An integrated research strategy for modelling and experimentation in agroforestry

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SUMMARY

A strategy for the integration of modelling and experimental work in agroforestry research is presented. The approach, in which modelling is perceived as a central feature determining and coordinating process-based experimental studies, aims to achieve a functional understanding of how agroforestry systems work. The underlying context concerns the effects of placing a variable number of trees into cultivated fields, and the mechanisms involved in the resultant interactions between tree and crop species. Four elements to the strategy are described; the modelling approach, the priority research areas, a knowledge base, and necessary organizational structures.

RÉSUMÉ

Une stratégie pour l'intégration de la modélisation et des travaux d'expérimentation dans le domaine de la recherche en agroforesterie est présenté. Dans ce cadre, la modélisation est perçue comme un élément-clé qui permet de déterminer et coordonner ce type d'étude expérimentale de processus. Par cette approche, on essaye d'acquérir une parfaite compréhension des systèmes agroforestiers et de leur fonctionnement. Les effets causés par l'introduction d'un nombre variable d'arbres au sein des cultures et les mécanismes impliqués dans les interactions entre arbres et cultures constituent les questions de base. Quatre éléments sont décrits pour cette stratégie: l'approche de modélisation, les domaines de recherche prioritaires, les prérequis et les structures organisationnelles nécessaires.

RESUMEN

Se presenta una estrategia para la integración de modelos y trabajo experimental en la investigación agroforestal. El enfoque, en el cual el modelo es percibido como una característica central determinante y que coordina los estudios experimentales basados en el proceso, pretende alcanzar un entendimiento funcional de cómo trabaja el sistema agroforestal. El contexto fundamental concierne con los efectos de colocar un número variable de árboles dentro de campos cultivados y con los mecanismos envueltos en las interacciones resultantes entre árbol y especies del cultivo. Se describen cuatro elementos de la estrategia; el enfoque del modelo, las áreas prioritarias de investigación, el conocimiento básico y las estructuras organizacionales necesarias.

BACKGROUND

The British Government's agency for overseas aid, the Overseas Development Administration (ODA), has a programme of funding for research on renewable natural resources. The research strategy comprises eight areas of study, with some funds earmarked for regions of common interest. One such region is the study of vegetation interactions in cultivated ecosystems, knowledge of which is fundamental in considering enhanced productivity from natural, semi-natural, and artificial ecosystems. The identification of interactive processes regulating productivity is important, with regard to developmental issues, because it enables the study of mechanisms rather than site specific net effects. The underlying systems and their components are elucidated, reflecting the need for understanding processes at work in systems of cultivation which are required, economically, to be both sustainable and of low input cost.

Process-based research yields findings that have a potential for extrapolation to other climates, soil types and plant communities, and thus represents good value for money. The approach lends itself to dynamic descriptions of the major components in the ecosystem in terms of mathematical models which can then be generalized and applied in a wider context by coupling with appropriate soil and climate models. The approach also represents a current trend towards networking, where research groups work on common objectives with comparable methods and results, and arrive at general conclusions.

The ODA's Renewable Natural Resources research area concerning agroforestry has been recognized as needing a viable, long-term plan which encompasses predetermined initiatives of wider relevance and allows financial assistance to evolve in a systematic way. As an initial step towards the formulation of a coordinated plan for process-based research, the current state of knowledge regarding ecological interactions in agroforestry systems has been reviewed (Anderson and Sinclair, 1993), as has the state-of-the-art in modelling such systems (Muetzelfeldt and Sinclair, 1993).

The conclusions of these two reviews can be summarized as follows:-

1. Agroforestry is primarily considered as a set of land use practices which aim to realize the benefits from growing woody and herbaceous species together, commonly by the addition, or increase in stocking density, of trees on cultivated land or pasture.
2. Most experimental field studies in agroforestry to date have reported net effects on productivity, so that the result of plant-plant interactions can be described as a positive, negative or nil effect on each species in the combination. These phenomenonological studies do not state the mechanisms involved, and are highly site specific.
3. The plant and its environment modify one another so that the environment causes a response in plant function and growth, and the plant then has an effect upon the environment by changing one or more of its factors. Agroforestry thus concerns the ways in which a plant can influence its neighbours by changing their environment. Mechanistic studies, which explicitly state the processes whereby individuals of one species influence individuals of that and other species, produce results that are amenable to modelling and are of more general applicability.
4. Species interactions can be advantageous, leading to an increase in total yield, reduced yield variability, and protection of the resource base. These ecological issues are analogous to socioeconomic concepts concerning productivity, vulnerability and sustainability in marginal land use systems.
5. Certain problems in modelling particular aspects of agroforestry systems exist, including the complexity of spatial geometry, the representation of a set of individuals, combining the effect of multiple influencing factors, the degree of disaggregation, and scaling across levels of organization. Regarding the shortcomings of current modelling environments, there is a need to develop criteria for model formulation, and it is difficult to integrate existing models of parts of agroforestry systems into larger models.
6. The success of a research strategy which aims to integrate experimental and modelling work will depend on (i) the development of software for the construction, modification, simulation and analysis of agroforestry models, and (ii) the development of standards for the preparation of data, equations and submodels which can be integrated into the modelling software package.
7. The development of a modelling environment will require a system which allows three key features to be handled: (i) a compartment-flow approach, (ii) submodels, ranging from simple equations to complex routines, and (iii) spatial disaggregation to capture the spatial arrangements in agroforestry systems.

The findings of the above reviews were presented to invited participants at an ODA funded workshop in July 1992, and then appraised by three working groups examining (i) research priorities, (ii) modelling requirements, and (iii) institutional structures. The first group's recommendations, concerning research priorities, emphasized the need to concentrate on below ground processes. Seven key areas of weakness in our understanding were identified: nutrient cycling, hydrology, erosion, organic matter, competition, genetics and germplasm selection, and productivity. Underpinning these areas was the need to (i) move away from site specific studies by noting the environmental limits for technologies, using contrasting sites in different ecological zones, and characterizing the environment, (ii) consider spatial heterogeneity and variability, and (iii) be aware of indigenous knowledge.

The working group examining a modelling approach and modelling environment recommended (i) the development of simple process based models of the tree-crop interface, (ii) the construction of a knowledge base representing qualitative understanding of functional relationships in agroforestry, and (iii) teaching workshops on modelling approaches. Ancillary to these specific recommendations were concerns with regard to modelling needs and approaches, including whom the models were to assist e.g. aid agencies, researchers, or farmers.

The third group considered a structure for communication between researchers, a structure for communication between modellers, the use of a directed mode research programme, and management of research knowledge. Under four headings they made recommendations concerning (i) networking (ii) the research programme (iii) data management, and (iv) modelling. These are discussed below.

It was subsequently necessary to integrate the above recommendations into one, viable strategy, in which the underlying context related to the *effects* of placing a variable number of trees into cultivated fields, and the *mechanisms* involved in the resultant interactions between tree and crop species. The remainder of this paper concerns the design of an appropriate research programme.

A STRATEGY FOR AGROFORESTRY RESEARCH

Figure 1 schematically presents an approach for the integration of modelling and experimental studies, in order to achieve a functional understanding of how agroforestry systems work. The modelling effort is perceived as a central feature, determining and coordinating future research priorities. Models developed within the strategy may be used either by individuals and organizations for future 'strategic research', or 'adaptively' as decision-support tools.

The extension of prefabricated technology packages has proved less effective in agroforestry development than incremental improvements that build on local practice (Buck, 1990; Bunderson *et al.*, 1990). Fundamental research that establishes yield responses to parameter changes has been recognized as complementary to adaptive research trials which compare alternative technology designs on-farm (Scherr, 1990), but the need to place a 'design' filter between research results and the farmer has not been justified by field experience. Agroforestry, by its nature, is complex and often conducted on a small scale by farmers with limited resources.

An effective research strategy should, therefore, aim to support farmers in making decisions about the incorporation of trees within their farming systems, based upon the results of fundamental research being made available to farmers, and the research and extension staff who work with them.

Because agroforestry practices are too complex and variable to be optimally designed by researchers for farmers, the most appropriate contribution of strategic research is to establish relationships between components of agroforestry practices, described in terms of controlling variables that can be measured at different sites. These relationships can then be combined and used to explore the implications of introducing or manipulating trees on farm land adaptively with farmer involvement. Such a strategy is underpinned by progress in functional understanding of how agroforestry practices work, is made relevant to different agroforestry species in different regions by the measurement of key parameter values at a range of sites, and is made available to the farmer through the use of decision-support tools by research and extension workers.

To make progress in understanding how agroforestry practices work, the results of research projects from different disciplines need to be integrated, and system behaviour examined. The centres of excellence for research on, for example, root architecture, nitrogen fixation and canopy processes are located in different institutions and, therefore, inter-institutional co-operation is required. The necessity for interdisciplinarity in agroforestry research requires a framework for coordinating the research effort and integrating results from different projects.

The most effective means of achieving integration of research results is through the construction of models that consist of explicit statements concerning the functional understanding gained through such studies. In agroforestry there is a requirement to combine models of various components and processes often over long time horizons; as research progresses, understanding is refined and models need to be updated. A central modelling effort is essential to the identification of gaps in knowledge that are priorities for research, and in combining research results from different projects in order to explore system performance and predict output, supporting both strategic and adaptive objectives. For this strategy to work, research and modelling have to proceed in tandem, and regular evaluation of progress, and refinement of objectives and priorities, must take place.

It follows that a research and modelling framework is required which will achieve the following objectives:

1. The integration of knowledge about agroforestry from different disciplines and institutions in order to produce a more holistic and, thus, more useful output that examines the effects of one component on another, and eventually explores the effects of management decisions on system output.
2. The continuous identification of gaps in knowledge that need to be filled to achieve (1).
3. The ability to predict what will happen, in terms of productivity and sustainability of agroforestry practices, in relation to various site-types, species and management regimes.

Several features of the strategy for model development follow from the above objectives:

- a modular structure for model development, with different sub-models developed by different research groups,
- regular integration of various sub-models developed in this way,
- regular interdisciplinary and inter-institutional discussion on sub-models and their integration,
- effective collaboration between modellers and researchers: vital for the development of sound models and in order to realize the objectives of the strategy by enhancing the compatibility of different research efforts and refining research priorities.

These features can be achieved by the construction of a modelling environment, described below, in which sub-models, developed in cooperation with research groups that have relevant expertise, can be combined. The environment, although centralized in its construction and maintenance, would be decentralized in its use, enabling researchers to manipulate models based on the relationships that they have developed, and enabling modellers to share implementations. The latter is particularly important in agroforestry, where a large programming effort is required to represent the structure of the system at an appropriate level of disaggregation. The modelling environment would provide a resource for the entire agroforestry research community and act as a focus for their combined effort.

THE MODELLING APPROACH

The major problems that currently hamper the construction, use and dissemination of models of agroforestry and related systems have been reviewed (Muetzelfeldt and Sinclair, 1993). These problems seriously undermine both the cost-effectiveness and the scientific rigour of modelling in agroforestry:

- its cost-effectiveness is poor because of the time that it takes to implement one model, the lack of re-useability of model components, and the failure to treat completed models as a valuable resource;
- the scientific rigour of the modelling process is low because of the difficulty of comprehending other people's models, the lack of a guaranteed correspondence between model description and implementation, and the virtual impossibility of exploring alternative but equally plausible model formulations.

These problems are not incidental to the success of a strategy that aims to integrate research into, and the modelling of, agroforestry systems. Rather, the success of this strategy critically depends on removing the barriers between researcher and modeller, removing the dependence on large, opaque, one-off models, facilitation of the model design-implementation-redesign cycle, and the pooling together of modelling contributions from diverse research groups.

Current modelling problems stem in large part from the use of conventional programming languages for model implementation. Therefore, the solution to these problems requires the development of an alternative mechanism for specifying and implementing models. Analogous solutions are now commonplace in other disciplines. For example, software for computer-aided design in architecture can now be found in architectural companies large and small; it not only greatly enhances the efficiency of the design process, but also facilitates communication between architects and other agencies, such as quantity surveyors and building control officers, through the use of computer media and a standard language for building description.

Similarly, there are various software packages to support the process of model design (Muetzelfeldt and Sinclair, 1993). In some areas (such as designing models of engineered systems) these have matured into standardized, routinely-used tools, and they demonstrate the feasibility and value of non-programming approaches to model implementation. Some of the more generic modelling packages are suitable for a subset of agroforestry models. However, none of them provide the range of features required for agroforestry modelling.

The following proposals are based on a number of assumptions about agroforestry modelling. First, it is assumed that most existing and future agroforestry models are amenable to description in terms of a reasonably small number of modelling 'constructs'. Examples of such constructs are equations relating one variable to others; submodels; and a particular form of disaggregation, such as spatial grid squares. This assumption is supported by an analysis of existing models (Muetzelfeldt and Sinclair, 1993). Second, it is assumed that a model can be fully specified in terms of such constructs. This assumption is supported by the effectiveness of software for computer-aided design in other domains such as engineering and architecture. Third, it is assumed that a model specified in terms of a set of modelling constructs can be translated into an executable implementation (such as a computer program in a conventional programming language), which can then be used to simulate the behaviour of the modelled system. Existing software packages for modelling all have this capability.

The proposal has two linked components:

- the development of software for the construction, modification, storage, display, simulation and analysis of agroforestry models;
- the development of standards for the preparation of data, equations and submodels which can be integrated into the modelling software package.

The software environment for agroforestry modelling

A modelling environment is required which will support the interactive construction and modification of models. This can be done as a screen-based design process (rather than conventionally as a programming task), greatly increasing the speed with which a model can be built, and increasing the accessibility of the modelling activity to research scientists who have neither the time or the inclination to implement models in the conventional way. The feasibility of this approach has been demonstrated by numerous examples of modelling software (Muetzelfeldt and Sinclair, 1993).

The environment also needs to facilitate the storage and re-loading of whole models and parts of models in a model library. This would be a common resource shared within the agroforestry research community, satisfying the requirement to extract maximum benefit from the investment in model development, maximizing re-useability of model components, and thus minimizing the wastefulness associated with duplication of effort by different workers.

Such an environment would enhance dissemination and understanding of other people's models, by permitting the selective retrieval of information on the models stored in the model library. For example, it would be possible to interrogate the system to find 'all the models that include the process of photosynthesis' or, for a particular model, to find the equations for all the processes involving the flow of water.

The environment would also allow alternative implementations of the same model to be produced. Thus, an executable program for a particular model could be produced in BASIC or Fortran, or even to run on a powerful parallel computer - depending on hardware availability and a particular researcher's preferred language. This improves the extent to which the same modelling environment can be used on a variety of hardware and software systems. A standard set of tools would be provided for assisting various stages of the simulation: setting up the initial conditions, interacting with a model during the course of the simulation (for example, to simulate pruning), and analysing model results in graphical or tabular form. Also, tools would be required for sensitivity analysis of model output to parameter values, for parameter calibration using observed data, and for determining the degree of fit between model output and independent data.

The proposed software environment supports three levels of use. At the first level, users would be able to access existing models, varying the values of parameters (e.g. site conditions) and management decisions to explore the behaviour of the model. This corresponds closely to the way that existing models are used, except that the environment would provide a standard user interface for setting the model up, and a powerful set of facilities for allowing the user to control the simulation and the display of results. Thus, users would not need to learn different conventions for each model, and the facilities for model use would be better than any one modeller could hope to provide.

At the second level, users would be able to modify the structure of a model (for example, by replacing one light response equation with another), or to construct a model from scratch. Mechanisms would be provided to facilitate this task, for example by selecting options from menus or by the use of a 'mouse' to build a diagram on the screen. This level of use is appropriate for those wanting to construct a particular model for management purposes, or for a particular group of scientists, perhaps working in an exploratory workshop, to investigate alternative model formulations.

At the third level, the environment would support the addition of new equations and submodels. Simple equations could be entered interactively, in much the same way that a formula for a cell can be entered into a spreadsheet. However, the environment would also support links with submodels implemented as routines in a conventional programming language. This should make a critical difference to the acceptability of the modelling environment in the research community, since it means that:

- existing models and submodels can be incorporated within the environment, thereby making the most of the effort that has been invested in producing them;
- modelling features that cannot be implemented in the environment directly can still be handled, since they can be developed in a conventional programming language.

As time goes on, it would be possible to re-implement existing models using the constructs provided by the system; and the range of constructs would increase, reducing the need for outside programming.

The development of this modelling environment should proceed in an incremental manner, beginning with a readily-implemented system capable of handling a major subset of the modelling constructs identified by Muetzelfeldt and Sinclair (1993). The number of constructs that can be used to build models would then be gradually increased to widen the range of models that can be constructed within the system. Inevitably, this would mean some restriction in the early stages, but this would be more than compensated for by the benefits of working within the environment. In any case, the initial system would be capable of representing the majority of existing agroforestry-related models.

To satisfy these requirements, the initial system would need to allow three key modelling features to be handled:

- *Compartment-flow modelling*. This conceptual approach is very common, and particularly appropriate for representing the behaviour of agroforestry components (in terms of flows of energy, water and nutrients).
- *Submodels*. Again, a common feature: many models are described in terms of the submodels that constitute them, ranging from simple equations to complex routines with many inputs and outputs.
- *Spatial disaggregation*. Essential for capturing the spatial arrangements that are fundamental to agroforestry systems. Initially, an approach based on horizontal grid squares and vertical canopy and soil layers would be required as a minimum.

The implementation of the strategy requires one central institution to develop, maintain, document and disseminate the software for the modelling environment, and manage the model library. The institution should work to a design remit drawn up by a management group comprising representatives from those actively involved in research and modelling in agroforestry and related areas.

The development of standards for the preparation of data, equations and submodels

The value of the modelling environment will be considerably enhanced if it can link to databases containing typical values for variables and parameters determined for components of agroforestry systems. Examples include species-specific growth rates under different conditions, typical nutrient levels in soils, or canopy light interception parameters. This requires the development of a standard terminology for these agroforestry-relevant quantities, including the specification of units and a formal definition of each term to remove ambiguity.

Standards also need to be laid down to permit research groups to contribute their own models or submodels to the model library within the modelling environment. Such contributions will be necessary both because limitations in manpower would prevent this being done centrally, but more importantly because it would foster an attitude of shared commitment to the modelling environment. This is needed to avoid the impression in the research community that a modelling approach is being imposed on them, rather than developed for them.

The standards for specifying models, submodels and equations will be technical ones, principally specifying the manner in which they should be programmed to enable them to interface to the rest of the modelling environment. This strategy would thus engender a shift in the primary task of a programmer/modeller associated with a particular research group, away from the implementation of one-off models, and towards the development and interfacing of models, submodels and equations to integrate within the modelling environment. This will result in a much more effective use of his or her time and skills.

THE RESEARCH PRIORITIES

The review of ecological interactions in agroforestry systems (Anderson and Sinclair, 1993) highlighted that agroforestry is 'system' rather than 'product' oriented and therefore requires a particular approach unlike that taken in forestry or agriculture. Furthermore it was apparent, during the process of reviewing published literature, that a gap currently exists between the theoretical basis to agroforestry already developed, and the results of field trials. The former concerns the processes occurring in agroforestry systems, whilst the latter provides information regarding the net outcome of species interactions. Such field work does not allow distinction of the mechanisms involved and their relative importance, and this is a fundamental problem in the present research approach adopted by many workers.

The gap between theory and field work can be bridged using models, which by their nature create a link between the specificity of field data that is phenomenonological in nature, and the general applicability of mechanisms involved in species interactions. Laboratory-based studies can also help in this linkage.

Anderson and Sinclair (1993) noted that experiments reporting the outcome of interactions between plant species had not contributed significantly either to understanding the mechanism of e.g. competition, or to generalizing about its effects (Harper, 1977). It was also noted that in order to focus on the fundamental processes operating in agroforestry systems, a different research approach, which explicitly states the processes whereby individuals of one species influence individuals of that and other species, is required (Tilman, 1988). The priority research areas detailed below have been identified as providing information which will contribute to a better understanding of the mechanisms behind the various interactions present in agroforestry systems.

Relating research projects to modelling needs

Proposals for research project funding under an agroforestry research strategy programme should make explicit reference to the contribution of the research to the modelling of agroforestry systems. This does not mean that each project should have a modelling component, but rather that at least some of the outputs of the research should have clear relevance to the modelling process.

The relevance of the research to modelling may in some cases be driven by existing modelling needs. For example, an existing model might include a term for leaf and root decomposition, based on minimal knowledge of the rates of these processes, or their dependence on temperature or soil moisture. A research proposal could make a specific claim to fill this gap. Such integration between modelling and research would be helped if those involved in developing agroforestry models published a list of the areas of uncertainty in their models.

In other cases the research may not be directed to filling existing gaps, but the results could still be expressed in terms that help in model design. For example, a study of the effect of soil moisture on tree growth could indicate whether it would be necessary to include a soil moisture component in

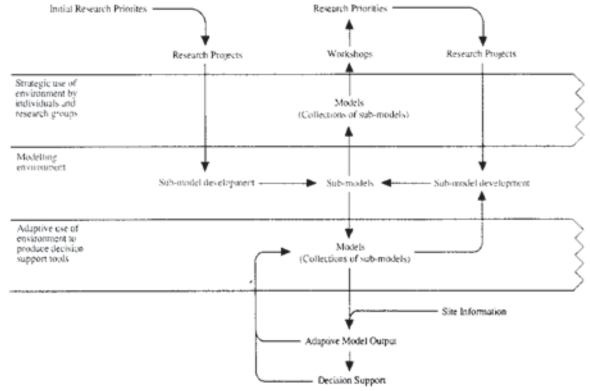

FIGURE 1. *Schematic representation of the use of an integrated approach in combining research and modelling to achieve a functional understanding of how agroforestry systems work. A central modelling effort drives and coordinates research and underpins the production of decision support tools for farmers, and research and extension workers.*

a yield model; whether the soil should be represented as layers or as a single compartment; or what the form of the relationship is between growth and soil moisture status.

An explicit statement of outputs relevant to the development of models on the research grant application form would provide a clear indication of the extent to which the research could be integrated with agroforestry modelling.

Environmental mediation of tree-crop interactions

In broad terms, future research should concentrate on the interface between tree and crop, in the context of the adoption of agroforestry by introducing trees at variable density into cropped areas. Interactions between species are mediated by the environment through the 'response and effect' principle (Goldberg and Werner, 1983), which states that the plant and its environment modify one another so that the environment causes a response in plant function and growth, and the plant then has an effect upon the environment by changing one or more of its factors to an appreciable degree. Research on the tree-crop interface will therefore primarily concern the ways in which a plant can influence its neighbours by changing their environment (Harper, 1977), either positively (e.g. by increasing soil nitrogen) or negatively (e.g. by using limited soil water), and either directly or indirectly.

The result of interactions between plant species is very dependent on density, and hence the numbers and configuration of trees added to the land use system must be carefully considered. Studies should concentrate on the tree component, which is a major determinant of the system and which can be manipulated by management practice. Resource capture by the tree should be examined in relation to the impact of trees on crop productivity and sustainability. The focus should be further narrowed to research specifically examining processes operating below ground at the tree-crop interface; below ground studies are of a higher priority than above ground studies because less is known about them. These studies should proceed in parallel with a modelling approach, which thus would also incorporate the effect of trees on crop productivity, and effects over time on the balance between supply and consumption of limiting resources.

Priorities in the context of ecological zones

Since plant-plant interactions are mediated through the environment, differences in environmental constraints between agroecological zones will markedly affect the relative importance of specific interactions. Key processes in one agroecological zone may thus assume a lesser role in other zones. For example, competition for water as a limiting resource will be critical in the semi-arid tropics but inconsequential in the humid tropics. Table 1 presents data for the extent to which five agroecological zones in the tropics are affected by a number of soil constraints (Sanchez, 1989)

Research priorities should consequently be modified by

TABLE 1. *Geographical extension of main soil constraints in five agroecological zones of the tropics (Sanchez, 1989)*

Soil constraints	Humid tropics	Acid savannas	Semi-arid tropics	Tropical steep-lands	Tropical wetlands
	% of ecological zone				
Drought stress	-	100	100	77	67
Low nutrient reserves	66	55	17	27	3
Aluminium toxicity	57	50	13	26	4
Acid, but not Al-toxic	18	50	29	16	29
Slopes steeper than 30%	17	16	15	100	1
High phosphorus fixation	38	32	9	21	-
Shallow soils	7	5	16	54	-
Poor drainage	13	7	10	-	100
Low cation retention	11	4	7	-	-
Gravel	1	3	5	10	2
Shrink-swell	1	-	10	-	-
Salinity	-	-	2	-	7

the geographical context because the environmental constraints, such as the availability of water and nutrients, will change with location. Table 1 should be borne in mind when considering how appropriate a given research project is in a given location.

Conversely, the use of contrasting sites, in terms of environmental limitations, can promote understanding of universal processes. For example, if a particular tree-crop combination leads to significantly different crop biomass values in different ecological zones, determination of resource availability at each site may reveal correlations between limiting resources and growth. There are, however, problems with this approach. Many factors will change from one site to another in an uncontrolled manner, producing a complex set of variables which confuse systematic examination of individual factors.

Key research topics in order of priority

1. **Below ground studies in agroforestry systems**

1.1 **root architecture**, including intraspecific and interspecific variation in rooting pattern for multipurpose trees, the effect of environmental factors on rooting pattern, the effects of pruning the canopy on rooting pattern, and differences in root development of trees in relation to different propagation and planting methods.

1.2 **root dynamics**, including root turnover and its contribution to soil organic matter accumulation and soil nutrient pools.

1.3 **root competition**, both intraspecific and interspecific, and evidence for reduction in the intensity of interspecific competition through niche differentiation (resource sharing), particularly in a heterogeneous environment; changes in the degree of competition caused by alteration in resource levels within the environment e.g. evidence for reduced competition for nitrogen through nitrogen fixation.

1.4 **depletion of resources** by the crop, and the seasonal development of resource capture systems, including the importance of nitrogen fixation and studies on mycorrhizal populations, their frequency of occurrence and relative importance for enabling nutrient uptake and transfer by trees and crops; phenological mechanisms for temporal sharing of resources.

2. **Nutrient and water cycling in agroforestry systems**

2.1 **Maintenance of the resource base** in agroforestry systems, involving studies of nutrient and water cycling, to include determination of absolute inputs and outputs, the distribution of these resources between components of the system, and evidence for facilitation by the tree acting as a 'nutrient pump' in the system and increasing nutrient availability to the crop through leaf and root turnover.

2.2 **Efficient management of nutrients** held in tree and crop litter, including studies on the factors controlling nutrient release from litter and hence synchronizing nutrient release with uptake requirements of the crop; determination of length of fallow required to return the nutrient base to pre-cropping levels.

2.3 **Soil amelioration**, and specifically evidence for improved nitrogen status of the soil resulting from the presence of nitrogen fixing species in the system; the importance of soil organic matter accumulation for the retention of water and nutrients in the system.

3. **Traditional practices in agroforestry**

3.1 **'Ecological combining ability'** of species mixtures, to include studies on the scientific basis behind indigenous knowledge, and particularly investigation of the physiological characteristics of 'good combination' species, such as water and nutrient use efficiency, phenology, carbon allocation patterns.

3.2 **Ecotypic variation** and study of adaptation to stress within selected indigenous species.

3.3 **Alignment of agroforestry design** with patchiness of the resource base, and the significance of spatial configurations traditionally employed.

Special topics

There should be flexibility within the research strategy to enable the funding of topics which are outside the main programme outlined above, but which are deemed to be relevant and important. Special topics could be identified at meetings of an agroforestry network, and would reflect future changes in thinking about the operation of agroforestry systems, novel designs and applications, or technological advances enabling the development of new techniques.

Links to other government aid programmes

The research strategy should aim to tie in with projects funded under other government aid schemes e.g. bilateral aid, joint funding. The major proportion of ODA forestry projects (85%) are currently funded under bilateral aid agreements between the British government and individual countries. If an agroforestry network were to include workers on bilateral aid projects linked to agroforestry then a greater sharing of knowledge and resources would ensue.

ODA have recently created an initiative in 'Adaptive and Field Research', to complement the Strategic Research Programme by providing a continuum to carry the results of research forward to the ultimate users. The initiative notes that an idealized research system would be genuinely responsive, with a respect for, and understanding of, the needs of end users, and a willingness to involve them in the research process such that their requirements are reflected throughout. Thus the system would incorporate both bottom-up and top-down components, and individual research project's aims would be determined by the needs of all parties, foremost amongst them being the end user.

The research strategy proposed here has attempted to consider the need for a continuum, by specifying traditional practices in agroforestry and indigenous knowledge as a priority area. A better understanding of the scientific basis behind such practices will assist in solving the problems of end users, by linking existing practice with knowledge gained from research on the underlying mechanisms in operation.

A KNOWLEDGE BASE OF RESEARCH FINDINGS

There is a formidable problem in agroforestry, as in many other areas, in making the results of research projects accessible to others. Currently, the outputs of such projects usually take the form of scientific papers, published reports, monographs, manuals and conference contributions. These methods of dissemination make it very difficult for others to know what work has been done, let alone find the results of the research.

Information technology has been successfully applied in other areas of information handling with a dramatic effect on the ease with which a large body of information can be brought together in one place, selectively searched for specific items of information, and analysed. Examples include bibliographic databases, databases of information on tree species, and geographic information systems. The success of these approaches depends on the ability to structure information according to a highly stylized format. For example, each record in a bibliographic database is one publication, with fields for author, year, title, and so on.

A large proportion of the findings of research projects also have a well defined structure. For example, some research findings relate to the value of an attribute under some conditions, such as the rate of leaf decomposition for a certain tree species in a certain climatic regime on a certain soil. Other research findings characterize the relationship between attributes (such as the relationship between rates of leaf decomposition and soil temperature). The utility of this information for people wishing to interrogate it can be greatly enhanced by incorporating subsidiary information, such as on animal and plant taxonomies, geographical relationships, and tables of soil properties.

The establishment of a knowledge base of agroforestry research findings requires:

- the design of appropriate formats for the representation of agroforestry research knowledge;
- choice of appropriate knowledge-base software;
- choice of a suitable computer system;
- choice of appropriate media for the dissemination of the knowledge base.

INSTITUTIONAL REQUIREMENTS

Four organizational elements are required to drive the research strategy. The first concerns communication between researchers, necessary in order to achieve a standardization of approach and task sharing, with the aim of gaining an understanding of agroforestry systems and the processes involved, as a whole, by the exchange of information. Improved communication can be promoted by the construction of an informal network of people, serviced by a regular newsletter and workshops.

To be viable, the network would require the following support and structure:

1. Integration within existing international networking arrangements, for example the Agroforestry Project Group of the International Union of Forestry Research Organizations (IUFRO).
2. Centralization around two or three long term research sites based in contrasting ecozones, with regular workshops, perhaps biennially, in connection with these sites.
3. Financial support for the administration of the network.
4. Financial support for the production of a newsletter to promote communication between institutions involved.

The second organizational element concerns the need for a 'directed mode' research programme. It is widely accepted that a government programme for research on renewable natural resources should fund specific pieces of a jigsaw, which, when put together in combination with previous findings, would enable a complete picture concerning the fundamental processes operating in agroforestry systems to emerge. Indeed this was the rationale behind the funding of the review; to establish areas of weakness with the objective of directing funding at those areas.

Data management forms the third organizational element. Data which is dispersed amongst the many institutions that have been involved in aid funded projects is difficult to access by modellers. A centralized repository is required to improve access to project data. In addition to the storage of data, dissemination should be considered. The production of species monographs has provided a useful source of data and information, and can be an effective means of dispersal. Further species monographs should be encouraged, and a knowledge base constructed, to act as a reference source for agroforestry related research knowledge.

Fourth, modelling should be a fully integrated part of research: the separation of modellers and researchers is undesirable. The agroforestry network, proposed above, would include both modellers and field researchers; the modellers forming a core group within the network, but fully involved in research discussions and *vice versa*. To assist standardization of modelling approaches, help communication between modellers and non-modellers, and help researchers rethink their approaches, teaching workshops should be held under the auspices of the agroforestry network.

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