MODELS AS PART OF AGROFORESTRY RESEARCH DESIGN

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ABSTRACT

Agroforestry deals with land use systems which are more complex than the usual agronomic experimental designs can cope with. A combination is needed of process-based models, simple summarizing parameters of component interactions, experiments to highlight the interactions and surveys of the real world variation in farmer developed agroforestry systems and possible components. A framework is presented for such a step-by-step approach, in which model development and experimental work go hand in hand.

INTRODUCTION

There is nothing special about 'models'. In fact 'modelling' is so common that we cannot speak, think or observe without using and modifying 'models', or 'abstractions' from 'reality' (if there is such a thing as 'reality' at all). However, there are many different types of models and languages in which they can be expressed and there are different ways how to go about developing and improving models. We will here discuss some of these in the context.of 'research design' for agroforestry.

Don't believe the models you'll see,
unless your observations and data agree

Don't believe your data, again,
unless your models explain

However, suspicion will be surely on you
if the agreement is 'too good to be true'

Agriculture and agricultural research have always had a healthy suspicion of theory. 'Don't believe until you see' has been a proven strategy to deal with new ideas. Attempts to formulate 'models' of agricultural systems have not had many obvious successes in the past. Von Liebig's theories in the 19'th century about nutrient balances ('a farmer must replace by fertilizer all nutrients removed from the field by crop harvest') were soon discredited by experiments, which showed that, at least in the initial years of long term experiments, the best crop growth was obtained with amounts and nutrient ratios in fertilizer very different from that in the harvested products. Was von Liebig's theory wrong? No, but it was incomplete and didn't have the time scale correct. Yet, the obvious failure of his predictions and the more tangible results of 'empiricists' who started the Rothamsted experimental station have certainly helped to establish a research tradition in soil fertility research based on 'trial and error', rather than models and theory. Important elements of the current wisdom in 'agricultural research design' are still based on the model that the yield of a crop on a given site and in a given year is equal to some intrinsically unpredictable 'control' yield, plus terms for the specific treatment combinations used with coefficients that are unknown beforehand, plus 'error' terms. There is a rigorous system for testing hypotheses, but little attention to how to generate hypotheses and build a logical framework.

Young children learn that every answer can be followed by a question 'yes, but why?' and that they can thus quickly disentangle the apparently reasonable and logical world picture (model) of their parents. 'Explanations' are not really different from 'descriptions' ('it is like this, simply because it is like this'). Yet, we often make a distinction between 'descriptive' and 'process-based' or 'explanatory' models. This is only a difference in degree to which each new observation is respected as a new 'fact' to be entered into the encyclopedia or database describing the world, or disentangled in terms of previously known 'relations' and 'facts'. It is the difference between being 'diligent' and being 'intelligent'. 'Explanations' are attempts to delay our 'out of memory' messages - if we can reconstruct time- and location specific observations by combining general rules and with time- and location specific inputs, we'll have learned to interpolate and may gain some confidence in our ability to extrapolate and predict.

Models are statements about interactions (relations) between components. If these relations are sufficiently specified, models can be formulated in mathematical terms and can use the tool box of mathematics to establish logical consequences of the stated assumptions. These model results. ('hypotheses') can then be confronted with the real world (or at least with our perception of the real world). If there is a discrepancy, we have a choice (Fig. 1):

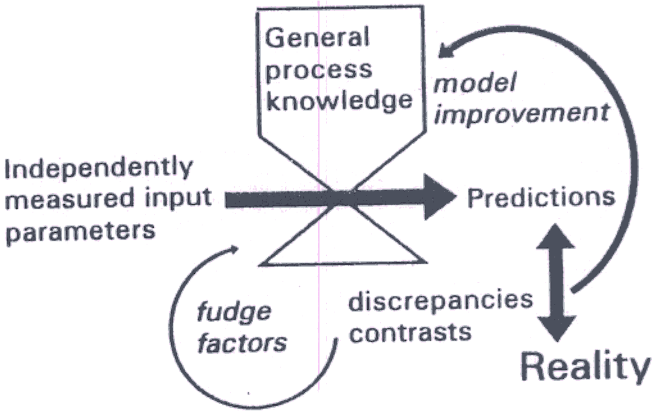

Figure **The model - observation cycle, with two methods for improving the performance of models.**

- we can question the model structure, the parameter values used to initialize the model or the internal consistency of the model (are the outcomes really the logical consequences of the stated assumptions ?),
- we can question the observations made in the 'real world' ('I will not discard my beautiful model because of some ugly facts'); no observations can be made without, implicitly, using other models, and these models may be as incomplete or wrong as the model which we wanted to test,
- we can abandon this field of research as being beyond our (current) capabilities to deal with it.

There is no such thing as 'model validation'. We may observe that the predictions of a specific model have been in accordance with the real world on a number of occasions, and that may increase our confidence in using that model again for a new situation, but we can never conclude that a model is valid in general terms. Generally, the more unlikely model predictions are at first sight, the more they'll increase our confidence in the model if real world observations are in line with them.

Doing experiments 'to test the effect of such and so treatments' is thus a waste of time. If we do not formulate our models, ideas, hypotheses, predictions beforehand, we'll never feel inclined to modify these ideas on the basis of research results.

Confrontations of model predictions with the real world give a test of the 'fitness' of the model. Often, models are formulated in such a way that they avoid the confrontation. Astrological 'predictions' and 'oracles' are good examples of statements which are so vague that they make everything 'understandable' in hindsight, but hardly exclude any possible outcomes for the future.

As the success of modelmakers is often evaluated on the basis of the success of their models, the 'survival of the fitter' emerged as strategy. By employing extremely flexible models, which in hindsight can be 'fitted' to any data set, they constructed models which are almost impossible to beat. Heuristic regression models are good examples of this: they never fail (by adding enough terms to the model we can always get a perfect 'fit'), and because of that we'll never learn much from them. Unless we naively believe that the coefficients established will be valid outside the range of observations from which they were derived. Regression models then are a way to formulate quantitative hypotheses for further tests, preferably in a new set of environments.

As alternative to this 'fitter' strategy of model development, we can have a 'tinker' strategy. Tinkers provide slight, temporary patch-ups to leaking kettles and pans. Modelmakers often have to resort to 'fudge factors' to make their models correspond with real world data. By doing so, their models 'degenerate' into regression type models.

Logical framework for Agroforestry research

So far we looked at agronomic research in general, with an example of crop-fertilizer response as something which may already be too complex to fully understand and model. What about 'agroforestry'? We have the choice between Z trees, Y crops, X spatial arrangements, W temporal arrangements of the components, V choices for other inputs, U options for managing the trees

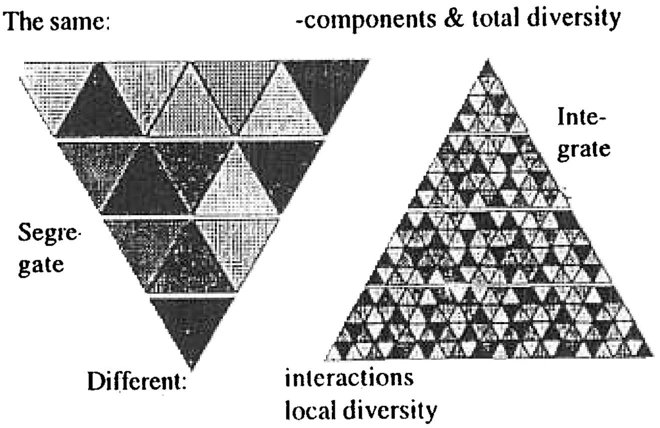

Figure 2. Segregate or integrate: the left and right hand triangle contain the same components with the same amounts of each, but in a different level of 'integration'.

Table 'Integration' and 'segregation' options of in land use

Functions	Segregated option	Integrated option
production of various tree products	a combination of trees, each for a different product	'multipurpose' trees
production of tree and crop products	crop fields and woodlots; sequential AF systems	simultaneous tree-crop AF systems
soil and water conservation & agricultural production	at *m-scale*: erosion in 'alleys' and sediment traps in 'contour strips'; at *100 m-scale*: erosion on slopes, filter strips along rivers, ricefields in valleys	continuous mulch cover
productivity and risk reduction	specialized farms with insurance schemes	mixed farms (crop - animal - tree)
biodiversity conservation and agricultural production	national parks and separate zones for intensive agriculture	agroforests, multifunctional forests
agricultural production and mitigation of greenhouse gas emissions	sinks (e.g. forest soils as CH_4 sink) make up for sources elsewhere (e.g. rice fields as CH_4 source)	crop and soil management to reduce on-site emissions
food security and economic growth	'economic efficiency' strategies; specialization; reliance on markets	'self reliance' strategies at national scale

by pruning etc., T time frames on which to evaluate the results, S ranges of soil conditions, R climatic zones, Q farmer preferences, P policy environments, O objectives to evaluate system performance, N sets of natural enemies, pest and disease pressures, M sets of market conditions, L situations of labour supply, K sets of indigenous knowledge, etcetera. Certainly, this is far too complex to model realistically. Certainly, this is also far too complex to deal with by trial and error. Imagine a K * L * M * N * O * P * Q * R * S * T * U * V * W * X * Y * Z type factorial design, even if we allow for only two levels per factor.

To integrate a practical and a theoretical approach, we need general principles of resource sharing (Cannel *et al.*, 1996) and more specific models of tree-soil-crop interactions (Van Noordwijk, 1996; Van Noordwijk and Garrity, 1995).

Land use systems serve different functions to different groups of people. These functions include the production of staple foods and tree products, the conservation of soil, water and biodiversity and the mitigation of greenhouse gas emissions. Advocates of agroforestry generally have optimistic views on how well these different functions can be combined. A central question for agroforestry research, which wants to critically examine and thus support the advocates and practitioners, is: which functions can be combined and which ones are better served separately. We need clear criteria for this choice. In theory at least, there is always a choice between simple (one function at a time - segregated) and more complex (combined functions - integrated) land use systems.

Table 1 indicates how the 'segregate - integrate' choice applies at different scales in the landscape and for different combinations of functions. The 'integrated' option should in each case be compared with its relevant 'segregated' option.

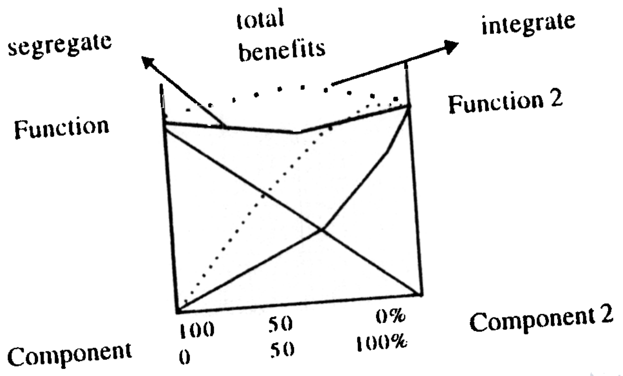

Figure 3. Replacement series design to compare the total benefits from a range of mixtures, at equal total density. This approach can be borrowed from the intercropping literature to investigate 'multi-functionality' of land use systems.

Trade-offs between tree and crop productivity in agroforestry systems are gradually recognized and the enthusiasm for intricately mixed simultaneous agroforestry systems based on trees and annual food crops is becoming less. Does this mean that in other versions of the 'segregate' - 'integrate' debate the arguments for the 'integrate' option have been over-estimated as well?

The 'segregate or integrate' choice for any combination of functions can be analyzed in the same way as the classical 'intercropping' analysis is done (Fig. 3). The balance of positive and negative interactions between the components associated with the various functions determines whether or not 'integrate' has a specific advantage. A key issue for agroforestry research is thus one of 'interactions' - biophysical interactions between components, as a basis of interactions between (outputs) functions of land use systems, as a basis for economic trade-offs and policy choices.

As a logical framework for agroforestry research at large, we can thus identify 'component interactions' as a focal point for research comparing 'simple' and 'complex' land use systems. We need a coherent way of making observations on these interactions in the real world, analyzing them in terms of independently observable characteristics of the components and the environment, and a synthesis model 'explaining' and 'predicting' interactions for a wide range of components and management choices.

WANULCAS model as quantitative hypothesis on resource capture

To start simple, the relations between a single crop and a single tree can be analyzed for a regular spacing and a constant (semipermanent) management regime. Alley cropping has been an ideal starting point for agroforestry research, because:

- it provides a simple model of agroforestry and is open for standard agronomic designs based on 'trial and error',
- the model does not work in the way it was expected, thus making clear that agroforestry needs serious research and not only 'spreading the gospel'.

In an attempt to analyze the considerable variation in crop yield obtained in 'alley cropping' experiments, a first model (Fig. 4) can be:

$$\mathbf{Y_c} = \mathbf{Y_0} + F_1 + F + C_1 + C_{n+w} + M$$

Table 2. A three-step approach to analysis and synthesis of tree-soil-crop interactions in simultaneous agroforestry systems, Direct experimental separation (1) of the terms in the equation is combined with quantification of key processes (2) and followed by model synthesis (3) to explore management options and system-site matching (Van Noordwijk *et al.*, 1997)

Y_c =	Y_0 +	F_l +	F +	C_l +	C_w +	M
Crop yield in interaction	Crop yield in monoculture	Direct fertility effect	Long term fertility effect	Competition for light	Competition for water and nutrients	Microclimate effects
1. Experimental		+/- Mulch transfer	Residual effect vs pure crop control	+/- Tree removal, + root barriers	Root barriers	
Process-level understanding		Litter quality, mineralization rates	Functional SOM fractions (Ludox)	Canopy shape, light profiles	Root architecture (fractal branching analysis)	
3. Synthesis model		WANULCAS				

stating that the difference in crop yield between a alley cropping and a no-tree control (Y_c and Y_0, respectively) is based on a generally positive effect of the trees on soil fertility, both on the short and on the long term (F_l and F, respectively), a generally negative effect of competition between tree and crop for above- and below ground resources (C_l and C_{n+w}, referring to light, nutrients and water, respectively) and modifications of the microclimate M, which may indirectly affect the pressure of diseases, pests, weeds as well as have direct effects on the crop development via temperature, humidity etcetera (Van Noordwijk, 1996). Table 2 indicates how we can attempt to separate the first four of these positive and negative interaction terms, by:

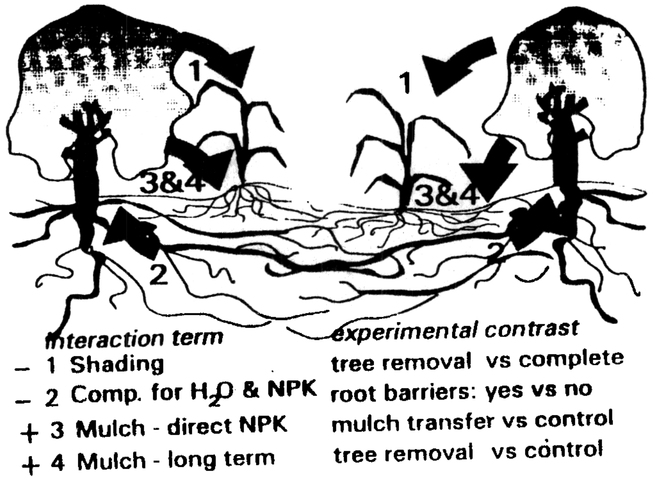

Figure 4. Schematic relations of tree-soil-crop interactions and the way to estimate them experimentally.

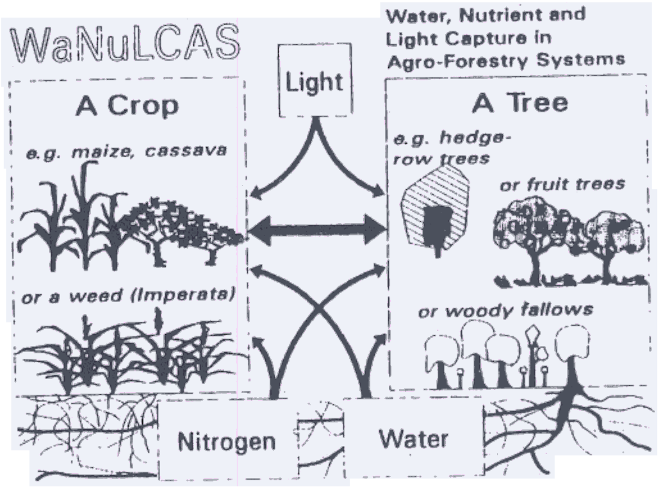

Figure 5. Elements of the WANULCAS model.

- mulch transfer treatments, testing the direct value of mulch to a crop outside the system,
- testing the residual soil fertility effect, after removing the hedgerow trees, in comparison with a long term 'no tree' control,
- testing the shading effect of the tree, by comparing crop growth on residual fertility plots with that in between hedgerows, but without root competition,
- testing the root competition by introducing barriers between the hedgerows and the crops.

Unfortunately, the M term has to be treated as a 'residual' factor and it may allow a (too easy ?) escape if the model based on the other terms does not fit. The M term may have to be further disentangled at a later stage.

Results for the overall interaction term (Table 3) show that positive overall effects do not necessarily depend on strongly positive F terms, but rather on moderately negative C terms. Maize yields in the alleycropping system exceeded that in the control only where the local tree *Peltophorum dasyrrachis* was used. For this specific site, process level research can focus on the question 'why is *Peltophorum* so much better than the other tree species?'. Explanations can be based on its relatively deep root distribution, the compact hedgerows with a high mulch/shade ratio, an appropriate timing of its nutrient mineralization, specific effects on Al detoxification or a combination of all these factors.

Table also indicates the major processes underlying the terms of the equation and how we can aim at a 'process level' understanding of each term. The final step then is one of integration of the various processes into a model of tree-soil-crop interactions.

Table 3. **Terms of the tree-soil-crop equation for maize in the 7'th year of a hedgerow intercropping experiment in Lampung (Indonesia); F = fertility effect, C = competition effect, I = overall interaction (I = F + C); data are expressed as percentage of monoculture crop yield (2.6 Mg ha^{-1} of grain); the values for are based on plots where replace in the fifth year of the trial.**

	F	C	I
Leucaena leucocephala	152	-159	- 7
Calliandra calothyrsus	120	-115	+ 5
Peltophorum dasyrrachis	58	-26	+ 32
Flemingia congesta	37	-89	- 52
Gliricidia sepium	19	-60	- 41

We are currently developing the WANULCAS (Water, nutrient and light capture in agroforestry systems) model for this purpose. The model makes use of the STELLA II(r) modelling environment and represents a four-layer soil profile, with a water and nitrogen balance. Uptake by a crop and a tree is based on their root length densities and current demand. The model allows for the evaluation of different pruning regimes, hedgerow spacings and fertilizer application rates. The model can be used both for simultaneous and sequential agroforestry systems and may help to understand the continuum of options from 'improved fallow', relay planting of tree fallows, to rotational and simultaneous forms of 'hedgerow intercropping'. The model explicitly incorporates management options such as tree (hedgerow) spacing, pruning regime and choice of species or provenance. The model includes various tree characteristics, such as root distribution, canopy shape, litter quality, maximum growth rate and speed of recovery after pruning. The model will be tested using data sets from ongoing alley cropping experiments.

Conclusions: Model - Experiment Synergy

In the past decades 'modelling' developed as a specialization. Now, 'nobody can afford not to model'. This may be a bit of an overstatement, but the new generation of modelling environments, such as the STELLA program, have reduced a lot of the technical constraints and, after familiarization, allow us to focus on the contents rather than the technique (points, comma's, formats) of the model. Although certainly not 'fool-proof', these model environments allow 'experimental' scientists to specify their 'mental models' and thus improve their 'experimental designs'. The feedback and feedforward cycle of models and reality of figure 1 can now be put into practice or, at least, can be tested as a model of doing science in agroforestry.

Nobody is really interested in the time- and location specific results of any agroforestry experiment, unless one has confidence in some method of at least interpolating results, but preferably extrapolating them to new environments and conditions. Without 'models', we cannot make sense out of 'experiments' or design them in a sensible way. Without 'experiments', our 'models' will remain castles in the air.

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