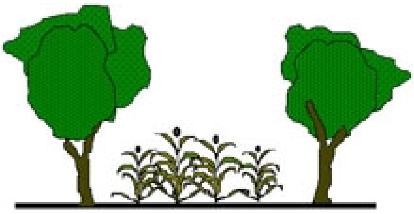
Agroforestry Modelling Project

Phase II (R6348)



Technical Summary

January 2000 (with Section 9 added September 2000)

Adobe PDF version has links to subcontractors reports, AMP Newsletters and other publications held on the AMP website (www.nbu.ac.uk/hypar)

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The report accompanies the HyPAR Technical Manual, HyPAR User Guide, 4 Subcontractor Reports and assorted publications submitted to the Forestry Research Programme in December 1999.

Any conclusions derived from the HyPAR model are the responsibility of the user and not that of The Institute of Terrestrial Ecology or the Department for International Development.

Agroforestry Modelling Project Phase II Technical Summary
Contents

1. Executive Summary

This report uses the DFID-Forestry Research Programme specified format[1], and describes the Background, Purpose Activities and Outputs of the FRP Agroforestry Modelling Project (AMP). These sections describe the success of the AMP in meeting its collaboration and model building targets, but much more modest achievements in developing a usergroup of overseas researchers who employ the models with real experimental data, rather than simply as an aid to teaching or understanding of processes. Activities of the AMP are also summarised in a series of newsletters which are appended to this report, and in a wide range of reports which are stored on the project website, and cross-referenced as live links within this document. Appendices are provided to clarify the Project's actions following a Mid-Term Review by Professor Porter of Copenhagen University.

Two final sections evaluate the success of the Project's Outputs in meeting its Purpose, and suggest reasons for current lack of uptake of the model by researchers and extension officers in target developing countries. Suggestions are made for a modest continuation project which focuses on the creation of libraries of parameter files for common trees, crops and soils; the maintenance of user-support for HyPAR and WaNuLCAS models, and continued support to the Agroforestry Modelling Newsletter, Discussion Group and Website to exchange up-to-date information on relevant projects, literature and meetings.

2. Background

This report gives a summary of the DFID-FRP Agroforestry Modelling and Research Co-ordination Project (Phase II), R6348, which itself is a continuation of the AMP Phase I (R5651). The first of these projects started in January 1994, and the second finished in March 1999. Since that time, limited user support has been maintained by the Institute of Terrestrial Ecology (Edinburgh). Appended with this summary report are:

- HyPAR v3.0 User Guide (April 1999);
- HyPAR v3.0 Technical Manual (December 1999);
- Agroforestry Modelling Project Annexes (December 1999) - comprising reports by Hodnett (Institute of Hydrology), Livesley (Reading University), Taylor (University of Edinburgh) and Thomas (University College North Wales);
- assorted publications associated with the Agroforestry Modelling Project (December 1999), including recent Agroforestry Modelling Newsletters.

The FRP Agroforestry Modelling Project (Phase I) arose from a workshop in 1993 (Anderson *et al*. 1993), where the potential for agroforestry to sustain yields and soil fertility in situations of increasing population pressure was agreed, but where major scientific uncertainties were highlighted affecting the potential uptake of this 'new' technology. A further workshop (Lawson & McIver 1995) concluded that, whilst many agroforestry field-studies had reported overall increases in crop yields, there were also contradictory results, and the net effects were highly site-specific and difficult to predict. The workshop summarised the position as:

- Species interactions have complex implications for ecological diversity, risk and socio-economic uptake - that are best understood through a ***modelling approach***.
- Plants modify their environment and vice versa, therefore ***mechanistic*** studies which identify these feedbacks should be included in models to make them applicable to different mixtures and locations.
- Modellers and experimenters should emphasise ***below-ground interactions***, including root-architecture, root-turnover, nutrient uptake, leaching and resource partitioning.
- ***Different nutrients are limiting in different areas*** and climates, and more attention is needed on nutrient-water interactions, the effects of soil structure and heterogeneity, and phosphorus limitation in the humid-tropics.
- ***Planned comparative experiments*** are necessary on contrasting sites and slopes, with a wider range of agroforestry types.

[1] *The document style matches that used in the HyPAR User Guide and Technical Manual.*

- ***Pruning*** influences water uptake, root growth and canopy photosynthesis in a manner that is often crucial to the success of agroforestry, but is poorly understood.
- ***Light interception*** is comparatively well studied - and there is a place for both complex single-tree models, and generalised canopy models - but the partitioning of assimilates to root or shoot growth is poorly understood.
- Species and varieties of both trees and crops can be ***optimised for particular locations*** and mixtures, and tree ideotypes should be sought with light crowns and deep roots.
- ***A generic agroforestry 'shell'*** is needed which links existing sub-models in a manner which synthesises knowledge and predicts the effects of management; this requires a mechanism to link modellers and experimenters, common standards for sub-model communication and minimum datasets for observations.
- A ***modular modelling framework*** should be developed to links alternative modules, with different levels of complexity, in a user-friendly environment.
- Models should predict long-term agricultural ***sustainability***, and interface with ***socio-economic factors***, including a comparison between low-yield-low-risk and high-yield-high-risk options.
- Process, system and knowledge based models should always ***consider the end-user****.*

The Agroforestry Modelling Project Phase I ran from June 1993 to May 1995 (R5651), the achievements of which are described in Lawson *et al*. (1995). Phase II ran from July 1995 to March 1999 (R6348), although the final nine months represented an extension. The main programming effort was completed by March 1998 and the final period was devoted to improvement of the Agroforestry Modelling Environment (University of Edinburgh), development of socio-economic agroforestry templates (UCNW), measurement and modelling of nutrient and water relations in an agroforestry experiment in Kenya (Reading), improvement of pedo-transfer functions (IH) and building a graphical user interface to the HyPAR model (ITE). Reports from these subcontracts are appended with this summary.

The AMP was lead by Professor M. G. R. Cannell and co-ordinated by Mr G. J. Lawson of the Institute of Terrestrial Ecology. Drs D. C. Mobbs and J. Arah (ITE) undertook the main programming effort. Main subcontractors were Dr S. Allen, Professor J. Wallace and Dr M. J. Hodnett (Institute of Hydrology), Dr N. M. J. Crout (University of Nottingham), Professor P. J. Gregory and Dr S. J. Livesley (University of Reading), Dr T. H. Thomas (UCNW), Dr R. Muetzelfeldt, Professor P. Jarvis and Dr J. Taylor (Edinburgh University), Dr R. Matthews (Cranfield University), Dr S. Jagtap (IITA, Nigeria) and Professor C. Ong (ICRAF, Kenya). Many other scientists have played a role, particularly those managing FRP experimental agroforestry projects. Most are included in authorship of the publications listed in Section 5.1.

3. Project Purpose & Outputs

The purpose of the project was: **'knowledge of crop-tree interactions in the below and above-ground environment improved and incorporated into management strategies'**. The following Outputs were planned:

1. To promote liaison between agroforestry modellers and those involved with agroforestry practices in ODA bilateral, FRP and JFS projects, and in ICRAF, GTCE, IITA and TSBF, in order to add value and rigour to information obtained from experiments and models, and to improve advice given to farmers. To maintain the Steering Committee, the Agroforestry Modelling Newsletter, regular contact between collaborators, and an International Agroforestry Newsgroup on Internet.
2. To promote the integration of information obtained from agroforestry models and experiments in order to define optimal agroforestry practices in different regions. The scientific and technical objectives were:
   - to develop process-based agroforestry simulation models that couple tree, crop and soil processes (the C, N and water cycles) and are driven by daily climate (the main model product will be HyPAR (Hybrid-Parch), but other models will be developed to address particular problems);
   - to use the models to test hypotheses regarding the competition between trees and crops for light water and nutrients, and to explore options for different management regimes in a large number of different soil types and climates;

- to interact with field researchers in defining the processes represented in models, and the parameters to be measured in the field;
- to develop a modular modelling framework to link component sub-models and provide a friendly user interface.

3. To validate HyPAR and the simple modular models using datasets on tropical trees, crops, soils and climates provided by ICRAF, IITA and international agroforestry networks, and to deliver a working, fully documented model, to these customers.

4. Research Activities

The AMP has 12 stated Activities. The first 24 months were mainly devoted to developing and improving biophysical models in conjunction with potential users. The final 12 months concentrated more on dissemination, validation and continuing model improvement.

4.1 Liaison

1) Produce a six-monthly 'Agroforestry Modelling Newsletter', reporting progress in this project and in related work elsewhere. Issues published during Phase II of the project were: 5 (Jan 1997), 6 (Jan 1998), 7 (Oct 1998) and 8 (July 1999). Circulation of issues 5 and 6 took place by post, but later issues were distributed mainly by email. All of these are available on the project website (http://www.nbu.ac.uk/hypar).

2) Hold meetings with collaborators in the FRP, ICRAF, IITA, TSBF and GCTE (including visits to ICRAF and IITA) in order to exchange information, data and programme components. Since June 1996 papers on the AMP have been presented at the following principal meetings and a number of other lectures and courses.

i) Liaison group on crop modelling using the PARCH Model, Newcastle (10-11 September 1996)

ii) GCTE Focus 3 meeting on 'Multi-species Agroecosystems' (Bogor, Indonesia, 18-20 March 1997).

iii) IUFRO/INRA/CIRAD meeting on 'Agroforestry for Sustainable Land Use' (Montpellier, France, 23-28 June 1997).

iv) UK Agroforestry Forum, (7-9 July 1997, Silsoe, UK).

v) Course on 'Agroforestry Options for Ghana' (28 July -1 August 1997, Kumasi, Ghana).

vi) GCTE Focus 3 meeting on 'Modelling Inter-plant Competition in Natural and Agro ecosystems' (Wageningen 12-14 November, 1997).

vii) Agroforestry modelling travelling workshop held at Edinburgh, Silsoe and Reading from 8 - 25 June 1998. Participants included Daniel Mugendi (Kenyan Forestry Research Institute), Paxie Chirwa (Forestry Research Institute of Malawi), David Mungai (University of Nairobi), Herman Odhiambo (ICRAF, Kenya), Betha Lusiana (ICRAF, Bogor, Indonesia), Didik Suprayogo (Brawijaya University, Malang, Indonesia), Agustin Mercado (ICRAF, Phillipines), Salvador Hernandez (UNAM, Mexico City).

viii) ICRAF internal workshop on agroforestry Nairobi, Kenya, 14-17 September 1998, with 15 participants from 8 countries.

ix) EU-DGXII meeting on 'Strategies for Sustainable Development in Dryland areas of East Africa' (Addis Ababa), 9 -12 November 1998 (in press)

x) Agroforestry modelling satellite workshop, CATIE, Costa Rica, 22-23 February 1999. This accompanied the CATIE-IUFRO meeting on multi-strata agroforestry systems, and took place over two-days. Twenty-five Participants from 13 countries took part and were able to explore the HyPAR and WaNuLCas models.

xi) A DFID Systems Programme meeting at Rothamsted on 26 October 1999 considering potential applications and impact of the PARCH crop model.

The project assisted Dr M. van Noordwijk (ICRAF) to visit the UK for 2 weeks in February 1997 he visited subcontractors in Edinburgh, Reading and Wye. Six-liaison meetings of sub-contractors took place during the AMP Phase II, including oversees participants such as Professor C. Ong (ICRAF), Dr S. Jagtap (ICRAF) Professor J. Porter (Univ Copenhagen) and Mr J. Ingram (GCTE). Subcontractors have produced a number of papers relating to their agroforestry modelling activities (see Section 5.1).

3) Organise a second Agroforestry Modelling Workshop in Spring 1997 to assess progress with data collection and programme development. This workshop took place in Edinburgh on 28-30 May 1997, and the proceedings were reproduced as a special issue of Agroforestry Forum (Vol. 8 No 2). There were 17 individual short papers in the issue, and the style was intended to be accessible to students and extension officers. 150 copies were distributed to participants in subsequent courses and lectures.

4.2 Modelling

a) Fully couple the tree and crop components in HyPAR with the carbon, water and nitrogen cycles integrated on a daily timestep. HyPAR v2 was fully coupled for light, water and nitrogen in multi-layer soil profiles where the roots of trees and crops compete for limiting resources according to their relative root length densities in each layer (Mobbs et al. 1999). HyPAR v3 introduced full 3-dimensional disaggregation below and above-ground. From v2 both trees and crops grow on a daily basis, although canopy size and light infiltration is incremented only when trees are actively growing. Crop growth in HyPAR is limited by phosphorus, but its effect on tree growth has also been introduced into the HyCAS model (Matthews 1998), and routines are available for inclusion in HyPAR.

b) *Develop the overstorey canopy sub-model of HyPAR so that it is capable of simulating simple disaggregated canopies with different geometries and spatial arrangements*. Shadow convolution was first introduced in HyPAR v2. Initially calculations were made for areas of the field with different shading intensities, but HyPAR v3 now calculates shading for a user-selectable grid of points across a field between trees placed at actual positions. Calculations of the light filtered out by surrounding trees is time-consuming, and is only done when one the canopy of a tree grows by more than a set percentage. To simplify these calculations light is assumed to be distributed following a 'standard overcast sky formula'. This gives a good approximation to average light conditions in much of the tropics. The effect of disaggregation on predicted crop yields has found to be considerable (Mobbs et al. 1998), potentially changing crop yields by as much as 50% compared with predictions from older 'undisaggregated' versions of HyPAR.

c) *Develop tree-root growth routines to: i) simulate the abstraction of water and nutrients from different soil layers and at different distances from the tree-trunk, ii) simulate the geometry of structural- and fine-root growth and how this might change in response to concentration gradients of water and nutrients*. A number of alternative soil-water movement models have been introduced into HyPAR v3 and the user is given a choice between these. Three types of 'pedotransfer function' have been used to predict the water movement model parameters from routinely measured or estimated textural information, such as bulk density and soil/silt/clay proportions (Arah & Hodnett 1997). Trials have demonstrated great sensitivity of model predictions to the choice of hydrology model and pedotransfer function (Lott 1998, Livesley 1999), and guidance is given in the form of a look-up table of the types of function that are appropriate for different soil types (Hodnett 1999). Root uptake of water and nutrients is closely linked to soil water content, root length density and plant demand. Several collaborative FRP projects have provided information on changes in tree-root profiles in response to management practices, and the most-probable estimates for root growth-seasonality and longevity (R6363, R6364, R6321, R6076). These studies have reinforced the importance of good measurements of root distribution, but also confirmed that that fine root biomass does not vary seasonally in proportion to leaf biomass, and that the uptake 'activity' of fine roots is not always proportional to length (Wilson et al 1998). Nevertheless, in the absence of better understanding, the simple algorithms of proportionality remain in HyPAR v3. Significant improvements have also been made in the representation of carbon allocation within the tree routines (Lawson & Mobbs 1998), enabling the model to be used more effectively to simulate coppicing and pollarding. Photosynthate is frequently observed to be allocated to root growth rather than leaf growth in situations of poor nutrient or water supply, but here again, there is insufficient quantitative evidence at this stage to make this allocation ratio a function of soil conditions.

d) ***Introduce a simulation of the way in which temperature and humidity of tree and crop canopies interact****.* The Institute of Hydrology's ERIN model (Allen et al. 1998) demonstrated that microclimatic interactions between tree and crop canopies can be highly significant. Tree canopies clearly reduce the amount of light reaching the ground, but they also alter the efficiency of heat and water vapour exchanges with the atmosphere and these in turn modify microclimate. During 1998 this work was considerably extended and simulations of interdependent fluxes of heat and water vapour in a tree-crop-soil system have been found to agree well with field measurements (Hall 1999).

e) ***Simplify and modularise the MAESTRO model so that it provides a comprehensive tree canopy sub-model****.* This component was funded for only 12 months and is reported in the 1994-95 Annual Report. Progress with modularisation has continued at Edinburgh University outwith the AMP.

f) ***Develop a modular modelling environment which links a range of agroforestry submodels at different levels of complexity****.* Further development of the AME (an Agroforestry Modelling Environment) has taken place including: (i) completion of the graphical user interface for diagrammatic model construction; (ii) developing a low-level language for representing model specifications, and tools for manipulating these specifications; (iii) a program generator that can produce runnable versions of a model in either C or Tcl; (iv) extensions to the program generator for models with multiple, interacting individuals; (v) demonstrations that existing agroforestry (sub)models can be re-implemented within AME; (vi) production of a simulation environment for models produced within AME; (vii) implementation of 2 or 3 example models for demonstration and training purposes; (viii) provision of a generic mechanism that allows anyone to produce their own customised input and output tools; (ix) production of a program to generating an html model-description document for any model; (x) production of documentation as a web page; and release of the AME software. This software has been used in a further FRP project to examine issues controlling farmer behaviour at the forest margin (the Flores project).

4.3 Validation and Extension

a) Obtain from the literature, and ongoing experiments, the best available parameters required by HyPAR for tropical trees and crop species, and compare model outputs with measured data from a range of locations and crops. Collaboration with IITA and ICRAF (Jagtap and Ong 1997) has identified data from a number of existing alley-cropping trials, but significant problems have been highlighted in the availability and reliability of such data. Release of a 'user-friendly' version of the model to these institutes has been undertaken, but uptake has been limited by staff transfers and lack of parameter libraries for a range of typical crops (q.v.). Another aspect related to extension is liaison with other modelling groups. The International Consortium for Agricultural Systems Applications (ICASA) links a large international group of crop modellers, and provides an integrated shell for generic models of grain crops (CERES-maize, wheat, sorghum, millet, rice, barley), legumes (CROPGRO-soyabean, peanut, drybean), and root crops (e.g. CROPSIM - cassava). Latest versions include models for sunflower, sugarcane and pasture. ICASA formats are used by agronomists worldwide to access libraries of soil, weather and experimental yield data held in standard format. Cranfield and ITE jointly merged the Hybrid tree model with the ICASA cassava model 'GUMCAS' in a similar way to the approach used with HyPAR. This resulting model (HyCAS - Matthews 1998) has been made available to IITA for validation with field experiments (Ekanayake 1999). Similar hybrid models could be developed with comparative ease for other crop models within the ICASA family. HyPAR has been used for predictions across rainfall transects, where trees were shown to have a very deleterious effect on crop average yield and reliability below a rainfall of 800mm, but this early assessment did not include the option for trees to tap a deep water-table (Cannell et al. 1998). Recently HyPAR was also used to predict the long-term capacity of agroforestry to sequester carbon in Kenyan soils (Ong et al. 1999).

b) Obtain data from intensive agroforestry experiments at one or two specific sites (conducted within the FRP or by ICRAF) which can be used to parameterise HyPAR, and test against measured yields in agroforestry systems*.*

Validation runs of PARCH are reported in three studies from Kenya. The first was completed in February 1998 as part of the FRP (Nottingham-IH-ICRAF) funded CIRUS project (Complementarity in Resource Use on Sloping Land - R5810). Detailed measurements of two crops (maize and cowpea), and a tree *Grevillea robusta*, were made over a 30 months period, and complemented by further information on tree growth, hydrology and microclimate available over a 4.5-year period. This preliminary study was mainly conducted with the July 1997 Version 1, and provided useful experience of the difficulties in parameterising the model with field data, and of the significant problems which existed with early representations of soil hydrology. Problems also existed because in HyPAR v1 the tree canopy grew only annually, and was rounded to 1m height growth steps. The results of this study are presented in on the AMP website (Lott 1998). Most of the faults reported have been addressed in later versions of HyPAR but two of Lott's criticisms remain unaddressed: mixed crops cannot be simulated, and only one crop is permitted per year. The latter problem is serious limitation to assessing the long-term impacts of different crop rotations, and may limit uptake by experimenters and extension officers.

Two further studies in collaboration with ICRAF used HyPAR v2.6 in conjunction with data from Embu (Mugendi unpublished) and Nyabeda (Livesley 1999) in Kenya.

Mugendi worked with the Kenyan Forestry Research Institute and ICRAF. He used version 2.6 of HyPAR with maize growth data from Embu, and achieved moderately successful matches to crop and tree growth (Mugendi 1999). However, he found great difficulty knowing which parameters to alter to calibrate the model with specific varieties of trees and crops, and did not have the benefit of the more complete datasets collected at Machakos and Nyabeda. There is much more which can be made of this data since it is theoretically one of the most complete datasets held by ICRAF (Section 7).

Livesley (1999), working at the University of Reading and in association with ICRAF, conducted a field-study component of the AMP using data collected from field and laboratory studies in the sub-humid highlands of western Kenya. *Grevillea robusta* tree lines and *Senna spectabilis* hedges were intercropped with maize on a deep Oxisol. Objectives of this component were: to (i) measure nitrogen uptake of the trees and crops over the growing season; (ii) measure the spatial distribution and density of tree roots before and after maize cropping through trench sampling, and that of maize roots during the cropping season through augering; (iii) measure spatial and temporal distribution and concentration of nitrate and ammonium before and after maize cropping through trench sampling; and (iv) measure the spatial and temporal distribution of water using a neutron probe, (v) use the HyPAR model to simulate results.

Using HyPAR v2.6 Livesley tested all 13 possible hydrological frameworks within which HyPAR can operate, but found only 7 to be viable for the site's soil characteristics. There was great variation in the predicted amount, mode and temporal pattern of water loss and this had a direct effect upon NO_3 accumulation, movement and loss. In a year receiving 1875 mm of rainfall, there was between 19 and 1184mm of evaporation and between 291 and 1808mm of drainage from a bare soil surface depending on the water model chosen. Simulations with one 'pedotransfer function' predicted significant N leaching losses from a bare fallow, whereas the other simulations predicted accumulations of NO_3 in the upper 45 cm of > 80 mg kg^{-1} in the first year. Hodnett (1998) has provided guidance on the selection of 'correct' pedotransfer functions, but clearly this advice needs to be formalised in a look-up table provided within the HyPAR User Interface.

By adjusting root and grain related parameters, HyPAR was able to reasonably simulate the measured growth, yield and resource uptake by maize, except for insufficient development of maize leaf biomass and area[2]. HyPAR accurately simulated the measured tree growth and carbon allocation in the first 150 days, but predicted an exponential increase in *Grevillea* biomass in the medium term[3]. After the first simulation year, there was a large annual decrease in maize yield, mainly because of competition for water but also for light close to the tree row. The trees easily dominated the uptake of available water and NO_3. Livesley,

[2] which in Version 2.6 was erroneously capped
[3] which was due to erroneous capillary replenishment of water in both v2.6 and the Beta v3.0

like Lott, criticised the lack of an ability in HyPAR to simulate two crops in a year, and felt that the number of parameters and sheer size of output files (particularly in the disaggregated version) meant that, whilst HyPAR is a useful tool for process level understanding and research development, it not yet sufficiently developed to be used for yield prediction and management evaluation in the hands of extension officers (See Section 7). A Microsoft Excel spreadsheet, *hypar.xls*, is now included in the HyPAR package. This file contains a set of macros that assist the user to open and examine the required HyPAR output files and rapidly create a range of standard graphs. A more extensive set of plots could be added if required.

c) Add a socio-economic component to the modular modelling environment, which allows the outputs of biophysical models to be interpreted in meaningful terms for the end user.

This activity was scheduled to take place mainly in the final phase of the project (Thomas & Willis 1998). Templates were developed to link predictions from HyPAR and AME with spreadsheets (Thomas 1999). The spreadsheet files were designed to be generic in that data from any intercropping system could be used and modelled. The system can include a tree component that has a main product, for example a fruit or a nut, which can be processed into eight end products, a byproduct that could be leaves and timber. The analysis can include the on-farm processing of all the end products. There can be two perennial crops and two biennial crops. There can also be up to five annual crops grown over two seasons within a single year. The crops can be rotated between years, or within years in the case of the annuals. Different crops may be more suitable at different times in the rotation depending on competition with the tree component for light and water so a succession of crops can be accommodated. The files were created in and should be used with Microsoft Excel version 6.

5. Outputs

ITE organised 3 workshops (UK, Kenya, Costa Rica), gave lectures to several University of Edinburgh courses, the UK Agroforestry Forum (Cranfield University), an EU-DGXII meeting on 'Strategies for Sustainable Development in Dryland areas of East Africa (Addis Ababa), an IUFRO/CIRAD symposium on temperate agroforestry, and GCTE meetings in Bogor & Wagingenen. Other sub-contractors have presented their work at a similarly large range of locations.

5.1 Publications

5.1.1 Refereed Publications

- Allen A, Roberts J, Smith M, Jackson N & Lawson GJ (1997). Simulating the interaction between tree cover and crop temperature. Agroforestry Forum 8(2): 20-23.
- Arah J & Hodnett M (1997) Approximating soil hydrology in agroforestry models. Agroforestry Forum 8(2): 17-20.
- Cadisch G, Rowe E & van Noordwijk M (1997). Nutrient harvesting - the tree-root safety net Agroforestry Forum 8(2): 31-33.
- Caldwell RM (1997) Common ground for comparing models and datasets. Agroforestry Forum 8(2):4-7.
- Cannell MGR, Mobbs, D.C. & Lawson G.J. (1998). Complementarity of light and water use in tropical agroforests. II. Modelled theoretical tree production and potential crop yield in arid to humid climates. Forest Ecology and Management, 102: 275-282.
- Cannell MGR., Wilson J., Deans J.D., Lawson GJ. Mobbs, D.C. & Leakey RBB (1998) Tropical forestry and agroforestry. p34-39. Scientific Report of the Institute of Terrestrial Ecology 1997-1998,
- Fawcett RH, Nkowani K & Smith CJN (1997) Multiple objective socio-economic models of agroforestry systems. Agroforestry Forum 8(2): 42-45.
- Hall RL, Milne R, Lawson, GJ, Verhoef A, Mobbs DC, Brown T, Allen SJ and Wallace JS (1998). Combined growth and water use modelling of mixed vegetation. CEH Integrating Fund Project T06050P2. IH Wallingford.
- Jagtap S & Ong C (1997). Perspectives on issues, needs, and opportunities for agroforestry models Agroforestry Forum 8(2): 2-4

- Lawson GJ & Wright HL (1997) Agroforestry in British overseas aid programmes. Agroforestry Forum 8(2): 49-52.
- Lindley DK, Diagne O, Deans JD & Dione D (1997). Nutrient budgets in a chronosequence of *Acacia senegal* plantations. Agroforestry Forum 8(2): 27-30.
- Livesley SJ, Gregory PJ and Buresh RJ (1997). Approaches to modelling root growth and the uptake of water and nutrients. Agroforestry Forum 8(2): 24-27.
- Livesley S J, Gregory P J and Buresh R J (1997) Tree root and soil nitrogen and dynamics in a maize-based tree line agroforestry system. In Proceedings of Agroforestry for Sustainable Land-use Fundamental Research and Modelling Conference, Montpellier, France. CIRAD/INRA, p. 315-320.
- Livesley S J, Stacey C L, Gregory P J and Buresh R J (1999) Sieve size effects on root length and biomass measurements of maize (Zea mays) and Grevillea robusta. Plant and Soil (in press).
- Lott JE, Black CR & Ong CK (1997). Resource use and growth in semi-arid agroforestry systems. Agroforestry Forum 8(2): 35-37.
- Matthews RB & Lawson GJ (1997). Structure and applications of the HyCAS model. Agroforestry Forum 8(2): 14-17.
- Mobbs DC, Cannell MGR, Crout NMJ, Lawson GJ, Friend AD & Arah J (1998). Complementarity of light and water use in tropical agroforestry. 1. Theoretical model outline, performance and sensitivity. Forest Ecology and Management 102: 259-274.
- Mobbs DC, Crout NMJ, Lawson GJ & Cannell MGR (1997) Structure and applications of the HyPAR model. Agroforestry Forum 8(2): 10-14.
- Monteith JL (1997). Agroforestry modelling: a view from the touchline. Agroforestry Forum 8(2): 52-54.
- Muetzelfeldt RB & Taylor J (1997) The suitability of AME for agroforestry modelling. Agroforestry Forum 8(2): 7-9
- Noordwijk van M, Lawson GJ, Soumare A, Groot JJR, Kurniatun H (1996). Root distribution of trees and crops: competition and/or complementarity. In: 'Tree-crop interactions - a physiological approach, Chapter 9 (p319-364), P. Huxley & C. Ong (eds). CABI-ICRAF, Wallingford-Nairobi
- Taylor JA & Muetzelfeldt R. A modular modelling system for agroforestry.. Workshop on 'Agroforestry for Sustainable Land Use', 449-452, CIRAD/INRA/IUFRO Montpellier 23-29 June 97.
- Thomas TH & Willis RW (1997). Linking bio-economics to biophysical agroforestry models. Agroforestry Forum 8(2): 40-42.

5.1.2 Internal Reports:

(Many of these are available from the AMP website -http://www.nbu.ac.uk/hypar)

- Annual and Quarterly Reports each quarter from September 95 to March 99.
- Lawson GJ, Cannell MGR, Mobbs DC, Crout NMJ, Muetzelfeldt R, Allen S, Gregory PJ, Matthews RB, Thomas TH, Jagtap S, Arah J, MacDonald KJ, Taylor J, Sharp L, Roberts JM ,Jackson N, Smith SM, Livesley SJ, Willis SW, Wright HJ and Ong C (1997) Annual Report (July 1996- June 1997) Agroforestry Modelling and Research Co-ordination Project, 98pp. ITE: Edinburgh.
- Lawson GJ & Mobbs DC (1998). Carbon allocation in individual tree models: a literature review and description of recent modifications made to the HyPAR model. In: Combined growth and water use modelling of mixed vegetation. Centre for Ecology and Hydrology Project T6050P2. 23p.
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5.1.3 Others

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- Lawson GJ (1998). Agroforestry Modelling Newsletter, no.7. 6p, ITE Edinburgh, October 1998.
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5.2 Workshops & Meetings

Workshops in Bogor, Nairobi, Kumasi, Manilla and Turrialba; travelling workshop in Edinburgh, Cranfield and Reading. Presentations at international meetings in Montpellier, Bogor, Nairobi, Wageningen and Reading (see Section 4.1).

5.3 Related publications mentioned in Section 4.

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- Ekanayake IJ (1999). Activities in Cassava Modelling, Productivity, Food security and Global Change. Final Report of ATART Visiting Scientist Fellowship. ATART Report No IJE-01- 99.
- Mugendi (unpublished). Progress report on use of the HyPAR model with data from Embu, Kenya.

5.4 Programmes

HyPAR Version 3.0, HyCAS Version 1.0, Agroforestry Modelling Environment (AME) are available from their respective websites, together with other programmes like ERIN (IH) and a merged Edinburgh Forest/Hurley Pasture model (ITE) which are available from the developers but are not actively supported. Long-term support for these three models cannot be guaranteed, and is discussed in Section 7.

6. Contribution of Outputs to Project Goal

6.1 Mid-Term Review Assessment

A 'Mid-Term Review' by Professor John Porter (Copenhagen) covering the period June 1995 - May 1997 was submitted on 1st June 1997. This found 'the project to be of a high international standard' and 'saw no need to recommend large changes in direction'. However it did recommend a focussing of effort during the remaining months to achieve the remaining goals before the planned end of the project (originally by March 1998) (Appendix I). It also recommended that certain aspects of the project be offered short extensions: these included: developing pedotransfer functions for a range of tropical soil types (IH), completing the characterisation of root profiles in Masena, Kenya (Reading), implementing a version of WaNuLCas in the AME (Edinburgh), including phosphorus relations in the HyCAS (Cranfield), and continuing development of interfaces to socio-economic spreadsheets (UCNW), and developing a graphical user interface for HyPAR (ITE).

Thus the contract was revised in January 98 to provide an additional £79k in financial year 98-99 shared between ITE (£13.4k), UE (£14k), UCNW (£4k), Reading (£13k), Cranfield (£15k), IH (£15k), and workshop costs (£5k). The completion date was moved to 30th September 1998, and subsequently, at no cost, to 31st March 1999.

6.2 Project Self-Assessment

Whether agroforestry benefits farmers depends on the **biophysical** implications of environmental conditions, species choice and management regimes, and the **socio-economic** implications of agroforestry activities versus other uses for the farmer's resources.

The HyPAR biophysical model has potential to provide a **predictive** tool for researchers and extension officers, but it will also provide an insight into the processes taking place when predictions apparently 'fail'. HyPAR potentially allows hundreds of combinations of soil, climate, tree, crop and management scenarios to be tested that could never be investigated experimentally, and ICRAF have recently argued that agroforestry experiments should not be undertaken unless the hypothesis can first be tested using a model (Coe 1999).

Whilst models have the potential to assist overseas scientists and extension officers in evaluating agroforestry systems, the most extensive application of HyPAR so far to real data has been carried out by two UK PhD students. ITE researchers have published papers on 'boundary-conditions' for agroforestry, but these have not yet been compared to observed data. Around 80 scientists or extension officers in developing countries have been exposed to HyPAR and 20 provided with training for at least one day. There are 31 registered users (December 1999), and many have appreciated its power as a teaching tool, and for evaluating the changing interactions between different limiting conditions, yet careful application of the HyPAR model to field results has so far been very rare. There are a number of reasons for this

- Raw data across the full range of environmental, crop and tree measurements necessary to parameterise or evaluate the model has proven lacking, even in well-know international experiments where such data was expected to be available: there are problems here of poor data storage, data reliability, data ownership protocols and experimental design.
- Users do not have access to the range of literature necessary to make approximations to parameter values, and tend to be overawed by the complexity of the model, and number of parameter values which it requires. Libraries of typical parameter values for major tree and crop species and soil types would alleviate this problem (q.v.).
- Users do not have familiarity with the need to optimise certain parameter values to achieve a good fit to local data.
- Users are presented with 4 hydrology models and 3 pedotransfer functions (methods of predicting hydrology model parameter from soil structure measurements) - this is a bewildering choice and one which greatly affects the final predictions, as do assumptions over soil crusting and cracking - development of a look-up table to guide users in the selection of correct options for their specific soil types is a priority.
- Users do not have the larger computers necessary to run the disaggregated options in a realistic period of time (although this constraint is diminishing).

- The crop model was based on Nottingham University's PARCH model, but after 1995 the DFID supported crop modelling community appeared to move away from PARCH and developed a range of rather uncoordinated alternatives - which meant that the HyPAR team could not rely on the development of external crop parameter libraries and validation papers that we had expected - in retrospect it could have been preferable to join the Hybrid tree model with a models from the large and well tested DSSAT/ICASA family of models. Many users overseas did not use HyPAR because they have never heard of PARCH, and could find no published papers on it.
- Initial soil water and nutrient conditions are difficult to predict and seldom measured - it has proven difficult to persuade users to 'spin-up' the model for a number of years till these values equilibrate, rather than expecting the model to work perfectly from simulation day one.
- Full below- and above-ground disaggregation was not developed till version 3.0, and did not work satisfactorily till February 1999 - this was too late to allow evaluation within the Project's lifetime - and discouraged users who decided to wait till the 3-D version was available before testing with their own data.
- The HyPAR Graphical User Interface is reasonably sophisticated but can't meet the need of every user - during several of the user workshops there were minor (and inevitable) teething-problems, which discouraged some users.
- Some users complain that the output files are too big and complicated; whilst others complain that certain variables have not been printed out and should have been included in the files. The Graphical User Interface provides user-selection on the type of output files which will be created and the new Excel Macro program (HyPAR.xls) provides a range of standard graph options for inexperienced users.
- Radiation change beneath trees is modelled, and temperature and humidity changes modelled in a stand-alone version of the IH ERIN model, but this model is not routinely connected to HyPAR because of its large computing time requirements - this reduces the predictive power of HyPAR to a significant extent.
- Many management options are included in the interface (complete flexibility of fertiliser, manure, pruning, pollarding, green mulch timings and rates etc.), yet other users come up with farmer's practices that are not included.
- The inability of HyPAR to represent multiple crops, mixed crops and relay-intercropping is a disincentive - although users do recognise that the last two would be extremely difficult to implement.
- Departures from reality are treated as failure, whereas they often open greater insights into the workings of the system - models are inevitably a simplification that can never completely work (and problems of root distribution, activity and seasonality are discussed above).
- HyPAR (as opposed to the BEAM economic spreadsheet) does not consider products (e.g. fruits), and wider impacts (e.g. erosion) or social factors (e.g. risk-accepting strategy) may be more important to the farmer than average yields, but could not form part of the current project.
- Success of the project in demonstrating a linkage between the BEAM economic spreadsheet with HyPAR or the AME was not great.
- HyPAR operates at a plot scale, whilst agroforestry is often important at the edges of fields or in widely dispersed strips, which needs several plot-scale sub-models to be integrated in a farm-scale model.

However, the AMP has had numerous plus points. The mid-term review pointed out that the progress made in the project would have cost much more, and involved a larger team had it be conducted anywhere but Britain! An extensive list of outputs has been completed. Modellers have evolved their aims to cater for the needs of users - initially the AMP had no economic component, and did not aim to use small-scale experimental results. Experimentalists have changed their designs and measurement to provide data suitable to parameterise models, and in several cases have realised that they were failing to measure crucial variables, or storing data inadequately. Trainers and extension officers have been exposed to the models and have indicated their enthusiasm and intention to use them in the future.

Some reviewers and users question whether HyPAR is too complicated and over-parameterised a model to have used in this project, others have claimed that the models are too simple to represent the complex interactions in agroforestry systems. Some reviewers have criticised the economic component in the project as being too modest; others have doubted the worth of including economics when the predicted yields are still uncertain.

Some users have doubted whether the detailed plot-based disaggregated version of HyPAR should be used with general regional predictions of 'boundary conditions', yet we have shown that disaggregation and daily allocation of carbon makes a great difference to local and regional predictions. The AMP has attempted to evolve to please all potential users, generally by delivering more than originally promised. We feel that a powerful and comparatively user-friendly model has now been made available, but because of its late completion the uptake by potential users has been disappointing. A modest follow-up project is proposed which could greatly assist this uptake.

7. Required follow-up

Models can never be 'finished' but several of the AMP's products are now ready for adoption. The AME, as a modelling framework for the forest-agriculture interface in SE Asia is already being supported by the FRP. HyPAR and ICRAF's WaNuLCAS represent different approaches: HyPAR is a comprehensive biophysical model where users concentrate on parameterisation rather than changing the code; WaNuLCAS is a somewhat simpler (although not below-ground) component-framework-type model where users can alter the representation of processes and components. We recommend that a small 'adaptive phase' project could

- commission the creation of libraries of parameter files for common trees, crops and soils,
- maintain user-support for HyPAR and WaNuLCAS,
- continue production of the Agroforestry Modelling Newsletter, Discussion Group and Website to exchange up-to-date information on relevant projects, literature and meetings in an easily read manner.

Continuing collaboration with ICRAF and a core network of users and data holders is proposed. Collaboration is also required with the DFID Systems Programme who have funded a number of projects on the development and dissemination of the PARCH crop model.
User support would be provided not by inviting senior staff in a given institute to attend glamorous-sounding seminars on modelling, but by selecting a core of the most computer literate and motivated individuals in given country, providing them with self-instruction tutorials, and supporting remotely their attempts to use the models, and to participate in discussions on the email list. They in turn will undertake dissemination to their colleagues, and provide a more sustainable method of extending the modelling approach.
This project would run for only 12 months. One output is the identification of continuation funding; another is closer integration with international modelling efforts, such as those co-ordinated by ICASA. Considerable DFID and ICRAF effort has been devoted to the development of the two supported models. We consider that it is not best value for DFID at this stage to support alternative agroforestry models, nor to further develop approaches to systems dynamic modelling, which are either currently or potentially provided by proprietary software packages such as ModelMaker or Stella – the latter having been used to build the WaNuLCAS model. HyPAR and HyCAS provide sophisticated models of tree and crop growth, whose strengths are their potential accuracy provided the correct values are given to a large number of parameters, their weakness is the difficulty in providing these parameter values, particularly for novice users. This project proposal therefore aims to provide an expert system to assist in parameter selection for the three models, many of whose parameters are common.
WaNuLCAS is a powerful alternative to HyPAR/HyCAS which allows enthusiastic users to manipulate the way that tree and crop growth processes are represented within the model. The aim is to integrate the user-groups of HyPAR/HyCAS and WaNuLCAS, to stress the different approaches and strengths of each model, and to ensure that significant numbers of researchers in the six target countries are applying the models to their own data, disseminating the results of their simulations, and participating in plans for further (non-FRP-funded) workshops by the end of the 12 months period. An anticipated output is that the user-group should be self-supportive by the end of the project.
HyPAR users in institutions from a number of target countries (CIAT-Bolivia, UNAM- Mexico, ESALQ, Univ Sao Paolo, Brazil, FRIM Malawi, University of Harare, Zimbabwe, FRIU Uganda etc.) are starting to use the modelling software with their own experimental data.

Users of WaNuLCAS are mainly focused in SE Asia (Indonesia 15, Vietnam 20, Philippines 20), but no attempt has yet been made to disseminate in DFID-target countries. Email support will be focused on those institutions that make most active use of the models.

Alternative funding sources will be explored to link predictive outputs from biophysical models with multiple-objective household economic models and GIS databanks of physical and economic information, and to move towards a true decision support system for agroforestry, which can potentially 'optimise' the agroforestry system recommended by an extension officer to meet the specific objectives of a given farmer.

Use could also be made of MSc or PhD students who would receive training in the models in the UK then visit CGIAR or NARS sites and assist local scientists to take best advantage of their existing data on agroforestry experiments.

8. Appendices

8.1 Appendix I. Summary of Responses from the AMP team (August 1997) to Professor Porter's External Review of June 1997.

We find the report to be extremely thorough and fair, and are pleased that Professor Porter feels our project to be of a high international standard, with outputs significantly in excess of those specified in the application for funding. He concludes that we have provided excellent value for money, but makes a number of recommendations to tighten the final dissemination phase, and improve the usability of the packages that have been developed. We accept his recommendations and priorities. I have collated and numbered those that relate to the remainder of the project, and will comment briefly on these (in italics) and summarise their financial implications.

Professor Porter's recommendations and priorities shown in normal type, AMP team comments in italics.

Liaison

1. Issue 6 of the Agroforestry Modelling Newsletter should be produced as soon as is relevant, followed by a final Newsletter in March or April 1998 **Priority 1**. *The AMP Workshop proceedings have been published as a special issue of Agroforestry Forum 8(2), and summaries made available on the web (http://www.nmw.ac.uk/ite/edin/agro.html). Newsletters are planned in August 97 and March 98 (EXISTING BUDGET)*

2. Output from AMP2 be presented at international conferences and workshops. I would recommend that copies of the final software are demonstrated at such meetings. **Priority 1.** *HyPAR and its preliminary Graphical User Interface (GUI) were discussed and demonstrated at the 2nd ODA agroforestry modelling workshop in Edinburgh in May, at a CIRAD/ INRA/IUFRO Agroforestry Conference in mid-June, at the UK Agroforestry Research Forum meeting early July, and at a workshop in Kumasi on 'Agroforestry Options for Ghana' in late July'. Completion of the GUI and users manuals are crucial to the uptake of HyPAR. Participation in two future workshops is planned (OPTION A).*

3. Customer individuals and institutes should be well represented at the 2nd Agroforestry modelling workshop. **Priority 1.** *ICRAF and IITA were represented, but many more potential users were reached at the Ghana Workshop, and will be trained at the ICRAF Nairobi workshop (qv).*

Modelling

4. Complete the implementation of competition for nitrogen **and phosphorus** in HyPAR v2.0. **Priority 1.** *Nitrogen is completed but linking phosphorus requires an extra time allocation, because significant new code must be written for the tree model (OPTION B)*

5. Complete implementation of daily allocation of photosynthate to leaves and roots in the tree component of HyPAR v2.0. **Priority 1.** *Agreed (OPTION A)*.

6. Discontinue development of the Edinburgh and Hurley Pasture Models within the Agroforestry Modelling Environment (AME) to allow more time for HyPAR v2.0 to be completed. *Accepted.*

7. Provide PARCH and Hybrid as selectable options from the DSSAT Shell for use alongside other IBSNAT models (e.g.Cassava), but the main method of disseminating HyPAR models should be within the AME. **Priority 2.** *This refers to extension of the prototype Hybrid - Cassava model (HyCAS) developed recently by Cranfield and ITE. Techniques in this prototype could be used with the other generic IBSNAT models (for cereal and legume crops), allowing different crop rotations to be modelled and providing access to a large worldwide dataset of crop growth data (OPTION C). A more modest activity would be to provide an interface to HyPAR V2.0 which can read crop, soil and climate datasets in IBSNAT format (OPTION A).*

8. Investigate the incorporation of HyPAR v2.0 into the AME. **Priority 1.** *This is indeed a high priority, but it is a 3 month task needing a significant extra budget (OPTION C)*

9. Repeat the analyses of regional suitability of agroforestry using the enhanced HyPAR v2.0. **Priority 1.** *Agreed (OPTION A).*

10. Include the ERIN model as an option in HyPAR v2.0. **Priority 3.** *This will not be undertaken given the low priority level.*
11. Provide 2-D convolution as an option for calculation of yields along transects between single trees and groups of trees. **Priority 1.** *Agreed (OPTION A).*
12. Discontinue possible disaggregation of the Hurley Pasture/ Edinburgh Forest Model - *Agreed.*
13. The main emphasis of the soil-root work should be on experimental analysis of the detailed sets of root data being collected in different agroforestry situations. **Priority 1.** *One AMP subcomponent, and three related FRP projects are engaged in this.*
14.Develop simpler 'demand based' models of root growth. **Priority 2.** *This is mainly the responsibility of Reading University (OPTION B).*
15. Introduce temperature and VPD modifications to crop and tree photosynthesis and transpiration calculations in HyPAR. **Priority 1.** *IH and ITE have made significant progress on this already (future funding from the NERC SCIENCE BUDGET - 'INTEGRATING FUND')*
16. Improve HyPAR v2.0's water-balance calculations using pedotransfer functions to derive soil hydraulic parameters from simple measurements of particle size distribution and bulk density. **Priority 1.** *Agreed and significant progress made already, but more comprehensive compilations of pedotransfer functions necessary in different regions (OPTION B).*
17. Modularisation of the MAESTRO model is desirable from a long-term perspective. **Priority 3.** *This will not be undertaken within the AMP given this low priority rating*
18. Develop a Graphical User Interface for the AME and produce specific dialog boxes. **Priority 1.** *Agreed - largely undertaken already (OPTION A).*
19. Develop the AME module library of ecological relationships. **Priority 2.** *Agreed, this is not crucial to the delivery of a working model framework but extends its utility (OPTION C).*
20. Produce AME manuals and release software. **Priority 1.** *Agreed (OPTION A).*

Validation and extension

21. Explore climatic boundary conditions and sensitivities for different agroforestry systems and management strategies. **Priority 1.** *Agreed - this is a main goal of the project and requires to be undertaken with the improved radiation, water and nutrient treatments in HyPAR 2.0. (OPTION A)*
22. Confirm PARCH and DSSAT predictions with sorghum experimental yields for a range of soils and climates. **Priority 2**. *Agreed as task for Nottingham (OPTION C)*
23. Parameterise Hybrid for Eucalyptus sp and compare measured volumes from permanent sample plot data. **Priority 2.** *Agreed as task for ITE (OPTION C).*
24. Liaise with experimentalists at ICRAF and IITA to evaluate HyPAR 2.0/AME using experimental data. **Priority 1.** *Agreed. (EXISTING BUDGET).*
25. The AME should include an option for output to a spreadsheet based bio-economic model. **Priority 1.** *Agreed as task for UCNW and UE (EXISTING BUDGET FOR UCNW, OPTION A FOR UE).*
26. Modify the economic subprogramme in DSSAT to run with agroforestry options. **Priority 2.** *The central task for UCNW was to use the DSSAT economic subprogramme as a model to introduce in HyPAR, allowing the prediction, and optimisation, of yield and economic options to be fully integrated. UCNW prefer the spreadsheet approach however (EXISTING BUDGET).*
27. HyPAR v2.0 should be offered to DSSAT and run under the DSSAT shell, with full compatability with DSSAT inputs and output formats. This activity should run in parallel with development of the AME and not substitute for it. **Priority level 1.** *DSSAT no longer has a donor and relies on a network of voluntary support from scientists worldwide. They are unlikely to wish to use* HyPAR *v2.0 because it duplicates their existing crop models. This was the reason for developing HyCAS - as an example of how Hybrid routines could be integrated with minimum change in existing DSSAT programmes. This largely repeats Recommendation 7.*

Funding Implications

The Porter Report makes 27 specific recommendations. Of these 4 are already completed or duplicated elsewhere, 5 are covered by the existing AMP budget, and 3 involve discontinuing project activities. The remaining 15 require extra funding to be completed satisfactorily. We offer 3 funding packages to complete these in decreasing order of priority.

Option A

Recommendations 2 and 24 stress the high priority of a final project workshop at ICRAF Nairobi, to demonstrate the results of initial collaboration with ICRAF/IITA, and to expose users to the models and frameworks. The costs of ITE staff travel and participants expenses are included in the existing budget, but for the many aspects of the AMP to be represented we'd like Muetzelfeldt (UE), Crout (Nottingham), Matthews (Cranfield) and Allen (IH) and Thomas (UE) to attend as trainers. The extra cost will be approximately £5,000.

Recommendation 18, 20 and part of 25 involve completion of different aspects of the AME. As top priorities this would involve: (a) release AME, and provide documentation and training on its use; (b) implementation of a link between AME and economic spreadsheet models; (c) production of a technical evaluation of possible methods for incorporating HyPAR v2.0 in AME; (d) provision of more complete sample agroforestry models. The total cost is the £12,000 recommended by Professor Porter.

Recommendation 2 (HyPAR manuals and user interface), 5 (daily photosynthate allocation), 7 (reading DSSAT input files), 9 (updating regional analysis of agroforestry boundary conditions) complete the essential aspects of HyPAR. Professor Porter recommended an allocation of 100 days HSO programming time to Dr Mobbs to allow these tasks to be completed by March 1998. By demoting recommendation 4 (phosphorus linking) to Option B, we could complete the tasks in 60 days at a cost of £15,180.

Thus the total for Option A = £32,180

Option B

Option B would undertake the Recommendations in Option A and would additionally include recommendations 4 (linking phosphorus in HyPAR), 14 (improving root growth models), and 16 (developing pedotransfer functions). These would be tackled by ITE, Reading and IH respectively. They have not been costed in detail, but each represents a very important area restricting the applicability of agroforestry models.

Option C

Option C includes the recommendations in Options A and B, and in addition addresses recommendations 7 (integration of agroforestry into the IBSNAT family of models), 8 (integrating HyPAR within the agroforestry modelling environment), 17 (completing modularisation of the MAESTRO canopy interception model), 19 (developing ecological libraries as part of the AME), 22 (extending testing and calibration of the PARCH) model in crop monocultures, and 23 (calibration and testing of Hybrid in plantation monocultures). These extra activities have not yet been costed.

8.2 Appendix II. Conclusions of an AMP Review Meeting on 6th August 1997 between John Porter (Manager FRP), GJ Lawson & DC Mobbs

1. John Palmer agreed to Fund Option A, and would consider Option B if costings were presented together with recommendations from the Directors of ICRAF and IITA that the 3 areas (phosphorus, root models and pedotransfer functions) are particularly important to their Institutes.
2. He stressed the vital need to demonstrate that the models were responding to users demands prior to and during the March workshop at Nairobi (19-24/8/98). ICRAF and IITA should sponsor a bid next year to the Holdback Fund for further application of the models.
3. He suggested funding 2 staff from each of ICRAF and IITA to visit ITE and Edinburgh University in Autumn for training in HyPAR and the AME.
4. He was concerned that the two main target institutions, ICRAF and IITA, propose to validate in-house the models developed. He appreciates that this avoids arguments over data ownership and access, but thought that that there needs to be a transparent protocol for the validation. Project participants should make time to develop and agree such a protocol.
5. He was concerned that project team should made provision for resolution of different interpretations associated with the development of model components, and with experiments feeding into model development. In particular, he was concerned that are the various hydrological and root studies may not all be in agreement?
6. He was concerned over the lack of data from ICRAF and IITA in suitable form to validate the model. I indicated that this concern was shared by the whole team, and data collation was a priority during the remainder of the 'dissemination phase'.
7. Arne Heineman's FRP-funded survey of alley cropping experiments would be sent to Lawson & Leakey for liaison with ICRAF on whether the data justified wider FRP-sponsored dissemination.

8.3 Appendix III. Registered HyPAR users - January 2000.

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9. Comments relating to FRP Supplementary Final Technical Report Instructions[4]

The Forestry Research Programme Supplementary Institutions for Project Leaders (updated 14th August 2000) require emphasis on the following points:

- how the problem was identified;
- how the research process and objectives were clarified jointly with collaborators and target institutions;
- the research results;
- the policy and socio-economic developmental implications of the research results, especially for the target institutions. This is especially important since DFID now requires (since 29 June 1998) that target institutions should adopt the results of the research.

The previous sections give much more detail but it hoped that these concluding comments provide a useful commentary specifically on the above points.

9.1 Problem identification

The project largely arose from a Forestry Research Programme (FRP) workshop in 1993 and was perhaps more driven by a researchers' view of priorities than might be the case at present, when the FRP makes strenuous attempts to identify and rank research priorities as perceived by our developing country partners. However, even in 1993, the workshop was widely representative of not only the UK research community, but also users of this research in national and international research institutes. The workshop reflected major concerns that had started to develop after a previous conference in Edinburgh on agroforestry in 1989. This conference had challenged the accepted wisdom that tropical agroforestry, particularly in the form of 'alley-cropping' using nitrogen fixing species, was an easy and immediately applicable technical solution to soil degradation throughout the tropics. At that time agroforestry was being launched in massive extension programmes and appeared a panacea.

However, competition between trees and crops for resources of light, water and nutrients is a complicated process, and whether agroforestry produces a net benefit to the farmer depends greatly on the species chosen, the management used, the soil and climate combinations and the degree of attention that the farmer is able to give to maintenance. Analysis from 1989 onwards of earlier tropical agroforestry results was showing that too much faith had been placed in results derived from unreplicated demonstration plots, from excessively small experimental areas where control plots were situated too near to neighbouring trees, from tree species which were later damaged by pest attack, from 'alley-cropping' trials which sampled only a small range of soil fertility and rainfall combinations, and from studies which emphasised the yield benefits without realising that the labour required to achieve these yields was unacceptable to most farmers. Successful extension appeared to have taken place, but subsequent analysis showed that farmers may have initially adopted the 'new' techniques to gain what they perceived to be potential favours from the research institute.

1993 was a time to take stock of the millions of dollars which had already been invested by many tropical research institutes in the development and extension of agroforestry systems such as alley cropping. It was recognised that little of the research had provided a **predictive insight** into which type of tree-crop combination and management is appropriate for a specific location. Nor had the research adequately considered farmers multiple objectives, scarce resources of land, labour and money, and other factors such as risk-acceptance, relationships to neighbours and differences in land-tenure, which affect the adoption of new technologies. The 1993 workshop recognised that interactions between trees, crops, soils, climates and people were so complex that there was no guarantee that the results observed at one site would be repeated at another. The workshop also felt that research on underlying **processes** was urgently needed to help explain the **reasons** for

[4] *Added 29.9.2000*

these differences in the effectiveness of agroforestry, and concluded that the processes are so complicated that only computer models could hope to represent them   Emphasis was placed on developing a collaborative modelling team which would a) integrate our current understanding of complex agroforestry systems, b) pinpoint gaps in knowledge, c) prioritise work on these; d) extrapolate research results to new combinations of soil, climate, species and management system (too numerous to be studied with field experimentation), e) provide decision support to researchers, extension agents and policy makers, and f) develop team-work amongst researchers and extension agents.

The intention was that these predictions and the models behind them would be available to researchers in developing countries. In 1993 the bio-physical modelling problems appeared so challenging that any attempt to include socio-economics or farmers choices was postponed. This was not because the importance of these factors was belittled, simply the intention was to focus initially on the largest and most difficult task - developing the bio-physical model.

9.2 How the research process was clarified jointly with collaborators and target institutions

The initial phase (94-96) focused on the technicalities of building a complex model. A scientific steering group met twice and two UK workshops were held to bring together the modellers, with UK researchers and international collaborators. The final workshop devised a strategy for a continuation project, and published proceeding in the semi-popular journal ‘Agroforestry Forum’.

The second phase (96-99) continued developing the model, adding refinements and a more integrated representation of 3-D competition for light, water, nitrogen and, to a lesser extent, phosphorus. A dissemination phase allowed the models to be presented at three hands-on workshops and the tutorial guides and Graphical User Interface to be developed (Section 5).

Our partners in ICRAF, IITA and other international institutions such as CATIE recognise the need for biophysical models in evaluating and ranking different types of experiments. Such models may be parameterised on one experiment and ‘validated’ against similar experiments. This ‘validation’ is necessary as a ‘reality check’, but ICRAF are keen to point out that models are useful even when they “fail” - which they frequently will! This failure represents a discrepancy between assumptions in the model and the real world, and therefore provides an effective means of identifying and ranking areas we don’t know enough about. Models can never make perfect predictions, and are never ‘finished’; nor can they replace experimentation, but they do allow a large number of hypotheses, scenarios, and proposed 'experiments' to be evaluated. Some in ICRAF (Coe 1999) have argued that field experimentation should not be undertaken unless the hypothesis can first be tested using a model. For example, the hypothesis might be that 'adding green mulch in alleys increases crop yield', but the model could demonstrate that crop-tree competition for water means that the hypothesis is only valid in situations with low nitrogen and high water supply.

Many simulation models of crop and tree monocultures exist. However, they often contain a large degree of empiricism, meaning that the models can be parameterised to make accurate predictions for a particular species or ecotype, but fail dramatically when applied to situations outside their calibration range. Attempts to combine models of different species were previously disappointing because most monoculture models don’t require to represent rooting systems accurately. Models developed in this project (e.g. HyPAR) and those worked on in parallel by our partners (e.g. WaNuLCAS) reflect this three-dimensional competition, and are quite unique in their representation of root architecture

9.3 The research results

Section 4 deals with research Activities and Section 5 with Outputs.

HyPAR 3.0 is a Fortran programme whose use is facilitated by a Windows 95 interface of tabs and buttons which are used to edit the run conditions (site, climate manipulation, periodic resetting of state variables, management options), soil characteristics (layers, texture, cracks, pores, hydrology options), tree parameters controlling growth of a generic tree or woody shrub, crop parameters controlling the growth and development of generic grain crop, and output data options. It can simulate crop and individual tree growth on a field with up to 400 plots – although with this number of plots it runs slowly.

HyPAR v1.0, was written in 1995 by combining the tropical crop model PARCH (Bradley & Crout 1994) with components of the tree model Hybrid v3.0 (Friend *et al.* 1997). HyPAR v1 calculated light interception and water use by a horizontally-uniform tree canopy (which was always above the crop), annual tree biomass increment (net primary productivity), the light and water available to an understorey crop and hence crop growth, and potential annual grain yield (assuming optimum management and no pests or pathogens). It included the soil water movement and uptake routines of PARCH, and utilised those parts of Hybrid which determine light interception, water use and tree productivity and biomass partitioning.

Hybrid v1.0 is described in Mobbs *et al.* (1997), and was used by Cannell *et al*. (1997) to predict the 50-year mean 'potential' sorghum yields and overstorey net primary productivity in nine climates (348mm - 2643mm rainfall) with uniform overstorey leaf area indices of 0 to 1.5. They concluded that simultaneous agroforestry may enable more light and water to be 'captured' than sole cropping. However, in regions less than 800 mm rainfall, because of low water use efficiency of trees and sensitivity of crops to shading, it is difficult to increase **total** productivity without jeopardising food security. The authors recognised, however, that conclusions from this early version of HyPAR ignored the soil fertility relations of trees, their potential access to deep water-tables, and other economic benefits such as shade, fuel and fodder.

HyPAR v2.0 introduced competition for nitrogen and was used by Lott *et al.* (1997) to test predictions of maize growth in Kenya. Later versions included improved soil water routines and options for management of the tree canopy. HyPAR v3.0 includes daily allocation of tree photosynthate, routines to represent disaggregated (i.e. clumped) canopy light interception, and 3-D competition for water and nutrients between the roots of trees and crops. Software, documentation, and newsletters are available from http://www.nbu.ac.uk/hypar/ (Section 5).

Close collaboration has also taken place with ICRAF in their development of WaNuLCAS, which is a written in the Stella system dynamic language, and which therefore remains open to user modification. Emphasis in WaNulCas is placed on below-ground interactions, where competition for water and nutrients is based on the effective root length densities of both plant components and the current demand by tree and crop. It represents climate, soil, water balance, nitrogen balance, growth, uptake, demand, competition for water and nitrogen, root growth, soil organic matter fluxes and light capture through a network of nested compartment flows and influences (van Noordwijk & Lusiana 1999).

HyPAR and WaNulCas are similar in approach, but differ significantly in detail. Each has advantages in different circumstances, but they share the need for a large set of parameterisation information. This report has proposed a modest extension to **collate a parameter library of crop, tree and soil information** which will assist users select appropriate parameter values, as a first approximation to their own situation, without facing the daunting initial task of collating such information afresh from the literature. These parameters can be classed into 3 groups:

1. those which the average user can take as fixed;
2. those which vary within known ranges;
3. those which we have little information on.

Then for any agroforestry question the parameters in Group 3 to form “experiments” or “sensitivity analyses”. Those in Group 2 generate uncertainty, or the error term, in these experiments.

Participants at workshops using both models have concluded that the approaches used in the models are essential to enable researchers and extension staff to understand the complexities of agroforestry systems. Some participants found they **only required part of the models** – like the shade pattern predictor, or microclimate modifier, or the N-leaching routines. In WaNulCas the user can relatively easily extract the relevant modules and create his/her own model. In HyPAR options are provided in the interface to switch off part of the model (e.g. ‘no crop’, ‘no tree’, ‘reset trees at end of year’, ‘reset soil conditions at end of year’). These options may need to be expanded (e.g. trees shade but don’t grow). Numerous extensions have been suggested in workshops, and the interaction of users with modellers is analogous to a ‘process project’, where stakeholders modify the activities as the project proceeds. Possible extensions include factors such as completion of P cycling in HyPAR, SOM-related N-retention coefficients, long-term feedback of organic matter and root accumulation on soil structure, addition of flowers, fruits and resin extraction, predicting mulch effects on weed germination, consideration of root crops and bananas, inclusion of pests and diseases etc. However the danger has to be recognised that **models can easily grow to become too complicated**, **and modellers could become too wedded to their own particular approach.** A suite of models (or sub-models) may be needed for different purposes, and both open-structured compartment-flow models (in Stella, Modelmaker, AME or ACSL) and conventional models in modern modular programming languages (C++, Fortran 90), with well documented user interfaces are required.

9.4 The policy and social development implications of results

There has been a rapid increase of interest in agroforestry modelling since the project began. Applications range from calculations of the best timing and intensity of tree pruning, through the effect of hedges on soil erosion and catchment water yield, through to calculations of the effects of climate change on the productivity of agroforestry systems and the impact of agroforestry on local climates and its potential for carbon sequestration and the impact that this may have on Kyoto Protocol negotiations (q.v.). A significant proportion of the following biophysical papers used models developed or presented within workshops organised by the AMP.

There is no doubt that the really exciting aspect of agroforestry modelling is now in taking the existing models of bio-physical processes and combining them with improved representations of farmers multiple objectives, so that extension officers and planers can not only predict the immediate effect of different management options, but project the long-term trends in soil fertility and yield sustainability for a realistic period and the effects that this will have on farmers livlihoods and priorities.

Four Agroforestry Modelling Consortium members, including ICRAF, have submitted a small continuation project which addresses the comparative lack of uptake of existing models by proposing: to develop libraries of tree, crop and soil parameter values, to disseminate the models in conjunction with partners in South America and South East Asia, to integrate with the international ICASA modelling effort, and to start to develop **dynamic** linkages between bio-physical and socio-economic models. This integrated modelling package will offer a genuine planning tool which is based on the best available predictions of yield and environmental change following the implementation of different agroforestry management options, backed up by a parameter library of information for major crops, soils and trees.

Recent Examples of the use of bio-physical or socio-economic models in agroforestry

- Carbon-sequestration – modelling yield and carbon sequestration value of agroforestry and improved forest management in southern Mexico (De Jong et al., 2000).
- Climate – modelling the impact of climate change on forests and agroforests in different soils and climates and the parallel impact of vegetation change on climate – therefore providing a potential tool to assess the economic value of land use change incentives (Bazzaz, 1998; Dixon et al., 1999; Thornley & Cannell, 1996).
- Decision support – using land labour and cash constraints to generate a DSS which can be used to determine optimal agroforestry farming systems (Garciadececa & Gebremedhin, 1991).
- Drainage – calculating the effect of trees and root channels on soil water drainage and irrigation implications (Karajeh & Tanji, 1994a).
- Drought – assessing the water use of trees and the risk of their worsening the effects of drought in Australia (Hingston et al., 1998) and the impact of climate change in Senegal(Venema et al., 1997).
- Economics – a dynamic resource model is used to predict the effect of agroforestry on crop and timber production as well as labour organisation and amenities in southern France (Etienne & Rapey, 1998).
- Economics – a simulation model for farmer behaviour indicates that as land continues to be subdivided in Kenya competitive pressures and markets are such that tree cover may actually increase (Patel et al., 1995)

- Economics – calculation of economic yield from timber and non-timber forest products in riparian strips established for water quality control (Robles-Diaz-de-Leon & Kangas, 1998; Robles-Diaz-de-Leon & Nava-Tudela, 1998) and relative efficiency of different policy instruments (Wu et al., 1995).
- Economics – comparing the economic returns of silvoarable systems in Europe using a biophysical grass and animal model and together with traditional forestry yield tables (Bergez et al., 1999).
- Economics – comparing the economic value of different agroforestry designs and conventional forest plantations in midwest USA (Benjamin et al., 2000).
- Economics – comparing the economics of weed control by permitting smallholder agroforestry in rubber plantations with conventional chemical methods and shading (Grist & Menz, 1996).
- Economics – comparing the profitability and impacts of agroforestry, afforestation, natural succession, and 'new' agricultural systems in NE Germany.
- Economics – comparing the profitability of different farm models of crop and alley cropping mixtures in Sri Lanka (Nuberg & Evans, 1993).
- Economics – computing the intertemporal and interspatial total productivity of four intercroppping systems in SW Nigeria relative to stocks of major soil nutrients (Ehui & Spencer, 1993).
- Economics – modelling farmers choices dictating adoption of adoption of live hedges in Burkina Faso (Ayuk, 1997).
- Economics – modelling reasons for farmers choice of agroforestry systems in Cameroon (Adesina et al., 2000)
- Economics – modelling the expected yield of combinations of 5 timber species, 3 site indices, 5 crop species and common crop rotations to optimise the best long-term net present value (Campbell et al., 1991).
- Economics – multi-objective models of peasant households in northern Zambia and their views of alley cropping systems as means of replacing exiting cropping systems and reducing soil degradation (Holden, 1993).
- Economics – multiple objective linear programming analysis of Spanish farming, forestry and agroforestry (Despotis & Siskos, 1992), and in regional agricultural planning in Tunisia (Siskos et al., 1994)
- Economics – predicting the optimum spacings and management of loblolly pine cattle mixtures on marginal land in the US (Harwell & Dangerfield, 1991).
- Economics – providing a dynamic optimisation model for agroforestry where tree biomass and soil salinity evolve over time in response to harvest and irrigation water quantity and quality (Knapp & Sadorsky, 2000).
- Economics – study of the threshold net present values of tree-crop interactions needed to induce agroforestry in the US (Dyack et al., 1998).
- Economics – use of a STELLA model to simulate the negative ecological and economic impact of trees on crops and optimise the extensionist's recommendations for the number and type of trees which should be retained on fields (Chivaura-Mususa et al., 2000).
- Economics – using a spreadsheet model to predict the profitability of a wide range of agroforestry systems (Thomas, 1991; Wojtkowski & Cubbage, 1991; Wojtkowski et al., 1991).
- Economics – using linear programming models to determine the optimum combination of trees and crops for different farm groups and resource situations (Mahapatra, 2000).
- Economics – using the SCUAF model to quantify the value of soil conservation and erosion control following use of Napier grass strips and hedgerow intercropping in SE Asia (Magcale-Macandog et al., 1998; Nelson et al., 1998; Nuberg & Evans, 1993).
- Education – biophysical and socio-economic models are particularly important in agroforestry education (Lassoie et al., 1994).

- Erosing – calculating the sustainability and economic efficiency of agroforestry systems in Embu District, Kenya (Tamubula & Sinden, 2000)
- Erosion – calculating and modelling the erosion yield from different forested and agroforested areas in Indonesia (Kusumandari & Mitchell, 1997). and Haiti (Pellek, 1992).
- Erosion – scaling up ECOSYS, an individual tree growth model to integrate with a field-scale model of soil productivity and erosion for use at a regional scale.
- Fire – has been incorporated in a bioeconomic spreadsheet model of smallholder rubber agroforestry in Indonesia (Menz et al., 1999; Menz & Grist, 1996)
- Land use comparisons – quantitative multi-scale investigation of causes of different land use in Ecuador (de Koning et al., 1998) and the tropics generally (Lambin, 1997; Lambin & Ehrlich, 1997; Olson, 1998).
- Land-use comparisons – computer based GIS optimisation of forestry, agriculture or agroforestry under Mediterranean conditions (Delarosa et al., 1992; Mendoza, 1987; Mendoza et al., 1986).
- Management – optimising the degree of tree pruning of Grevillea in Kenya to conserve water and maintain growth (Jackson et al., 2000) and Erythrina in Brazil (Nygren, 1993, 1995; Nygren et al., 1996)
- Nutrients – measuring and modelling the use of bamboo fallows to maintain fertility in the Indonesian Italun-kebun agroforestry system (Christanty et al., 1997).
- Nutrients – modelling how coffee-agroforestry can conserve soil organic matter and reduce costly inputs of fertilisers and other chemicals (Alpizar et al., 1986; Beer et al., 1990; Beer et al., 1997; Fassbender et al., 1985; Fassbender et al., 1991; Gobbi, 2000).
- Nutrients – modelling the impact of different agroforestry practices on soil nutrient balances at the farm scale in the East African Highlands (Shepherd et al., 1996), and monitoring nutrient balances under different types of land use (Smaling & Fresco, 1993)
- Nutrients – models based on knowledge of the chemical composition of leaves will predict their speed and pattern of nutrient release when used as green mulch (Mugendi & Nair, 1997).
- Nutrients - Optimising the timing of nutrient application on Gliricidia – maize mixtures in Malawi (Ikerra et al., 1999), and predicting changes in erosion, soil carbon and soil nitrogen with time within various agroforestry systems in Zimbabwe (Vermeulen et al., 1993).
- Nutrients – quantifying and modelling the effect of forest removal, plantations, agroforestry and different cultivation practices on soil organic matter pools (Fernandes et al., 1997; Schroth & Zech, 1995).
- Nutrients – quantifying and modelling the effects of trees in increasing the grass growth and soil fertility in Senegal (Grouzis & Akpo, 1997).
- Nutrients – representing the different roles of trees as competitors or soil improvers in alley cropping systems (Haggar, 1994; Vandermeer, 1998).
- Nutrients – testing the ‘safety-net’ hypothesis that deep rooting trees prevent nutrients being leached from the system and recirculate them to shallow-rooted crops (Van Noordwijk & Lusiana, 1998)
- Nutrients - Use of a model of leaching from agroforestry strips to determine whether safe concentrations of nitrogen will be exceeded in water courses (Acutis et al., 2000; Huang et al., 1998).
- Nutrients – using models of nitrogen processes to predict optimum rotation lengths of Acacia fallows in Sudan and Senegal (Robertson, 1994).
- Policy - developing a tactical model of the management decisions required by a farmer or landowner to implement temperature agroforestry systems (Tourjee & Osburn, 1999)
- Policy – interactions between biophysical factors, perceptions and policy in Canadian forest landscapes (Domon et al., 1993).

- Policy – using a multi-seasonal model of agroforestry to compare tradeoffs for farmers according to different output criteria (Babu et al., 1995).
- Salinisation control – using models of tree growth and water uptake to predict how and where to plant trees and their effect on controlling increasing salinisation in coastal areas of Australia (Bui et al., 1996; Cramer et al., 1999; Lefroy & Stirzaker, 1999; Stirzaker et al., 1999) and elsewhere (Karajeh & Tanji, 1994b; Kroes et al., 2000; Letey & Knapp, 1995; Posnikoff & Knapp, 1996).
- Shelter – calculating reduction in windspeed near savanna woodland edges (Kainkwa & Stigter, 1994)
- Shelter – modelling the effect of shelter on the heat balance of sheep in the UK in relation to air temperature, windspeed, solar radiation, rain and humidity (McArthur, 1991).
- Shelter – quantifying the effect of tree windbreaks on pasture growth and animal production as a means of advising farmers on design and management (Bird, 1998).
- Water conservation – GIS and modelling techniques are combined to demonstrate that agroforestry combined with mulching and minimum tillage can improve water use efficiency (Liniger, 1992).
- Water conservation – modelling the interception of rainfall by tree canopies of different spacings shape and density (Teklehaimanot & Jarvis, 1991)
- Woodland grazing – modelling the impact and profitabity of livestock grazing , firewood collection, timber production and other uses in forests and agroforests of western Zimbabwe (Campbell et al., 2000).
- Woodland grazing – use of a non-linear multiple objective techniques to develop a decision support model for woodland grazing and agroforestry in the Chaco region, Argentina (Costanza & Neuman, 1997).
- Yield Prediction – assessing the probability distributions of yield from year to year with different climates and management methods (Vannoordwijk et al., 1994)
- Yield prediction – calculating the effect of forest management on and environmental conditions on growth of individual trees using biophyscial e.g. (Kirschbaum, 1999) or statistical (Knowles, 1991; Knowles et al., 1998) models.
- Yield prediction – identifying areas where rainfall totals and variability are likely to preclude certain agroforestry combinations (Cannell et al., 1998).
- Yield prediction – predicting optimum pruning intervals for Acacia saligna in Kenya (Droppelmann & Berliner, 2000) and shade under pruned trees in Australia (Reid & Ferguson, 1992).
- Yield prediction – predicting yield of tropical crops with different levels of shade and water competition (Black & Ong, 2000).

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