Chapter 1
Introduction and Objectives

This background document is written for two groups of readers:

1. Agroforestry researchers who are not very familiar with modelling or with quantitative descriptions of resource capture in agroforestry, but who may be tempted to use the model as part of their toolbox, for exploring new variants of agroforestry system before they embark on field experimentation,

2. Modellers who know little about agroforestry but a lot about component processes and who may find in WaNuLCAS a framework for exploring the system context of their favoured aspect of tree-soil-crop interactions.

The text of this background documentation is organized as follows:

Chapter 1: discusses some general considerations about agroforestry modelling which have lead to the development of WaNuLCAS,

Chapter 2: sketches an outline of the program to provide an overview of the components and the possibilities for use,

Chapter 3: gives a more detailed account, sector by sector of the specific assumptions made for the model and of the options provided for the model user,

Chapter 4: gives a number of worked-out examples of model applications

The appendices give detailed instructions on how to get the model started, suggest exercises to familiarize oneself with the model and provide descriptions of the model parameters.

1.1 Balancing pattern and process

A focal point in the analysis of where and how agroforestry systems work is still whether or not tree-crop systems can utilize resources of light, water and/or nutrients which would not be used in a simpler tree or crop system (Cannell *et al.*, 1996). A fair amount of detail in the description of above- and belowground resource capture by the component species is needed to evaluate both competition and complementarity (Sanchez, 1995; Ong and Huxley, 1996).

Tree-soil-crop interactions occur both in space and time. In 'sequential' agroforestry systems neighbourhood effects in a landscape mosaic still have a spatial element, while 'simultaneous' systems often have at least an element of zonation. The dichotomy between sequential and simultaneous agroforestry systems may thus have been overstated in the past and a modelling framework is desirable in which they are endpoints of a continuum.

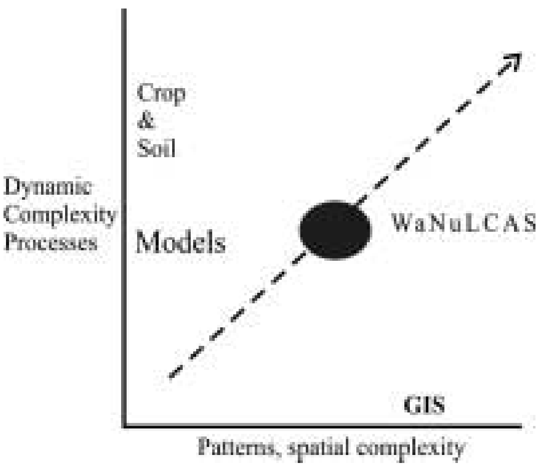


Figure 1.1 Schematic classification of the way crop growth models deal with spatial and temporal complexity; agroforestry models should explore the diagonal, rather than try to introduce spatial patterns in complex process based models

In modelling agroforestry systems, a balance should be maintained between 'process' and 'pattern', between temporal and spatial aspects (Fig. 1.1). Existing crop growth models tend to be detailed in 'processes', but they usually do not take spatial patterns into account. They (implicitly) assume a homogeneous 'minimum representative' area, with a one-dimensional variation between soil layers. Most GIS (geographical information systems) applications do not incorporate spatial interactions and estimate the total output of an area as the summation of area times output per unit area, for grid cells which are not dynamically interacting with their neighbours (similar to a 'stratified' sampling approach). For representations of agroforestry we need both spatial and dynamic aspects, and should therefore aim at models along the diagonal line in Fig. 1.1. Full-scale detail on spatial interactions may not be achievable for any reasonable process description, however, and it may be best to start in the lower left corner with fairly simple process and spatial descriptions, only to move to the upper right corner where research questions require more detail. As a starting point on the spatial side, we have chosen for a system of 'zoning', which can relate many types of spatial patterns to a model still covering essential aspects of real-world behaviour. Spatial interactions, such as shading aboveground and competition for water and nutrients belowground may occur over a range of distances. Instead of a black / white sharp boundary, every tree-crop interface may consist of several shades of grey in between. The zoning system we opt for appears to have the minimum complexity to do justice to such interactions.

In simultaneous agroforestry systems, trees and food crops are interacting in various ways. As both positive and negative interactions occur, optimization of the system will have to be site specific. The most important interactions probably are:

1. Shading by the trees, reducing light intensity at the crop level,
2. Competition between tree and crop roots for water and / or nutrients in the topsoil,
3. Mulch production from the trees, increasing the supply of N and other nutrients to the food crops,
4. Nitrogen supply by tree roots to crop roots, either due to root death following tree pruning or by direct transfer if nodulated roots are in close contact with crop roots,
5. Effects on weeds, pests and diseases,
6. Long term effects on erosion, soil organic matter content and soil compaction.

Interactions 3, 4 and 6 are positive, 1 and 2 are normally negative, and 5 can have both positive and negative elements. The positive and negative effects can interact during the growing season, and this may limit the use of end-of-season summaries of the tree-crop interaction effects. Yet, such summaries are helpful as a first approximation.

1.2 Tree-soil-crop interactions

The success of any intercropping depends on the balance of positive (facilitation) and negative (competition) interactions between the components Vandermeer (1989). Ong (1995) and Akeampyong *et al.* (1995) developed a simple equation for quantifying tree-soil-crop interactions (I), distinguishing between positive effects of trees on crop growth via soil fertility improvement (F) and negative effects via competition (C) for light, water and nutrients. Very much simplified, the interaction term is positive and the combined system may make sense if F > C, and not if F < C.

Cannell *et al.* (1996) attempted to clarify the resource base of the production by both the crop and the tree. Part of the 'fertility' effect of the tree is based on light, water and nutrient resources which the tree acquired in competition with the crop (F_{comp}); another part may have been obtained in complement to resources available for the crop ($F_{noncomp}$). Similarly, part of the resources acquired by the tree in competition with the crop is recycled within the system and may thus be used by a future crop (C_{recycl}). Tree products that are not recycled may have direct value for the farmer ($C_{nonrecycl}$).

One may argue that F_{comp} is based on the same resources as C_{recycl} and that in the longer run the two terms would cancel. The question whether or not a tree-crop combination gives yield benefits then depends on:

1. the complementarity of the resource use,
2. the value of direct tree products, specifically those obtained in competition, $C_{nonrecycl}$, relative to the value of crop products that could have been produced with these resources.
3. the efficiency of recycling tree resources into crop products, specifically for the resources obtained in competition with the crop, C_{recycl}.

Apart from yield effects of agroforestry, labour requirements have a strong impact on profitability, and for this one should compare additional labour use (eg. tree pruning) and labour saving aspects (eg. weed control). Complementarity of resource use can be based on a difference in timing of tree and crop resource demand. If the tree picks up the 'left overs' from the cropping period, as occurs with water in the Grevillea maize systems in Kenya (Ong; pers. comm.) and transforms these resources into valuable products, a considerable degree of competition during the temporal overlap may be acceptable to the farmer. If tree products have no direct value, agroforestry systems may only be justified if $F_{noncomp} > C_{nonrecycl}$. With

Table 1.1 Three-step approach to analysis and synthesis of tree-soil-crop interactions in simultaneous agroforestry systems. A direct experimental separation of the terms in the equation is combined with quantification of key processes and followed by model synthesis to explore management options and system-site matching (van Noordwijk *et al.*, 1998a).

Y_c =	Y_0 +	F_1 +	F_ω +	C_l +	C_{w+n} +	M
Crop yield in interaction	Crop yield in monoculture	Direct fertility effect	Long term fertility effect	Competition for light	Competition for water and nutrients	Micro-climate effects
1. Experimental		Mulch transfer	Residual effect	Tree removal	Root barriers	
2. Process-level understanding		Litter quality, mineralization rates	Functional SOM fractions (Ludox)	Canopy shape, light profiles	Root architecture (fractal branching analysis)	
3. Synthesis model	**W a N u L C A S**					

increasing direct value of the tree products, the requirements for complementarity decrease.

The efficiency of recycling will depend on the degree of synchrony between mineralization from these organic residues and crop nutrient demand, as well as on the residence time of mineral nutrients in the crop root zone under the site-specific climate and soil conditions (De Willigen and Van Noordwijk, 1989; Myers *et al.*, 1994, 1997).

As light is not stored in ecosystems, complementarity in light use is easy to measure. For water and nutrients complementarity has to consider time scales linked to the 'residence' times of the resources in the ecosystem; residence times tend to increase from water, via nitrogen and potassium to phosphorus. For P resources used by the tree it will be difficult to measure whether or not this P might have become available to the crop in the absence of trees. Indications of complementarity in belowground resource use can be obtained by observing the root distribution of both components. Actual uptake of resources will, however, depend on resource and root distribution as well as demand factors, and thus the degree of overlap in root distribution per se is not sufficient to predict competition.

Van Noordwijk (1996a) presented explicit algebraic solutions for an agroforestry model which links both the mulch production and its ensuing soil fertility effect and the shading which is assumed to have a negative effect on crop yields to the biomass production of the tree. The model leads to a simple mulch / shade ratio as a basis for comparing tree species. The model also predicts that at low soil fertility, where the soil fertility improvement due to mulch can be pronounced, there is more chance that an agroforestry system improves crop yields than at higher fertility where the negative effects of shading will dominate. The mulch / shade model, however, does not incorporate the interactions between water availability, N dynamics, crop and tree growth. Incorporating these elements on the basis of a daily time step extends the model beyond what can be solved explicitly and into the realm of dynamic simulation models, which keep track of resource stocks outside and inside the plants and use these to calculate daily resource flows and daily resource capture.

The tree-soil-crop interaction equation can be further analyzed by differentiating between short and long term fertility effects (F_1 and F_ω, respectively) and by separating the competition term in an above- and a belowground component (C_l and C_{n+w}, respectively). Van Noordwijk *et al.* (1998a) described a three-step approach to link these overall terms to experimental treatments, process research and WaNuLCAS as a synthesis model (Table 1.1). The total balance for belowground resources (water or nutrients) inputs into an agroforestry system is (Table 1.2):

$$\Delta Stored = Input + Recycle - Upt_{crop} - Upt_{tree,comp} - Upt_{tree,noncomp} - Loss \quad \textbf{[1]}$$

The term $\mathrm{Upt}_{tree,noncompetitive}$ represents the safetynet function of tree roots for nutrients and water leaching and percolating below the zone of crop roots and / or outside of the crop growing season (Van Noordwijk *et al.*, 1996), as well as a nutrient pump role for resources stored in the subsoil for longer periods of time (Young, 1997).

In summary, we argue that agroforestry systems do not make much sense from a biophysical point of view, unless there is at least some complementarity in resource capture. Direct empirical approaches to quantify complementarity are possible for aboveground processes, but more complex belowground, as resources there are stored over a longer period of time, making it more difficult to judge whether or not resources could have been used outside an agroforestry context. Models of tree-soil-crop interactions have to pay specific attention to the depth from which each component is capturing water and nutrients on a daily basis, in order to derive overall complementarity on a seasonal basis.

Table 1.2 Representation of resource capture (equation 1) in a simple tree-crop agroforestry system, where the crop roots are confined to the 'topsoil' and the tree roots explore the 'subsoil' as well; the subscripts 1, 2 and 3 refer to crop zones with increasing distance to the tree.

Term in eq. 1	Water	Nitrogen	Light
Input	Rainfall, irrigation runon-runoff	Fertilizer & organic imports	Sum of daily radiation
Recycle	Hydraulic lift into crop root zone	Litterfall, tree prunings, crop residues	-
$Uptake_{Crop}$	ΣW_Uptakecrop	N_fix(Crop) + ΣN_Uptakecrop	ΣLightcap_crop
$Uptake_{Tree,Competitive}$	Σ_{sub}W_Uptaketree	Σ_{top}N_Uptaketree	ΣLightcap_tree$_{1,2}$
$Uptake_{Tree,Noncomp}$	Σ_{sub}W_Uptaketree	N_fix(Tree) + Σ_{sub}N_Uptaketree	Lightcap_tree$_3$
Losses	ΣPercolation from lowest zone	ΣLeaching from lowest zone	1 - ΣLightcap
Δstorage	ΔWater content	Δ(Nmin & SOM)	-

1.3 Intercropping, crop-weed and agroforestry models

Attempts to link separately developed crop models into an 'intercropping' model have not been very successful yet (Caldwell *et al.*, 1996). A possible reason for this is that accurate description of both above- and below ground resource capture is more critical in a competitive situation than in a monoculture. Aboveground canopy structure does not matter in a monoculture as long as total LAI is predicted correctly. A coarse approximation of the allocation of current uptake of water and nutrients from the soil profile can be good enough, if the resources not used today still remain in the soil on the next day. In a competitive situation, however, it matters where the leaves of each component are relative to those of other components; belowground resources not utilized today may have been taken up by other components before tomorrow. It thus appears that a reasonable performance of a crop growth model in a monoculture situation is a necessary condition for expecting it to perform in intercropping, but not a sufficient condition. Additional detail may be needed to get above- and belowground resource capture correct.

Kropff and Van Laar (1993) gave an overview of models for crop-weed interactions: such models tend to emphasize the phenology of the species competing for resources, as they are meant to help in predicting the effect of interventions (weeding) at different points in the crop life cycle. Otherwise, crop-weed models differ only in name from intercropping models, as both describe resource capture in a system where at least two plants are interacting.

In intercropping models, however, both components have direct value to the farmer, whereas in crop-weed systems the 'weeds' have no direct value at all (although they may help in conserving nutrients in the system and reducing losses by leaching). Agroforestry models have to include a two-plant interaction (Fig. 1.2), similar to intercropping and crop-weed models, but differ in that one of the plants is a perennial species. Part of the inspiration for an agroforestry model may thus come from existing tree or forest models.

Rather than linking existing tree and crop models, an alternative approach is to develop a generic plant-plant interaction model. The focus should be on above- and belowground resource capture and its interplay (Fig. 1.3). Specific parameters for each component can be derived from more specialized component models, such as drivers for physiological development (onset of flowering, internal redistribution in generative stage). The model should, however, give a fair description of 'architecture' (spatial distribution of the relevant organs) above- and belowground and their consequences for uptake. A correct account of the spatial distribution of organs for resource capture is probably more important in plant-plant interaction models than it is in models for monocultural stands.

A major problem in linking a number of single-species resource capture models into a multi-species resource capture model with a single accounting systems for the resources, is one of priority assignment in the calculation sequence. Models which consistently assign priority to one of the components may vastly overestimate its resource capture, while the solution of some models of alternating priorities is not very satisfactory either (Caldwell *et al.*, 1996).

For a more balanced approach, the resource capture of the various components should be further integrated and applied simultaneously, avoiding priority assignment. One way of doing this is adding the root (for water and nutrients) and leaves in a common layer or zone, calculating a total resource capture and sharing this out over the two (or more) components in proportion to their root length density or leaf area. As resource capture is in most cases a non-linear function of root length or leaf area, this approach to resource sharing gives a different result from adding resource capture for the two components (the latter may overestimate potential uptake rates).

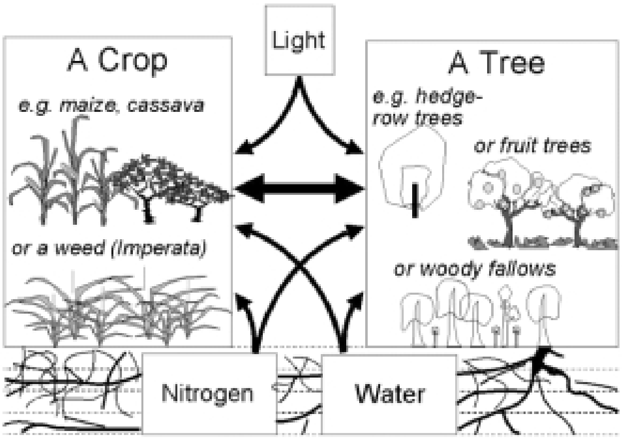


Figure 1.2 Components of the WaNuLCAS model

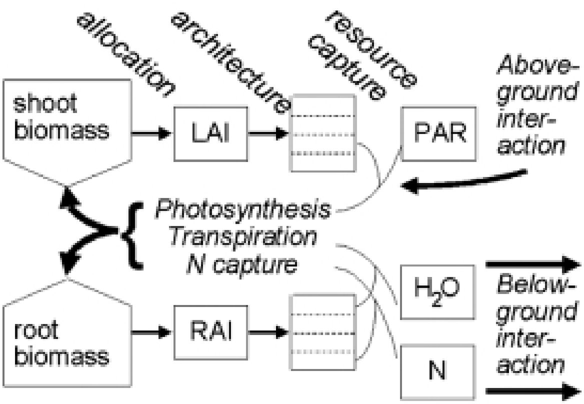


Figure 1.3 Resource capture framework for modeling plant growth, based on shoot and root biomass, allocation to leaf and root area index (LAI and RAI, respectively) and its spatial distribution (based on 'architecture') and capture of light, water and nutrients; aboveground plant-plant interactions modify resource flow, belowground they modify stocks

1.4 Objectives of the WaNuLCAS model

In developing a generic model for water, nutrient and light capture in agroforestry systems (WaNuLCAS), we aimed at a model which would:

1. integrate knowledge and hypotheses on below and aboveground resource capture by trees and crops (or any two or more types of plants)

at patch scale (the smallest 'self-contained' unit for describing the tree/crop interaction) as a basis for predicting complementarity and competition,

2. build on well-established modules (models) of a soil water, organic matter and nitrogen balance, and crop and a tree development to investigate interactions in resource capture,
3. describe the plant-plant interaction term as the outcome of resource capture efforts by the component species, as determined by their above- and belowground architecture (spatial organization) as well as physiology,
4. be applicable to spatially zoned agroforestry systems as well as rotational systems,
5. avoid where possible the use of parameters which can only be derived by fitting the model to empirical data sets and maximize the use of parameters which can be independently measured
6. be flexible in exploring management options within each type of agroforestry system,
7. be useful in estimating extrapolation domains for 'proven' agroforestry techniques, as regards soil and climate properties, as well as tree and crop architecture,
8. be user-friendly and allow 'non-modelers' to explore a range of options, while remaining open to improvement without requiring a complete overhaul of the model,
9. generate output which can be used in existing spreadsheets and graphical software,
10. make use of readily available and tested modeling software.

In view of objectives 8, 9 and 10 we chose the Stella Research modeling shell (Hannon and Ruth, 1994) linked to Excel spreadsheets for data input and output. The current model should be seen as a prototype; in the Stella environment it is relatively easy to modify or add modules or relationships.

Models can be of value ('validated' in the original sense of the word) if a) they adequately reflect the major assumptions one would like to make about component processes, if b) they operate smoothly in the parameter range where one would like to use them, and/or if c) their quantitative predictions agree with measured results in specific experiments (Van Noordwijk, 1996b). Before model validation is undertaken, (1) the purpose of the model, (2) the performance criteria and (3) the model context must be specified (Rykiel, 1996). At this stage we have concentrated on levels a and b of the validation process. WaNuLCAS model is meant as a prototype model, not including all possible tree-soil-crop interaction relationships that one can imagine, but incorporating a core of relations which we are fairly sure of for each specific case. In this sense the model can be viewed as a 'null model' (Gotelli and Graves, 1996) which can be used like a null hypothesis as a background against which specific data sets can be tested. The open modeling frame will allow users to add other relationships when and where they wish. Muetzelfeldt and Taylor (1997) have translated WaNuLCAS into a new modelling platform Agroforestry Modeling Environment (AME) as a platform. This modelling environment is now called SIMILE and is currently used in developing FLORES model. The European sylvo-arable agroforestry project SAFE is developing a model with greater spatial articulation HiSAFE.

Further information on agroforestry models can be found on the following web sites:

http://www.montpellier.inra.fr/safe/ for news on the HiSAFE model currently under development

http://www.wiz.uni-kassel.de/ecobas.html for database of ecological models

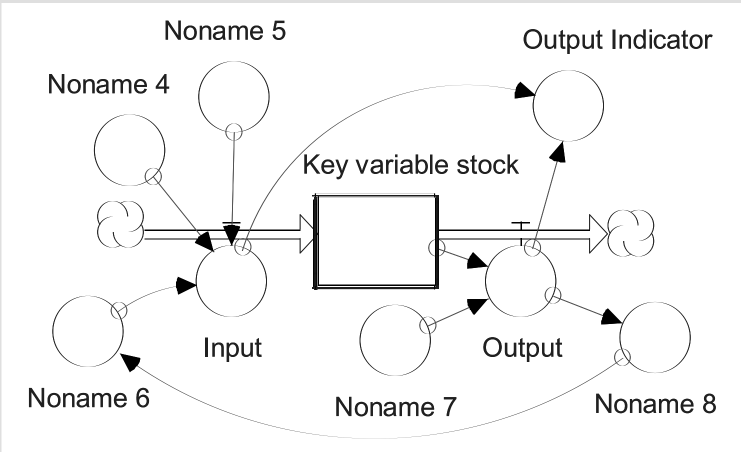
http://www.ierm.ed.ac.uk/simile/ for Simile - previously named AME - Agroforestry Modelling Environment

http://simulistics.com/projects/flores/ for FLORES model

http://www.forestresearch.co.nz/topic.asp?topic=AEM&title=Agroforestry%20Estate%20Model
for Agroforestry Estate Model, a Windows application which projects physical and financial yields for an agroforestry project

Intermezzo: Plant -- a first exploration of a dynamic plant growth model in the STELLA environment

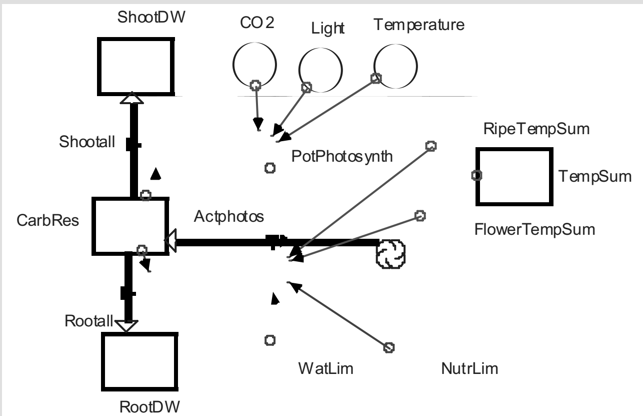
In making a simulation model you can start with an empty sheet of paper or screen, draw a key variable in the centre, consider its inputs and outputs, and the various influences on those inputs and outputs…:



You may realize that you are specifically interested in the 'efficiency' or rate of output per rate of input of the key variable, so this becomes your main output indicator. On further thought, one of factors that is influenced by the 'output' has a feed-back effect on one of the influences on the 'input'. The conceptual model starts to grow, and it becomes a little complex to imagine how the overall output indicator will respond to the various influences that you have recognized. You may want to see it change before your eyes. Wait, we cannot run the model yet, as we first have to specify what these red arrow mean: influences on a process need to be combined in the form of an 'equation'….

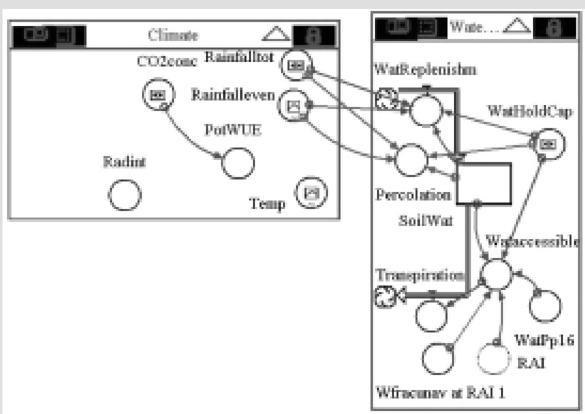
In a nutshell, the above process describes how a model such as WaNuLCAS started. But it has grown so complex that the origin is difficult to trace. In the following description of a basic 'PLANT' model, we introduce a couple of key concepts that are used in more elaborate form in the tree-soil-crop interaction model. PLANT follows the day-to-day development of a plant with leaves, roots, flowers and seeds. The plant takes up water from the soil, that comes from a stock of 'available water' replenished by rainfall. The plant also takes up and thus depletes a stock of soil nutrients. Its rate of photosynthesis is the prime driver of all growth, and requires the combination of light, atmospheric CO_2, stomata that can be open (so water stress shouldn't be too severe) and leaves that are green (so there is enough nitrogen and other nutrients to make the required enzymes and cell structures).

In describing how plants grow we can thus start with the concept of 'photosynthesis' that generates carbohydrate reserves that can be used to make either 'shoot' or 'root' tissues and adds to their dry weight. We can distinguish between a potential rate of photosynthesis that depends on factors such as CO2 concentration, light and temperature, and an actual one, that can be reduced by water or nutrient stress. An important thing to consider is the development of the plant from vegetative to generative (flowering and fruit production) phases - we may be able to link this 'phenological development' to a temperature-sum that keeps track of the past weather, plus parameters for the thresholds of flowering and fruit(seed) ripeness.

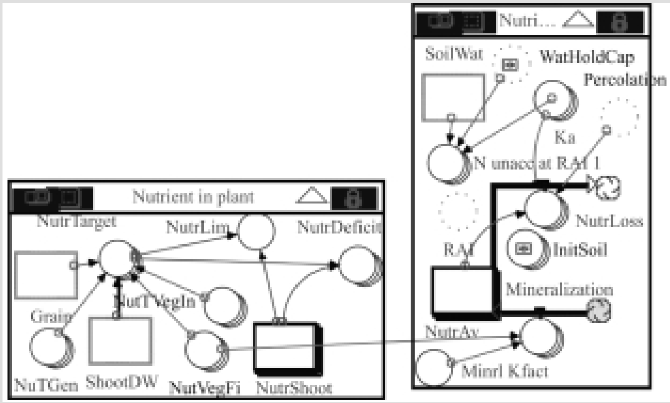


Hey, we're missing something important. Photosynthesis depends on the green leaf area exposed to light - so we need to relate the 'dry weight of shoot' to the leaf area available. Similarly, we need to specify how root dry weight is related to the WatLim and NutLim parameters that describe growth-limiting degrees of water and nutrient stress….

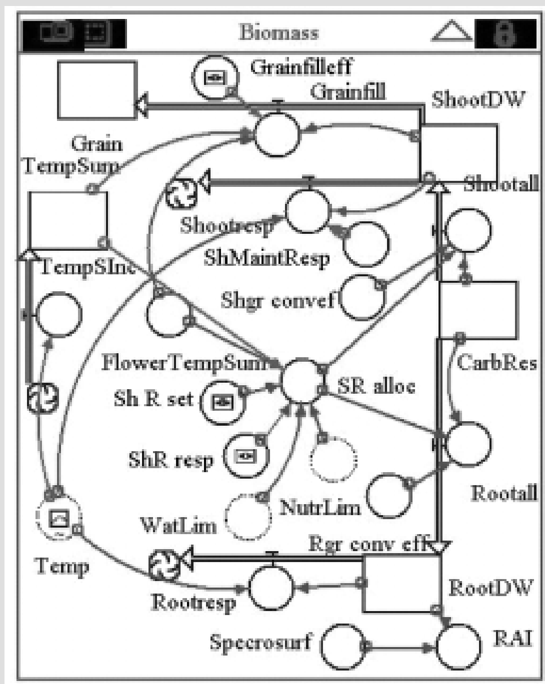
That means we need to add a stock that represents soil water and is replenished by rainfall.



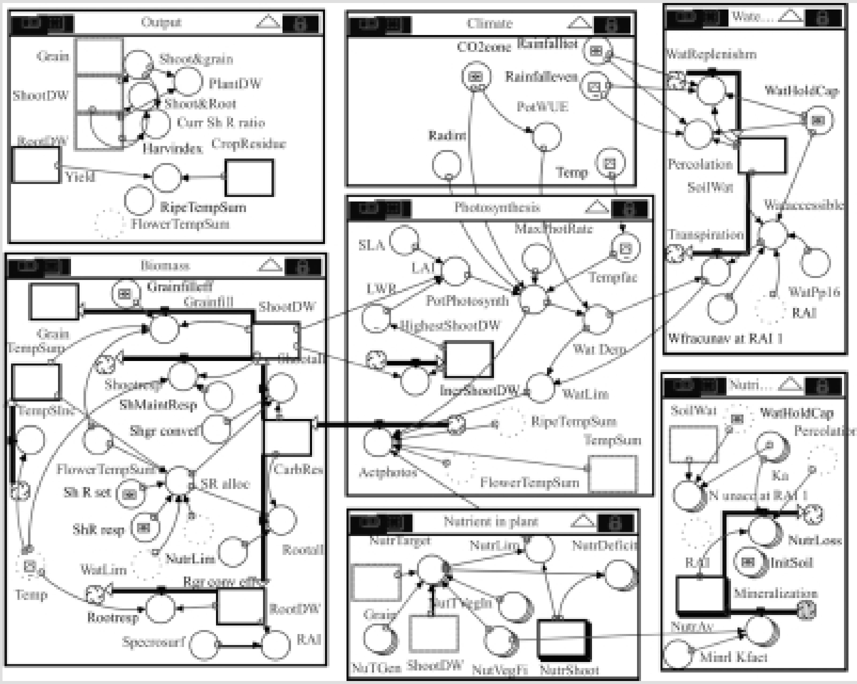
We also need to keep track of the pool of available nutrients in the soil, that can increase through 'mineralization' and be reduced by 'nutrient losses'.



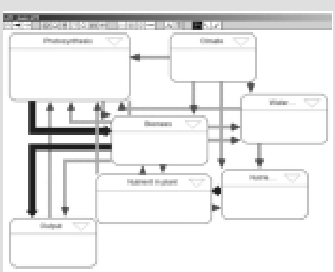
Finally, the basic allocation of available growth reserves in the plant over 'shoot' and 'root' tissue needs to be specified. A simple rule, consistent with the 'Functional Equilibrium' theory developed by the plant physiologist Rienk Brouwer in the early 1960's is that under water and nutrient stress the plant will allocate more of its resources to 'root growth', and in the absence of such stresses allocates mostly to aboveground tissues (leaves or fruits). Our simple plant model thus has a dynamic 'SR alloc' or shoot:root allocation parameter, that responds to a genetically determined set point, the current severity of water and nutrient limitations, and to the phonological development. After the onset of flowering the plant will focus its resource allocation on seed production (we use the rather restrictive term 'grain' here…).



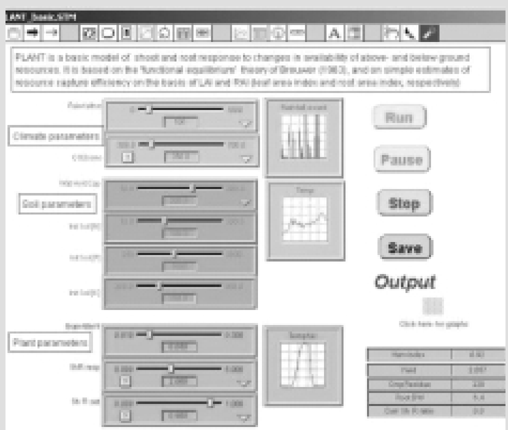
After adding these other stocks and flows, our 'simple model' starts to look complicated… but it is now possible to 'run' it, as we have specified all relationships.



Finally, we go the 'upper' screen and add some sliders for easy modification of input parameters, graphs for daily rainfall and temperature input, and buttons for run control. As outputs there is a stack of graphs and indicators of some of the ratios such as current shoot: root ratio and harvest index. The model is there to be explored, improved, used, expanded…



Sector map



Control screen