricity supply available with which to run a computer. Secondly, the level of education needed to successfully operate a computer is likely to limit uptake. Daniels and Chamala (1989) found in Australia that farmers' interest in computers was related to their level of education – those with higher levels of education were more interested, whereas those with less formal education preferred to go by experience. Even in DCs, poor computer literacy among farmers has hindered the uptake of IT systems (Hamilton *et al.*, 1991). In LDCs, where rural education is often of a low standard and where even the educational level of extension workers is low, the constraints are even greater. LDC farmers would require a huge amount of training and support to begin to use the systems in a useful way. Thirdly, it is, anyway, not at all certain that answers to the sort of questions that farmers are most likely to ask could be provided by operational DSSs. Nevertheless, despite all of these constraints, opportunities for the rural poor to participate in the information revolution are being explored – for example, fishermen in southern India are obtaining weather forecasts and wave-height predictions from the internet via centrally located computers in their villages (Le Page, 2002). It may be only a matter of time before output from crop–soil models is made available in the same way.

If it is anything to go by, the experience in DCs of using simulation models as operational decision support tools has shown that, rather than being useful as operational DSSs in their own right, they are probably more useful as research tools that provide solutions to constraints: these solutions can then be developed into simple rules-of-thumb. In Australia, for example, the SIRATAC dial-up crop management system was developed in the 1970s to help farmers make better tactical decisions with regard to spraying for cotton pests (Macadam *et al.*, 1990). The system's use by growers increased steadily in the early 1980s, but subsequently fell into decline as growers, having developed their own rules-of-thumb from it for the best times for spraying, found that they had no further use for it. There is no doubt that the models at the heart of the system had a major impact in terms of improving practices within the cotton-growing industry, and that without their use cotton-growing practices would not have been economically viable. However, the SIRATAC system's usefulness lay more in the provision of the underlying knowledge for optimal management rather than in its use as a tactical decision-support tool.

An emerging approach is the use of models in a participatory way, as pioneered in Australia and Zimbabwe by the APSRU (Agricultural Production Systems Research Unit) group. The APSIM (Agricultural Production Systems Simulator) package of models is currently being used to help farmers, policy makers, extension agents and researchers to improve their understanding of the trade-offs necessary between different crop and cropland management strategies under scenarios of climatic risk (Meinke *et al.*, 2001). Rather than focusing on a particular optimal strategy, the model is used to explore the consequences of various cropping practices that are suggested by extension personnel and by the farmers themselves, who are aware of their own labour and capital resource constraints. The modelling aspect is important, as it would not be possible to undertake such an analysis, either on farm or at a research station, in a reasonable time frame. Researchers found the model useful, as it made them more aware of the constraints faced by smallholders, and suggested new lines for research. A similar approach was suggested by Beinroth *et al.* (1998). In this approach, a model could be used to explore the trade-offs necessary between domestic requirements, irrigation demand and downstream use of river water in Colombia. This involved regular discussions between stakeholders, allowing new scenarios to be formulated and simulated in an iterative manner until a consensus was reached.

Clearly, by interacting directly with farmers, the flows of information that occur between model developers, users and beneficiaries are likely to improve. All have much to learn from each other; the models may be able to suggest improvements to existing practices, but farmers will be able to temper these suggestions with their practical experience. Of all the target groups discussed, direct interaction with farmers probably has the greatest potential to improve rural livelihoods, although the numbers of people whose livelihoods are actually improved as a result will depend strongly on the dissemination of such improvements outwards to others not directly involved.

3.4.7 How do we ensure uptake and impact of simulation models?

Matthews *et al.* (2002b) considered the route by which models will have an impact on the process of improving the livelihoods of farmers to consist of three phases: (i) the applicability of the models to particular problems; (ii) the uptake of models by end-users; and (iii) the translation of this use of models into a measurable impact. Failure to reach any one stage will prevent models from having any final impact.

3.4.7.1 Model applicability

Limitations inherent in the models themselves, some of which were discussed above, may prevent them from being applicable to certain problems. For example, a model assuming a uniform canopy could not be used to investigate the distribution of light in a spatially heterogeneous, mixed-species canopy. The inapplicability of models to real-life problems is one major factor that limits their wider use; most models have been developed as research tools, and several have been modified for use as decision support systems, but they still address problems perceived by researchers rather than farmers (Stephens and Middleton, 2002). A farmer is probably not that interested in knowing that he/she can obtain 2% more yield by applying fertilizer on March 25 rather than 1 week later if the main constraint is whether the fertilizer will be delivered at all!

3.4.7.2 Model uptake

Uptake of models very much depends on the needs of a particular end-user. Stephens and Hess (1996) classified a number of constraints to the uptake of the PARCH model by researchers in East Africa as 'intellectual', 'technical' or 'operational'. Often, the outputs of simulation models may be too complicated (both in terms of language and amount of information given by the model) for direct use by the beneficiaries (e.g. farmers, policy makers, etc.). In part, this problem is related to the mental models that each user has of the same system – a soil scientist's concept of soil fertility, for example, is usually very different from that of a farmer. The scientist may focus only on its nutrient status, without considering its physical characteristics (Corbeels *et al.*, 2000), whereas the farmer's perception of soil fertility is not limited to its nutrient status, but is often related both to integrative characteristics (such as the soil's ability to produce good crops), and to soil characteristics that they can actually see or feel (see also Chapter 2, this volume). Thus, recommendations derived from models and other scientific assessments need to be translated into a language that is easily understood by the beneficiaries. Efforts in this direction have been made by Giller (2000) who translated scientific findings based on the Organic Resource Database (Palm *et al.*, 2001) into parameters that could be understood by farmers (Fig. 3.3).

3.4.7.3 Model impact

The impact a model has is difficult to quantify, particularly as it may occur over different timescales (Collinson and Tollens, 1994). For this reason, factors that enhance the likelihood that a model will have an impact are difficult to identify. However, Matthews *et al.* (2002b) reviewed a number of examples, where, in their view, crop simulation models had had some impact. They listed the following characteristics as having some influence:

1. Involvement of competent modellers.
2. Working in multidisciplinary teams.
3. Participatory approach with practitioners.
4. Having a clearly defined problem.
5. Demand for solutions from a target group.
6. Long-term commitment by funding sources.
7. Quantification of risk in variable environments.
8. The need for quick answers.

They noted that, in nearly all of the examples they discuss, the only common factor was the involvement of competent modellers. This suggests both that modellers should be an integral part of a team involved in the overall

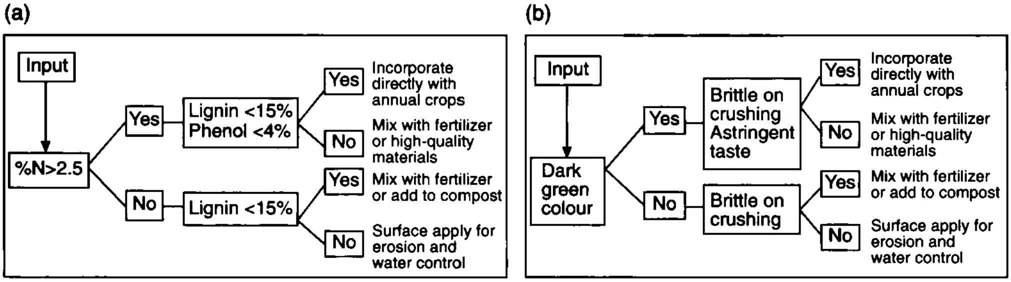

Fig. 3.3. Recommendations for use of organic resources in agriculture based on (a) scientific (chemical) plant quality attributes (Palm *et al.*, 2001), and (b) translated into easily observable parameters defined by farmers (Giller, 2000).

process of livelihood improvement, and that it is important that they also have the opportunity to enter into dialogue with farmers and other target groups. In the participatory modelling approach being developed by the APSRU group (discussed above), clients are involved in projects – this includes not only farmers, but all decision makers involved in agricultural development. If the clients are farmers, collaborative experiments are conducted, and the results are extrapolated in time using models to show the long-term consequences of the farmers' actions. If the clients are researchers, models are used for extrapolation of the research results in space and time or across environmental conditions (e.g. different soil types or weather conditions), in order to add value to expensive research. The approach described by Robertson *et al.* (2000), which was used to develop new cropping strategies for mungbean in response to changed external factors in Australia, is a good example of how this added value can be achieved. Van Noordwijk *et al.* (2001) have coined the term 'negotiation-support tools' for models used in this way.

Development of user support groups to provide help and model updates to users of existing models is one way of trying to encourage the maintenance and development of these skills after the main project has finished. Reviewing the SARP (Systems Analysis for Rice Production) project at the International Rice Research Institute (IRRI), Mutsaers and Wang (1999) found, first, that, despite the scale of the project and the foresight that the project's designers appear to have shown, modelling skills among the collaborating national scientists were being lost and, secondly, that the use of models was not likely to continue unless there were continued interventions from 'advanced' organizations. Lessons can perhaps be learnt from the experience of the IBSNAT project (Tsuji and Balas, 1993), whose DSSAT family of models are probably the most widely used family of crop simulation models in the world today. Part of the success of this family of models was no doubt due to the size of the project, and to the participatory and interactive relationship that existed between model developers and model users during the course of the project; the continued uptake and use of the models must, however, be due to the technical support that is still available, even though the project ceased in 1994. Users and developers still keep in touch via a listserver, so there exists a broad base of support, which is not dependent on one or two people. Users with a problem can post a query on the listserver and, usually within a day or two, can receive help and advice from other users or from the developers of the model.

In such support groups, emphasis should be placed on the applications of the appropriate models to solving practical problems of importance in the research areas of the members. For example, agroforestry models could be used to optimize the spatial arrangements of particular agroforestry systems, taking into account both biophysical and socioeconomic aspects that are influential. However, it is important that models contribute to the solving of a clearly defined problem, rather than just to the confirmation of what is already known by farmers.

3.5 Relevance to Larger Systems

It is important that models of below-ground interactions in mixed-species systems are seen as part of larger systems. The reductionist approach to science has been very successful in adding to our store of knowledge about the way the world functions, but there is a growing awareness that systems are more than the sum of their parts, and that they can only be understood fully by taking into account the complexity of 'emergent' behaviour in addition to the behaviour of their individual components (e.g. Coveney and Highfield, 1995). Improvements in one component of a system do not necessarily have a desired result at a higher scale. A good example of this is the promotion of *Mucuna* as a cover crop in Honduras in the 1970s in order to help intensification of cultivation, thereby raising yields and reducing the need for farmers to clear more areas of forest (Buckles and Triomphe, 1999). Those farmers practising the technology were able to grow twice as much maize on less land; but the resulting improvement in the local economy attracted an influx of migrants into the area, so that overall deforestation rates continued to increase at the same pace (Humphries, 1996). The key in this case is to understand the interactions and linkages between individual components of a system and how these relate to behaviour at a higher level.

3.5.1 Enhancement of livelihoods

In development circles, there has been a growing realization that single-factor-based research has not been able to address many of the problems faced by poor people, and that a much more multidisciplinary approach is required. For this reason, several international development organizations are currently promoting the use of the Sustainable Livelihoods (SL) framework as a way of thinking about objectives, scope and priorities for development, in order to enhance progress being made in terms of the elimination of poverty (Ashley and Carney, 1999). Such thinking has grown from the recognition that it is fruitless to try and solve technical problems without, at the same time, addressing the socioeconomic pressures against which they are set.

The main feature of the SL approach is that, instead of focusing on natural resources or commodities (as has been the case in the past), it places people at 'centre stage' and considers people's assets (natural, human, financial, physical and social capital) and their external environment (trends, shocks, and transforming structures and processes; see Fig. 3.4). Households adopt various strategies in order to achieve certain outcomes, such as increased financial income, increased food security, and a better quality of life. A key concept is that of 'sustainability' – a livelihood is defined as sustainable when it can cope with, and recover from, stresses and shocks, and maintain or enhance its capabilities and assets both now and in the future, while not undermining the natural resource base (Carney, 1998). As such, the SL framework encourages researchers to think about the whole livelihood system, rather than just some part of it.

In relation to developing agriculture, therefore, there needs to be more emphasis placed by the modelling community on problem-solving approaches, and on making *people* more central to their way of thinking. On one level, this means thinking of the problems faced by ordinary people in LDCs, and constructing and applying their models to address, and to contribute to solving, these problems. For this to be effective, modellers need to both define clearly who the beneficiaries of their mod-

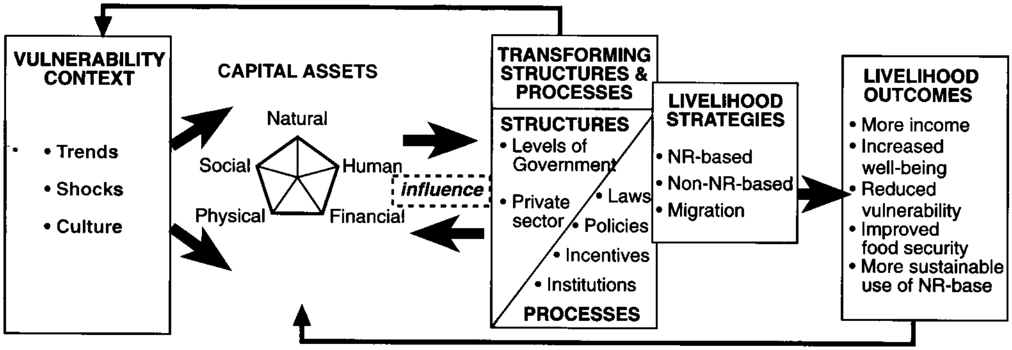

Fig. 3.4. The Sustainable Livelihoods framework (from Carney, 1998). Reproduced from Matthews and Stephens (2002) with permission.

els are and enter into dialogue with these people so that the final product is tailored to their needs. As part of this process, on one level, an increased effort needs to be made to disseminate the outputs of models, over and above the dissemination of the models themselves. On another level, there exists the need to consider people as integral components in the systems being modelled. The SL framework offers a good starting point from which to develop this methodology. It is hoped that this would eventually lead to the development of tools that practitioners could use to identify what are the real constraints to improved livelihoods in LDCs, so that future projects would be more realistically focused, thereby increasing their chances of having an impact.

Other chapters in this book are generally aimed at specific biophysical processes associated with below-ground interactions. However, although this approach is valuable from the point of view of scientific research, farmers do not necessarily think in the same terms as researchers. Rather, they are more concerned with how particular practices relate to their broader livelihoods. For example, in considering whether or not to adopt a particular research product, such as tree planting for deep nutrient capture, the kind of questions he/she is more likely to ask are 'How will my livelihood benefit from this?', 'Will I produce more food for my family if I do this?', 'Will I earn more cash if I take this up?' and 'Will my family's quality of life be enhanced?' For researchers, thinking about the products of the research process in these terms will mean that that their research will be more likely to result in improvements to the production system. Perhaps improved food security can be obtained through the greater use of agroforestry systems, so that the risk of crop failure is reduced. Increased cash generation may be obtained through planting fruit trees alongside crops and then selling the produce in the market. Quality of life could be enhanced by means of a more varied diet or through a reduction in labour requirements for different agricultural practices. Further questions may relate to specific practices, for example, 'Is it better to try growing apples or bananas in this particular environment?' or 'Is *Mucuna pruriens* or *Canavalia ensiformis* the better cover crop for weed control?' This approach is still reductionist, in that the overall system has been reduced to its components. The only difference between this and traditional approaches is that the definition of the problem and its solution has not been restricted to biophysical processes, but also includes the socioeconomic processes of the system. The key point is that the farm and its environment are seen as a complex adaptive system, rather than as independent components arising from single-discipline perspectives.

Many issues of global concern can also be addressed through a sustainable livelihoods perspective. For example, changes in the global climate and a reduction of biodiversity are concerns that are attributed, in part, to the loss of forested area as a result of clearing for agriculture. At this level, stabilization of the interface between forest and agriculture is generally seen as desirable in terms of preservation of the forested area. One line of thinking is that, by developing ways to improve the livelihoods of people at the forest margins, their need to move on and clear more forest will be reduced, which will contribute to solutions to the global problems (e.g. World Bank, 1992). In this way, improved productivity, through the adoption of resource management recommendations derived from, for example, a better understanding of below-ground interactions in mixed-species agroecosystems, could contribute to reducing the rate of deforestation. However, as has already been pointed out, it should also be recognized that the situation is not necessarily as simple as this. First, it is unlikely that the adoption of improved techniques alone can bring stabilization, without a concomitant improvement in infrastructure (i.e. in roads, hospitals, schools) and markets. Secondly, Johns (1996) noted that, where agriculture was successful in areas surrounding forest reserves, migration into the area was also increased and worked against biodiversity. The example of *Mucuna* in Honduras (discussed above) supports this observation. It is by developing models of these higher-order processes, in which models of below-ground interactions may well be a component, that we will understand these systems better.

Conclusions

1. A range of multispecies models exists with good below-ground process descriptions, but they are not widely validated.
2. To date, the users of simulation models are mainly within the research community, although they sometimes interact with indirect beneficiaries such as consultants, educationalists, policy makers, extensionists and farmers.
3. The impacts that crop–soil simulation models have had as decision support systems have, until now, mainly been the result of their contribution to the learning processes of practitioners and the subsequent development of rules of thumb.
4. Models should not be viewed in isolation, or thought of as being the sum of their individual components.
5. New approaches are being developed to include stakeholder participation and livelihood concepts.

Future research needs

1. Expanded databases for tropical systems (e.g. pedotransfer functions, root systems' characteristics and plasticity).
2. Models with an integrated livelihood perspective.
3. Integrative 'DSSs' (decision support systems) with the involvement of stakeholders.
4. More user-friendly input parameters.
5. Modularity and compatibility of components from different models.
6. Validation of models for a wide range of ecosystems and regions.