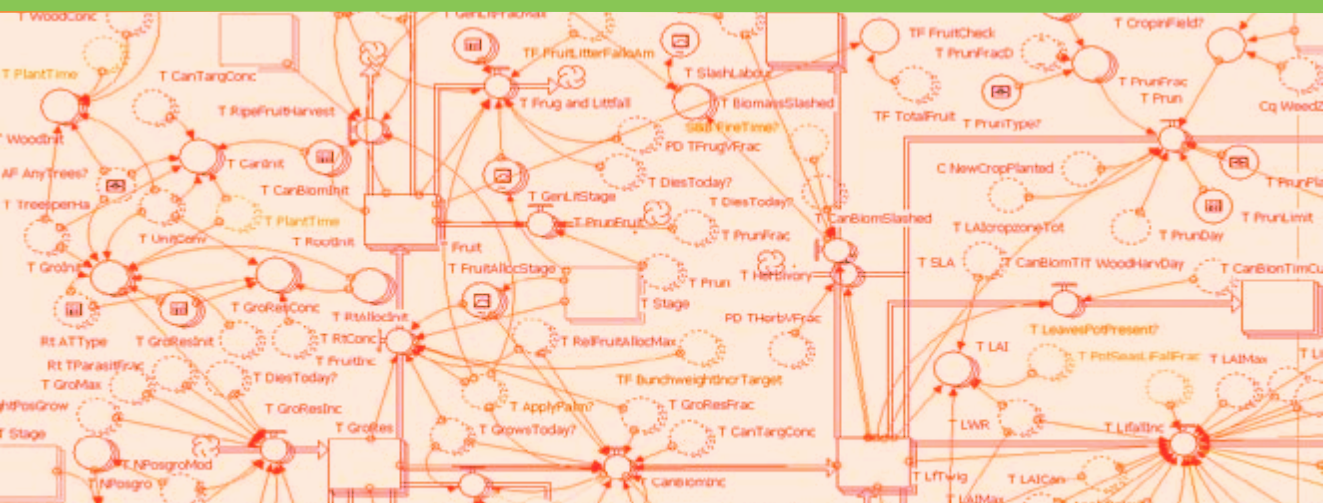


# Water, Nutrient and Light Capture in Agroforestry System



# WaNuLCAS 4.0

## Background on a model of Water, Nutrient and Light Capture in Agroforestry Systems

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Copies of the software available freely from the web:

<http://www.worldagroforestrycentre/sea>

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This is a third release of a general model of tree-soil-crop interactions in agroforestry. Although efforts have been made to incorporate relevant process knowledge on a range of interactions, the model is not more (and not less) than a research tool. Model predictions may help in developing specific hypotheses for research, in exploring potential management options and extrapolation domains, but they should not be used as authoritative statements per se.

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## 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.

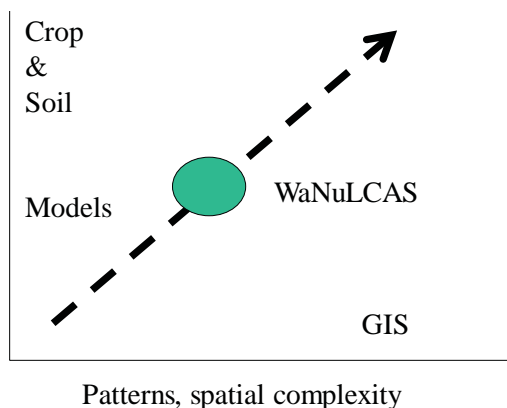


Figure 1.1. Schematic classification of the way crop growth models deal with spatial and temporal complexity; agroforestry models should explore the diagonal, rather than try to introduce spatial patterns in complex process based models.

In modelling agroforestry systems, a balance should be maintained between 'process' and 'pattern', between temporal and spatial aspects (Figure 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 Figure. 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,  $C_{recycl}$ .

**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).

$Y_c =$ Crop yield in interaction	$Y_0 +$ Crop yield in monoculture	$F_1 +$ Direct fertility effect	$F\omega +$ Long term fertility effect	$C_l +$ Competition for light	$C_{w+n} +$ Competition for water and nutrients	M 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 archi- tecture (frac- tal branching analysis)				
3. Synthesis model		W	a	N	u	L	C	A	S

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  $F_{\text{noncomp}} > C_{\text{nonrecycl}}$ . With 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  $F_\omega$ , respectively) and by separating the competition term in an above- and a belowground component ( $C_1$  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:

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

The term  $\text{Upt}_{\text{tree,noncompetitive}}$  represents the safety net 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).

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 runoff	Fertilizer & organic imports	Sum of daily radiation
Recycle	Hydraulic lift into crop root zone	Litterfall, tree prunings, crop residues	-
$\text{Uptake}_{\text{Crop}}$	$\sum W_{\text{Uptakecrop}}$	$N_{\text{fix}}(\text{Crop}) + \sum N_{\text{Uptakecrop}}$	$\sum \text{Lightcap}_{\text{crop}}$
$\text{Uptake}_{\text{Tree,Competitive}}$	$\sum_{\text{sub}} W_{\text{Uptaketree}}$	$\sum_{\text{top}} N_{\text{Uptaketree}}$	$\sum \text{Lightcap}_{\text{tree}_{1,2}}$
$\text{Uptake}_{\text{Tree,Noncomp}}$	$\sum_{\text{sub}} W_{\text{Uptaketree}}$	$N_{\text{fix}}(\text{Tree}) + \sum_{\text{sub}} N_{\text{Uptaketree}}$	$\text{Lightcap}_{\text{tree}_3}$
Losses	$\sum \text{Percolation from lowest zone}$	$\sum \text{Leaching from lowest zone}$	$1 - \sum \text{Lightcap}$
Δstorage	ΔWater content	Δ(Nmin & SOM)	-

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.

### 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.

6

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 (Figure. 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 (Figure. 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.

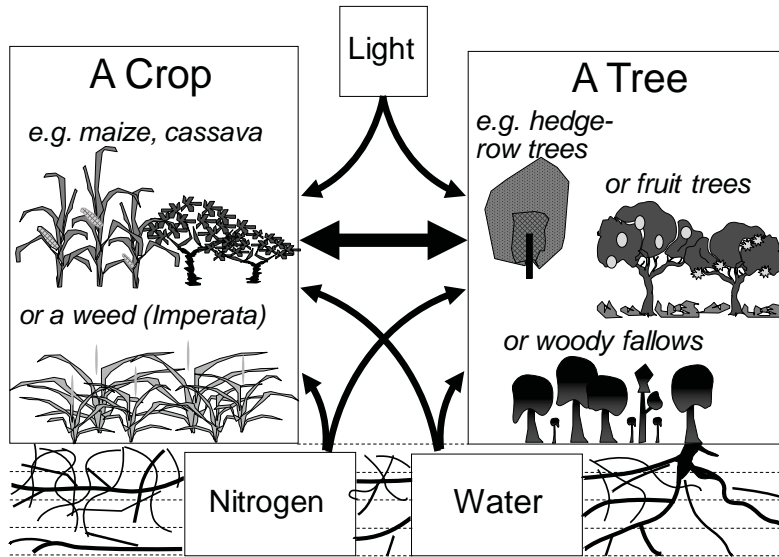


Figure 1.2. Components of the WaNuLCAS model.

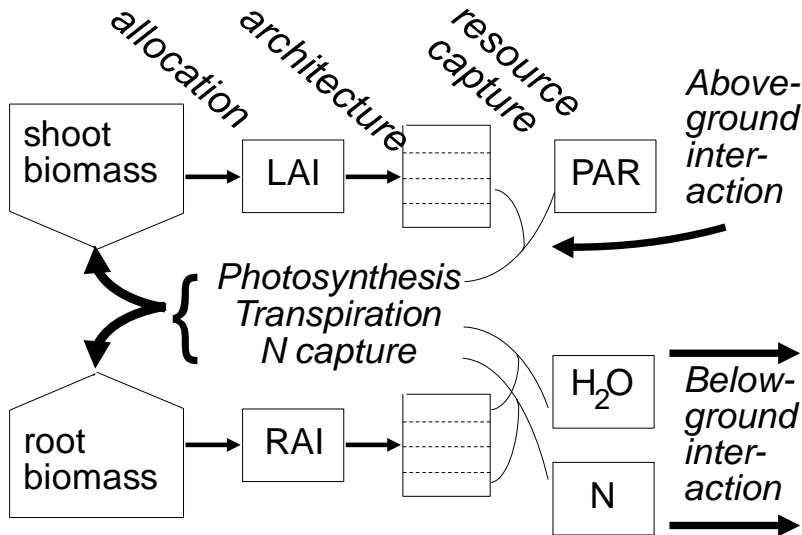


Figure 1.2. Resource capture framework for modeling plant growth, based on shoot and root biomass, allocation to leaf and root area index (LAI and RAI, respectively) and its spatial distribution (based on 'architecture') and capture of light, water and nutrients; aboveground plant-plant interactions modify resource flow, belowground they modify stocks.

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).

## 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 silvo-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

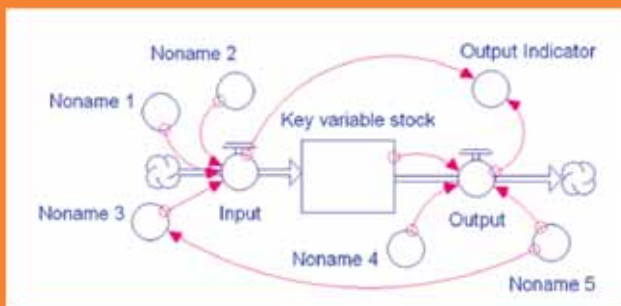
<http://www.ierm.ed.ac.uk/simile/> for SIMILE – previously named AME – Agroforestry Modelling Environment

<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....:

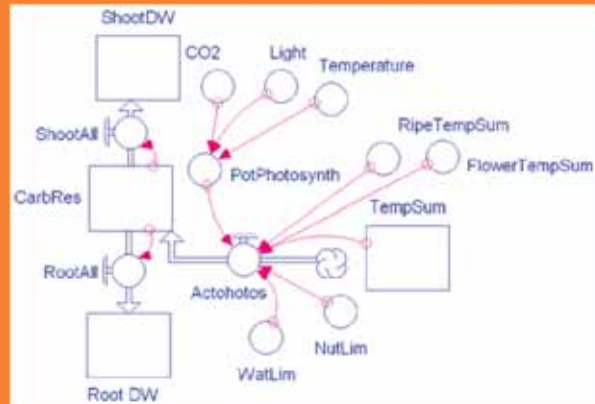


You may realize that you are specifically interested in the 'efficiency' or rate of output per rate of input of the key variable, so this becomes your main output indicator. On further thought, one of factors that is influenced by the 'output' has a feed-back effect on one of the influences on the 'input'. 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  $\text{CO}_2$ , 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).

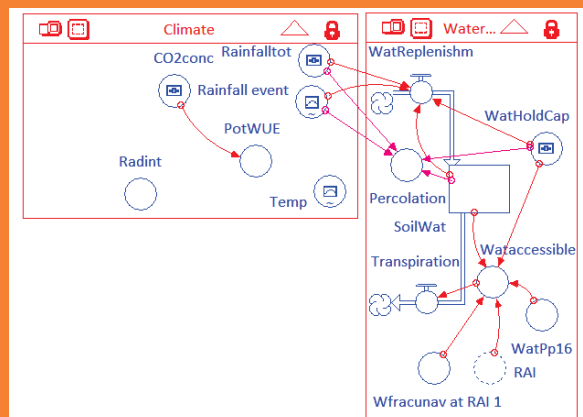
In describing how plants grow we can thus start with the concept of 'photosynthesis' that generates carbohydrate reserves that can be used to make either 'shoot' or 'root' tissues and adds to their dry weight. We can distinguish between a potential

rate of photosynthesis that depends on factors such as  $\text{CO}_2$  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.

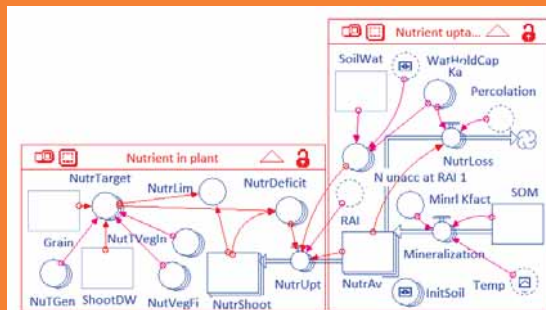


Hey, we’re missing something important. Photosynthesis depends on the green leaf area exposed to light – so we need to relate the ‘dry weight of shoot’ to the leaf area available. Similarly, we need to specify how root dry weight is related to the WatLim and NutLim parameters that describe growth-limiting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

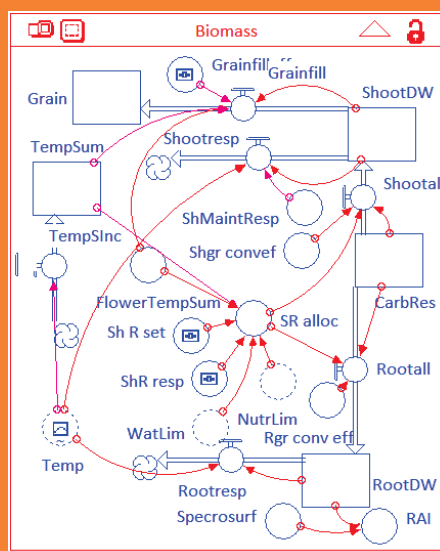
That means we need to add a stock that represents soil water and is replenished by rainfall.



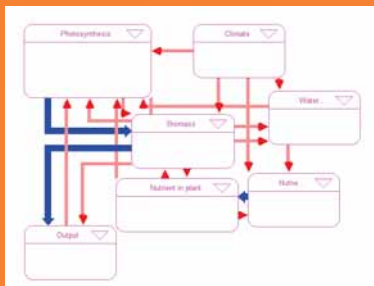
We also need to keep track of the pool of available nutrients in the soil, that can increase through 'mineralization' and be reduced by 'nutrient losses'.



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 phenological development. After the onset of flowering the plant will focus its resource allocation on seed production (we use the rather restrictive term 'grain' here).



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



PlantLab is a basic model of plant and control response to changes in availability of above- and below-ground resources. It is based on the functional equilibrium theory of Brownlee (1983), and on simple estimates of resource capture efficiency on the basis of LAI and fAPAR (leaf area index and red area index, respectively).

The interface includes the following sections:

- Control parameters:** Gain, Integral, Derivative.
- Disturbance parameters:** Amplitude, Frequency, Phase.
- Plant parameters:** Time constant, Dead time, Gain.
- Control:** Run, Pause, Stop, Save.
- Output:** Graph showing the system response.
- Samples:** Graph showing the sampled data.

The following table shows the current values for the parameters:

Parameter	Value
Gain	0.001
Integral	0.001
Derivative	0.001
Time constant	0.001
Dead time	0.001
Gain	0.001

Control Screen



### Overview of the Model

*Before we give a detailed description of model assumptions and formulation in chapter 3, we will give an overview of the model here .*

*The model is formulated in the **STELLA** Research modeling environment and thus remains open to modifications. Emphasis is placed on belowground interactions, where competition for water and nutrients (nitrogen and phosphorus) is based on the effective root length densities of both plant components and current demand by tree and crop.*

*Simulations require the prior definition of a soil profile and its soil physical and chemical properties per layer, of a degree of slope and hence lateral interactions, and of the climate.*

*Agroforestry systems are defined on the basis of spatial zones and a calendar of events for each zone, including growing and harvesting trees or crops, fertilizer use or slash-and-burn land clearing.*



## 2.1. Model features

A key feature of the model is the description of uptake of water and nutrients (N and P) on the basis of root length densities of the tree(s) and the crop, plant demand factors and the effective supply by diffusion at a given soil water content. De Willigen and Van Noordwijk (1994) and Van Noordwijk and Van de Geijn (1996) described underlying principles.

The model was developed to emphasize the common principles underlying a wide range of tree-crop agroforestry systems in order to maximize the cross-fertilization between research into these various systems and explore a wide range of management options. The model can be used for agroforestry systems ranging from hedgerow intercropping (alley cropping) on flat or sloping land (contour hedgerow intercropping), taungya-type transitions into tree-crops, via (relay-planted) fallows to isolated trees in parkland systems. Figure 2.1A and Figure 2.1B shows the different modules available inside WaNuLCAS model.

**Agroforestry systems.** The model represents a four-layer soil profile, with four spatial zones, a water, nitrogen and phosphorus balance and uptake by a crop (or weed) and up to three (types of) tree(s). The model can be used both for simultaneous and sequential agroforestry systems and may help to understand the continuum of options ranging from 'improved fallow' via relay planting of tree fallows to rotational and simultaneous forms of 'hedgerow intercropping'. The model explicitly incorporates management options such as tree 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.

If applied to hedgerow intercropping, the model allows for the evaluation of different pruning regimes, hedgerow tree spacing and fertilizer application rates. When applied to rotational fallow systems, the 'edge' effects between currently cropped parts of a field and the areas where a tree fallow is growing can be simulated. For isolated trees in parkland systems, equidistant zones around individual trees can be 'pooled' and the system as a whole can be represented by a number of circles (of different radius) with a tree in the middle (further explanation is given in section 3.1).

**Climate** effects are mainly included via daily rainfall data, which can be either read from a spreadsheet or generated on the basis of daily probability of rainfall and a division between 'heavy', and 'light' rains. Average temperature and radiation are reflected in 'potential' growth rates. 'Thermal time' is reflected in the speed of phenological development. Soil temperature is explicitly used as a variable influencing decomposition and N and P mineralization.

**Soil** is represented in four layers, the depth of which can be chosen, with specified soil physical properties and initial water and nitrogen contents.

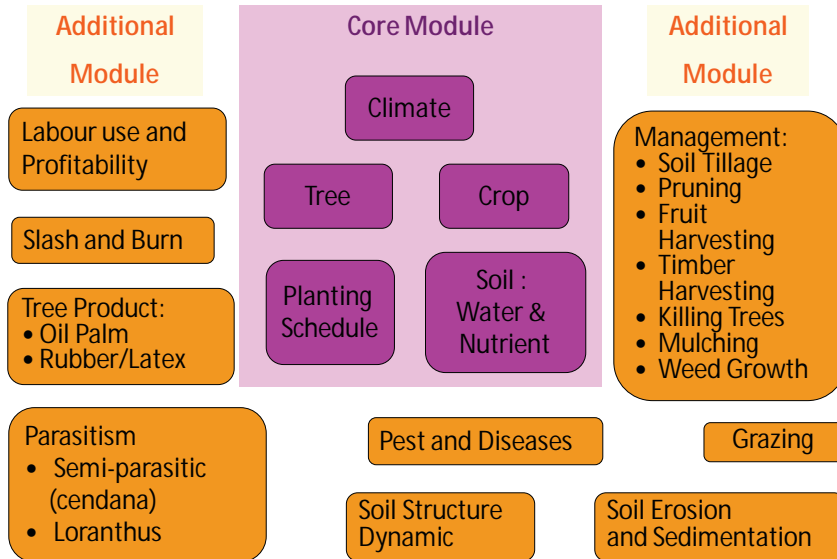


Figure 2.1A. Schematic diagram of different modules.

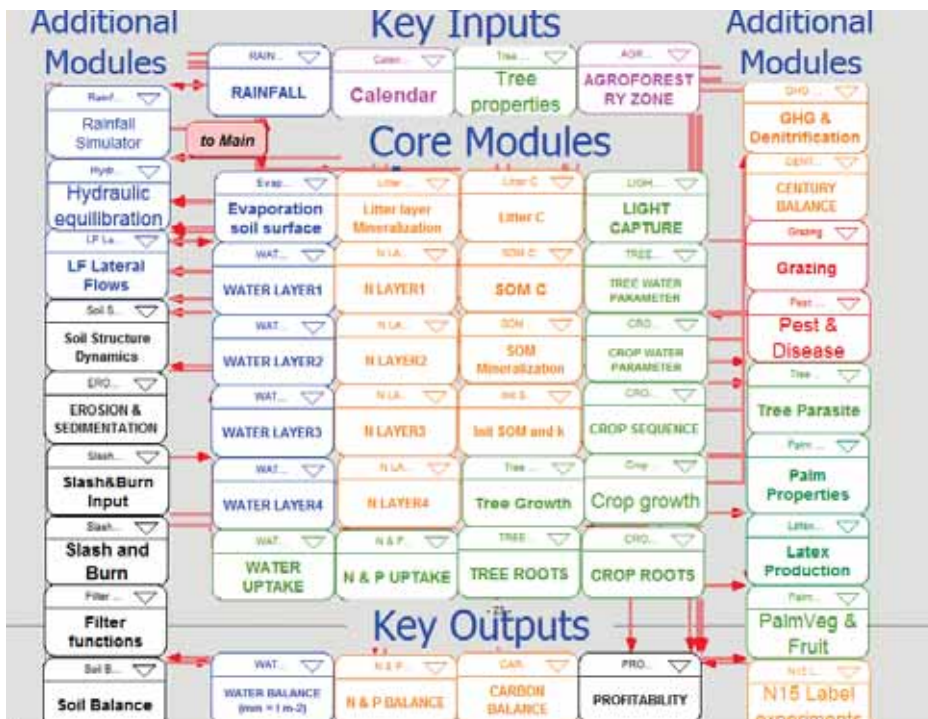


Figure 2.1B. Schematic diagram of different modules inside WaNuLCAS model.

**The Water balance** of the system includes rainfall and canopy interception, with the option of exchange between the four zones by run-on and run-off as well as subsurface lateral flows, surface evaporation, uptake by the crop and tree and leaching. Vertical as well as horizontal transport of water is included; an option is provided to incorporate (nighttime) 'hydraulic equilibration' via the tree root system, between all cells in the model.

**The Nitrogen and Phosphorus balance** of the model includes inputs from fertilizer (specified by amount and time of application), atmospheric N fixation, mineralization of soil organic matter and fresh residues and specific P mobilization processes. Uptake by crop and tree is allocated over yields (exported from the field/ patch) and recycled residues. Leaching of mineral N and P is driven by the water balance, the N concentrations and the apparent adsorption constant in each layer, thus allowing for a 'chemical safety net' by subsoil nutrient (incl. nitrate) adsorption.

**Growth** of both plants ('crop' and 'tree') is calculated on a daily basis by multiplying potential growth (which depends on climate) with the minimum of three 'stress' factors, one for shading, one for water limitation, one for nitrogen and one for phosphorus. For trees a number of allometric equations (which themselves can be derived from fractal branching rules) is used to allocate growth over tree organs.

**Uptake** of both water and nutrients by the tree and the crop is driven by 'demand' in as far as such is possible by a zero-sink uptake model on the basis of root length density and effective diffusion constants:

$$uptake = \min(\text{demand}, \text{potential uptake}) \quad [2]$$

For water the potential uptake at a given root length density and soil water content is calculated from the matric flux potential of soil water.

**Demand** for nitrogen uptake is calculated from empirical relationships of nutrient uptake and dry matter production under non-limiting conditions<sup>[1]</sup>, a 'luxury uptake'<sup>[2]</sup> a possibility for compensation of past uptake deficits and an option for N fixation (driven by the Ndfa parameter, indicating the part of the N demand which can be met from atmospheric fixation).

**Competition for water and nutrients** is based on sharing the potential uptake rate for both (based on the combined root length densities) on the basis of relative root length multiplied by relative demand:

$$PotUpt(k) = \min \left[ \frac{Lrv(k) \times Demand(k) \times PotUpt(\sum Lrv)}{\sum_{k=1}^n (Lrv(k) \times Demand(k))}, PotUpt(Lrv(k)) \right] \quad [3]$$

where PotUpt gives the potential uptake rate for a given root length density  $L_{rv}$ .

1 The assumptions are 5% N in dry matter up to a closed crop canopy (s reached at an aboveground biomass of about 2 Mg ha<sup>-1</sup>) and 1%N in new dry matter after that point with target N:P ratio = 10

2 An assumption that growth will not be reduced until N content falls below 80% of demand

This description ensures that uptake by species  $k$  is:

1. proportional to its relative root length density  $L_{rv}$  if demand for all components is equal,
2. never more than the potential uptake by  $i$  in a monoculture with the same  $L_{rv}$ ,
3. not reduced if companion plants with a high root length density have zero demand (e.g. a tree just after pruning).

At this stage we apply this procedure to four species ( $n=4$ , i.e. 3 trees and a crop or weed in each zone), but the routine can be readily expanded to a larger number of plants interacting.

**Root growth** is represented for the crop by a logistic increase of root length density in each layer up till flowering time and gradual decline of roots after that time. A maximum root length density per layer is given as input. The model also incorporates a 'functional equilibrium' response in shoot/root allocation of growth, and a 'local response' to shift root growth to favourable zones. For the tree, root length density in all zones and layers can be assumed to be constant, thus representing an established tree system with equilibrium of root growth and root decay or can follow dynamic rules roots similar to those for crop.

The **Soil Organic Matter** includes litter layer and organic matter. Both has three main pools (Active, Slow and Passive), following the terminology and concept of the CENTURY model.

**Light capture** is treated on the basis of the leaf area index (LAI) of all components and their relative heights, in each zone. Potential growth rates for conditions where water and nutrient supply are non-limiting are used as inputs (potentially derived from other models), and actual growth is determined by the minimum of shade, water and nutrient stress.

## 2.2. Model organization

STELLA allows the user three perspectives on a model:

1. On the upper layer, general information is provided, key parameters can be modified (Figure. 2.2A) and output can be obtained in the form of graphs and tables (Figure. 2.2B),
2. On the middle layer (Figure. 2.3A and Figure 2.3B), the model is presented as a complete compartment - flow diagram, with all equations entered at the respective 'converters'; double arrows indicate 'flows' from 'pools' in rectangles, while single lines indicate a flow of information; this is the working level for developing or modifying the model; a 1:1 relation is maintained between the diagram and the model relationships,
3. A listing of the model equations, with comments added.

At the middle level, the model can be arranged in sectors. To facilitate the process of finding parameters in the model, we made sure that all parameters in a sector start with letters referring to the sector. This way, an alphabetic listing of parameters as the STELLA shell does, gets functional significance. In chapter 3 we will start using the names of model parameters in WaNuLCAS. A selection of parameters (all those which are important as input values to be specified by the user) is given in Appendix 7.

In STELLA multiple representations of similar structures can be obtained by using arrays (indexed variables). In WaNuLCAS we use arrays for the 'zones' and in some cases, for the different soil

layers. We also use arrays for nutrients (N and P) as they can be treated in parallel. Despite the symmetry in the uptake description between water and nitrogen, we found that there are enough differences to merit separate representation in the model, rather than a generic 'belowground resources'. A number of parameters dependent on crop type are in an array called 'crop', and are utilized based on the crop sequence specified (see 3.1.4). To find out the various used in the model, see the array editor within the STELLA model.

The screenshot displays the 'TO INPUT LIST' section of the WaNuLCAS 4.0 model interface. It features several panels for configuring rainfall parameters:

- TO MAIN MENU** and **TO INPUT LIST** buttons at the top left.
- Rainfall Type** section with a slider set to 1 and a dropdown menu.
- Rain Type 1 : daily precipitation data** section with a dropdown menu set to 'Rain Type 1' and a table of parameters:
 

Rain YearStart	0
Rain Cycle?	1
- Rain Type 2 only** section with a dropdown menu set to 'Rain Type 2' and a table of parameters:
 

Rain UniorBimodal?	2
Rain Probability	0.5
Rain OffsetValue	-0.5
Rain Shape Max	1.5
Rain Shape Min	-0.5
Rain Pattern1 Max	0.06
Rain Pattern1 Min	-0.01
Rain WettestMonth Se...	1
Rain WettestMonth Se...	7
Rain Peakines Season1	1
Rain Peakines Seaso...	12
Rain Weibull Param	0.93
Rain MonthlyMean Rai...	333
Rain MonthlyMean Rai...	102
- Rain Type 2 only** section with three graphs: 'Rain Number of We...', 'Rain MonthlyMean ...', and 'Rain RelWet Persis...'.
- Rain Type 3 only** section with a dropdown menu set to 'Rain Type 3 only' and a table of parameters:
 

Rain HeavyP	0.5
Rain Heavy	42
Rain Light	9
Rain CoefVar3	0.05
Rain BoundHeaLi	25
- Type 3 & 4 : randomly generated rainfall data** section with a 'Rain GenSeed' slider set to 300 and a 'Rain DayP' graph.
- Rain Type 4 only** section with a 'Rain CoefVar4' slider set to 0.1000 and a 'Rain MonthTot' graph.

The interface is designed for setting input values numerically or in graph (table) form. The buttons 'to main menu' and 'to input list' allow one to navigate through the input section.

Figure 2.2A. Upper level view on the WaNuLCAS model options for setting input values numerically or in graph (table) form; the buttons 'to main menu' and 'to input list' allow one to navigate through the input section.

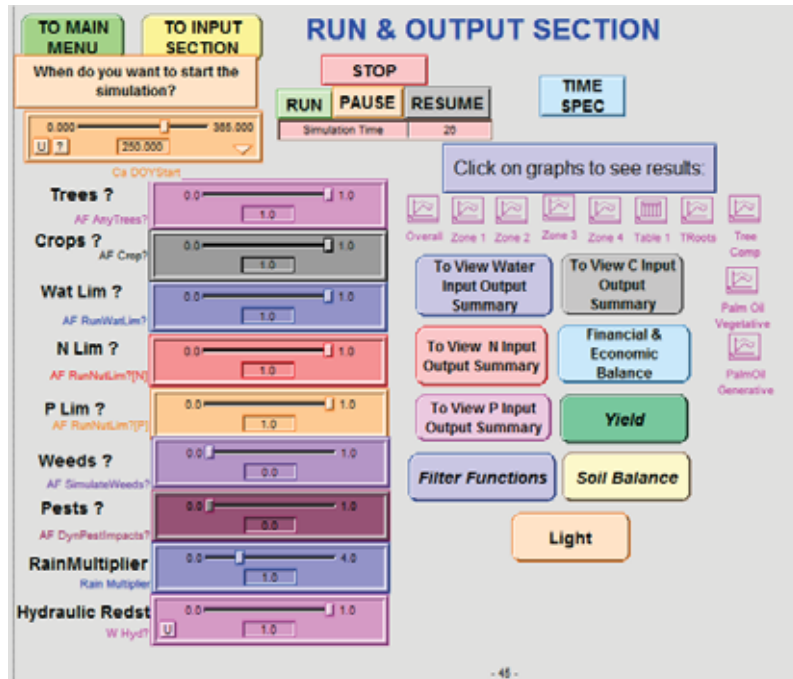


Figure 2.2B. Upper level view on the WaNuLCAS model with example of output graphs and tables.



Figure 2.3A. A Middle level overview of the WaNuLCAS model in version 4.0.



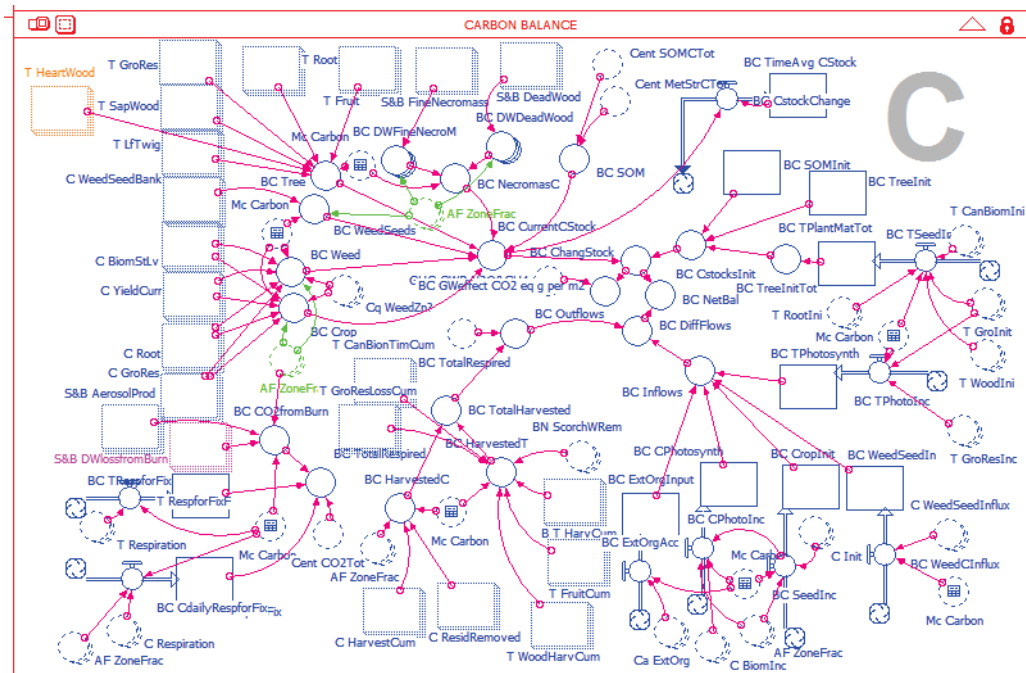
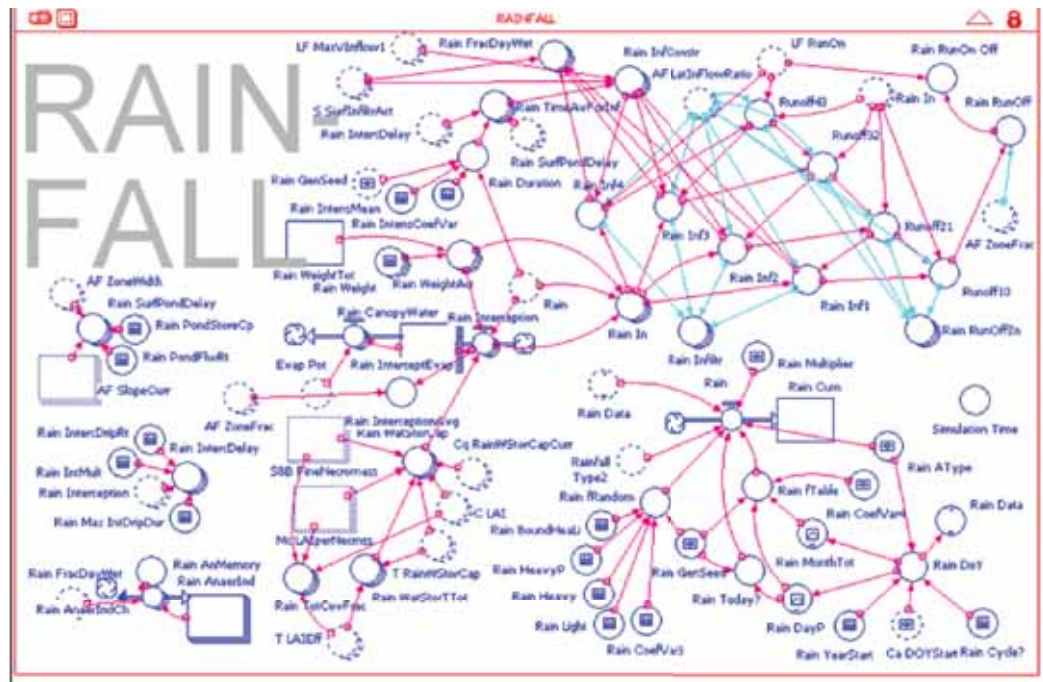


Figure 2.3B. Middle level view on the WaNuLCAS model with examples of 1 sectors.

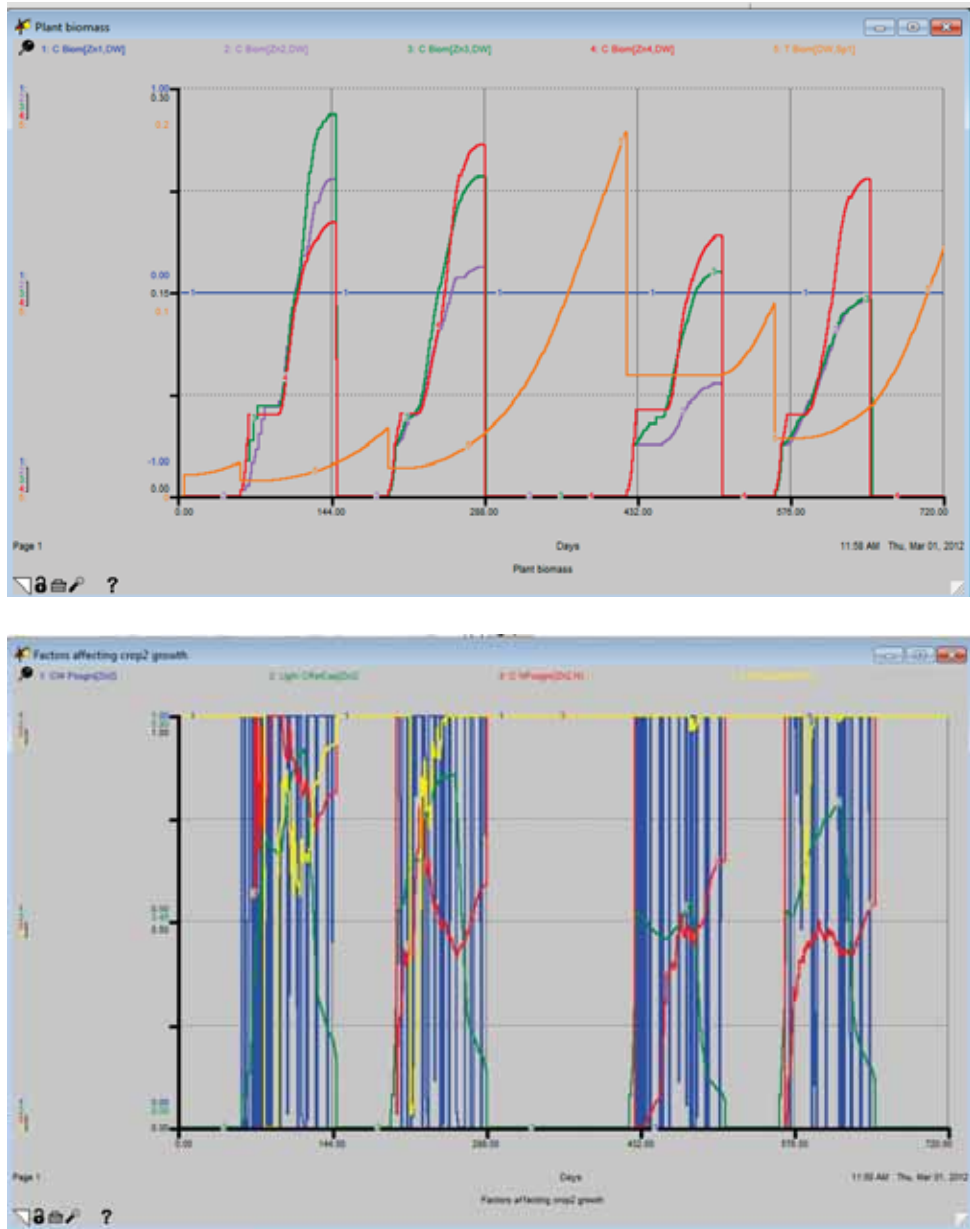


Figure 2.4. Example of output graphs.





### Description of Model Sectors

*Confidence in the use of a model may be based on:*

- 1. accepting the main assumptions made as reasonable first approximations,*
- 2. the use of reasonable parameter values, and/or*
- 3. a proven ability of the model to predict measured outputs on the basis of appropriate input parameters.*

*We will focus here on a description of the model structure chosen and its underlying assumptions.*

*Parameter names in WaNuLCAS always start with the first 1 or 2 letters of the sector in which they are placed. In this text, however, some of the parameter names are reduced to their core to make equations more readable. Please refer to Appendix 7 for the full list of parameter names.*

## 3.1. Agroforestry systems

### 3.1.1. Zoning of the agroforestry system into four zones.

Normally, the first zone will be used for trees only. The other three zones will normally be used for growing crops, but they can be shaded by the trees in zone 1 (depending on canopy size and shape) and can harbour tree roots, leading to belowground competition (Figure 3.1. and Table 3.1). Normally the intensity of interactions will decrease from zone 2 to 4.

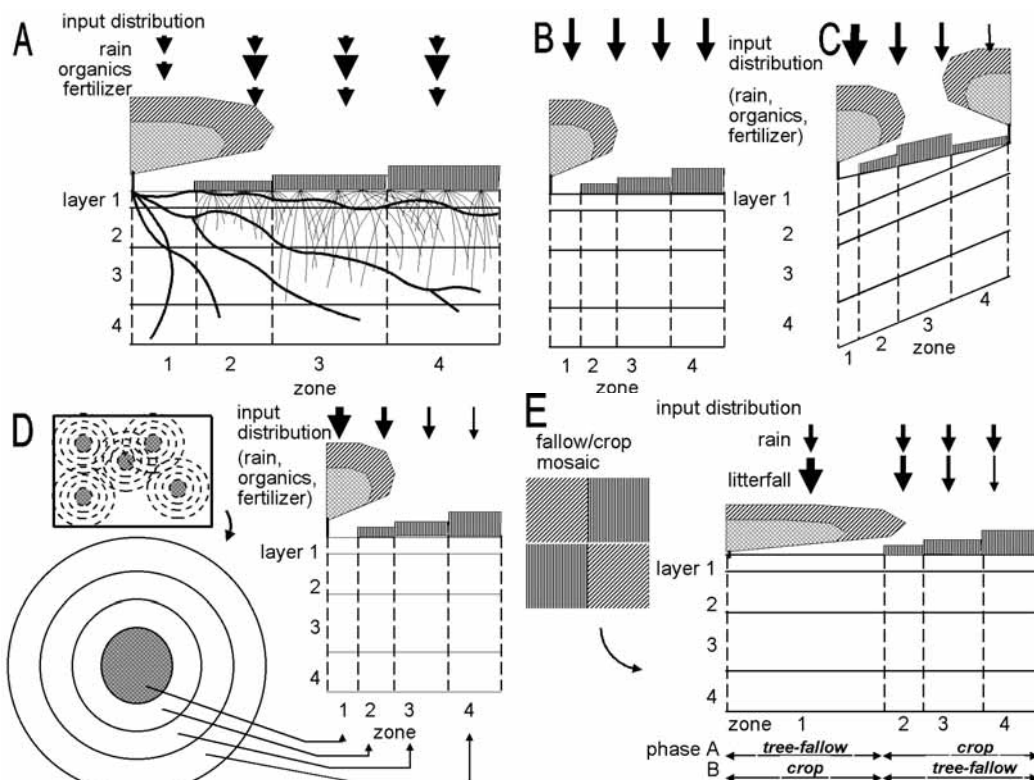


Figure 3.1. General lay out of zones and layers in the WaNuLICAS model (A) and applications to four types of agroforestry system: B. Alley cropping, C. Contour hedgerows on slopes, with variable topsoil depth, D. Parkland systems, with a circular geometry around individual trees, E. Fallow-crop mosaics with border effects.

In WaNuLICAS versions up to 3.2 two options were provided for tree locations: on the left (lower) side of Zone 1 or on the right (upper) side of Zone 4. The need for more flexible options arose when simulations were to be made for 'double row' systems as practiced for example in rubber, where the basic line of symmetry is in between tree rows.

Revising the algorithm for tree canopy development now allows for any position among the 4 zones to be used as the centre point of the tree crown, via two parameters: *AF\_TreeZone[Tree]* indicates the zone in which each of the 3 allowable trees (of the same or different species) is located, *AF\_TreeRelPos[Tree]* indicates the relative position [0-1] within this zone. *Note: adjustments to root distribution will (for now) have to be made manually.*

Table 3.1. Characteristic settings for nine types of agroforestry system.

	Geometry	Tree position, canopy	Topsoil depth	Water infiltration	Time sequence
Alley cropping on flat land	Linear, half alley + hedgerow	Zone 1, Zone 1 - 4	Homogeneous	Homogeneous, except for canopy interception	Continuous
Alley cropping on flat land, alternating hedgerow	Linear, alley + two hedgerows	Zone 1 + 4, Zone 1 - 4	Homogeneous	Homogeneous, except for canopy interception	Continuous
Alley cropping on slopes	Linear, alley + one hedgerow	Zone 1 + 4, symmetrical canopy	Gradient	Heterogeneous (-runoff + run-on)	Continuous (soil redistribution can be simulated)
Taungya transition into tree crops	Linear	Zone 1 + 4 Zone 1 - 4	Homogeneous	Homogeneous, except for canopy interception	Continuous
Agroforestation of <i>Imperata</i> grasslands	Linear, start with <i>Imperata</i> as 'crop'; half or whole alley	Zone 1 (+4), Zone 1 - 4	Homogeneous	Homogeneous, except for canopy interception	Continuous
Coffee+shade trees	Linear, use coffee as 'crop'	Zone 1 (+4), Zone 1 - 4	Homogeneous	Homogeneous, except for canopy interception	Continuous
Homegarden	Linear or Circle	Zone 1 (+4), Zone 1 - 4	Homogeneous	Homogeneous	Continuous
Parkland trees	Circle	Zone 1, Zone 1 - 4	Homogeneous	Heterogeneous	Continuous
Tree fallow/ mosaic	Linear	Zone 1, (fallow plot size)	Homogeneous	Homogeneous	Continuous or Switching between fallow and crop stage

### Tests

Two tests were used in checking the algorithm: if all zones have equal width, the results for *Zone 1, RelPos 1* should be identical to those for *Zone 2, RelPos 0*, while the results for *Zone 1 or 2, RelPos X* should be a mirror image of those for *Zone 4 or 3, RelPos (1-x)*. The current algorithm passed both tests.

### Basic concept

The canopy can expand both towards the right and towards the left of the tree position and will 'spill over' into the next zone to the left or right when it reaches the zone boundary. As

indicated by the arrow in Figure 3.2, when the tree is not in the middle of the zone, it will reach one boundary before the other, and the rate of increase of RelCanWidth[Zone] will be half of what it was before at the time the next zone starts to fill.

### Example of results

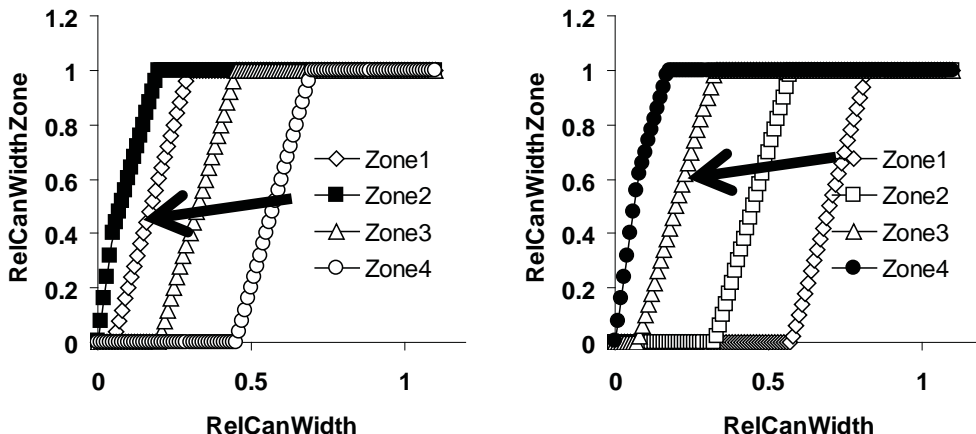


Figure 3.2. Examples of the relationship between RelCanWidth for the whole simulation area and RelCanWidthZone[Zone]; A. The tree is positioned in Zone 2 at RelPos 0.2 ; B The tree is in Zone 4 at RelPos 0.3; arrow explained in the text

### Technical implementation

```
TreeCanWidthZone[Zone] = IF AFZone[Zone] = 0 then 0 Else IF (TreeInZone?[Zone] = 1 then
MIN(1,(MAX(0,MIN(RelPos* AfZone[Zone],RelCanWidth))+MAX(0,MIN((1-RelPos)*
AfZone[Zone], RelCanWidth)))/ AfZone[Zone]), Else MAX(0,MIN(1,(RelCanWidth
- (Tree1ToTheLeft?[Zone] * RelAFZoneTreeLeft[Zone] + Tree2ToTheLeft?[Zone] *
RelAFZoneNextLeft[Zone] + Tree3ToTheLeft?[Zone] * RelAFZoneNxt2Left[Zone] +
Tree1ToTheRight?[Zone] * RelAFZoneTreeRight[Zone] + Tree2ToTheRight?[Zone] *
RelAFZoneNxtRight[Zone] + Tree3ToTheRight?[Zone] * RelAFZoneNext2Right[Zone] ))/
AfZone[Zone])))
```

With a number of auxiliary variables:

```
TreeInZone?[Zone] = IF AF_TreeZone = ZoneNumber[Zone] Then 1 Else 0
Tree1ToTheLeft?[Zone] = IF AF_TreeZone < ZoneNumber[Zone] Then 1 Else 0
Tree2ToTheLeft?[Zone] = IF AF_TreeZone < ZoneNumber[Zone]-1 Then 1 Else 0
Tree3ToTheLeft?[Zone] = IF AF_TreeZone < ZoneNumber[Zone]-2 Then 1 Else 0
Tree1ToTheRight?[Zone] = IF AF_TreeZone > ZoneNumber[Zone], Then 1 Else 0
Tree2ToTheRight?[Zone] = IF AF_TreeZone > ZoneNumber[Zone]+1, Then 1 Else 0
Tree3ToTheRight?[Zone] = IF AF_TreeZone > ZoneNumber[Zone]+2 Then 1 Else 0
RelAFZoneTreeLeft[Zone] = (1-RelPos)* (IF TreeZone=1 Then AFZoneWidth[1] Else If
TreeZone=2 then AFZoneWidth[2] else if TreeZone=3 then
AFZoneWidth[3] else if TreeZone=4 then AFZoneWidth[4] else 0)
RelAFZoneNextLeft[Zone] = IF TreeZone =1-1 then AFZoneWidth[1] else IF TreeZone =2-1 then
AFZoneWidth[2] else IF TreeZone =3-1 then AFZoneWidth[3] else
IF TreeZone =4-1 then AFZoneWidth[4] else 0
```

```

RelAFZoneNext2Left[Zone] = IF TreeZone =1-2 then AFZoneWidth[1] else IF TreeZone =2-2 then
                          AFZoneWidth[2] else IF TreeZone =3-2 then AFZoneWidth[3] else
                          IF TreeZone =4-2 then AFZoneWidth[4] else 0
RelAFZoneTreeRight[Zone] = RelPos* (IF TreeZone=1 Then AFZoneWidth[1] Else If TreeZone=2
                                   then AFZoneWidth[2] else if TreeZone=3 then AFZoneWidth[3]
                                   else if TreeZone=4 then AFZoneWidth[4] else 0)
RelAFZoneNextRight[Zone] = IF TreeZone =1+1 then AFZoneWidth[1] else IF TreeZone
                          =2+1 then AFZoneWidth[2] else IF TreeZone =3+1 then
                          AFZoneWidth[3] else IF TreeZone =4+1 then AFZoneWidth[4]
                          else 0
RelAFZoneNext2Right[Zone] = IF TreeZone =1+2 then AFZoneWidth[1] else IF TreeZone
                          =2+2 then AFZoneWidth[2] else IF TreeZone =3+2 then
                          AFZoneWidth[3] else IF TreeZone =4+2 then AFZoneWidth[4]
                          else 0

```

Where topsoil depth is varied between zones one should observe constraints so that average topsoil depth over the slope remains realistic (compare 3.2.7).

The model calculates mass balances for a basic unit of area (say 1 m<sup>2</sup>) in each zone or as (weighted) average for the whole system simulated. A weighted average is used, for example for expressing total yields of the system on an area basis, when accounting for tree roots and their uptake from the various zones. The relative weights are AF\_ZoneFrac[Zn*j*] and are calculated such that they add up to 1.0.

The four AF\_ZoneFrac[Zone] values are calculated from the following four input values: AF\_Zone[Zn1], AF\_Zone[Zn2], AF\_Zone[Zn3] and AF\_Zonetot. AF\_Zone[Zn4] is calculated by difference.

For example:  $AFZoneFrac[Zn1] = (AF\_Zone[Zn1]) / (AF\_ZoneTot)$  [4]

If a circular geometry is used (AF\_Circ = 1), the AF\_ZoneFrac[Zone] values are derived from the AF\_Zone[Zone] differently (on the basis of circle rings,  $(r_i^2 - r_{i-1}^2) / r_4^2$ ), but otherwise the model can run in the same way. The user has to specify four depths (thickness) of layers under the parameter name AF\_DepthLay*i*. The layers will be homogeneous for four zones in each layers.

### 3.1.2. Input weighting factors

A number of inputs to the soil surface can be distributed homogeneously (proportional to the respective AF\_ZoneFrac values), or heterogeneously. This way, we can for example account for. The model expects four input values 'Rain\_Weight[Zn*j*]' and calculates effective weights from:

$$RainWeightAct[Zn_i] = \frac{RainWeight[Zn_1]}{\sum_1^4 AFZoneFrac[Zn_i] \times RainWeight[Zn_i]} \quad [5]$$

This equation ensures that the average rainfall remains at the value specified; the units for the RainWeightAct parameters are arbitrary. Multiplied with the rainfall per unit area (overall

average), we then obtain the rainfall per unit area in each zone  $i$ . Similar weighting factors are used in T\_LitfallWeight, T\_PruneWeight for allocating tree litterfall and tree prunings over the various zones, while conserving their overall mass balance. The units for these weighting factors are arbitrary, as they are only used in a relative sense.

### 3.1.3. Calendar of events

The year in WaNuLCAS starts with Year 0, while the day is value from 1 to 365. Starting day of the simulation can be specified at any time after DOY 1 of Year 0.

Before a simulation, the user can specify a number of events that will take place at a given calendar date usually by specifying the Year and Day-of-Year (DOY) in which they will occur. Some events will be triggered internally, such as crop harvest when a crop is ready for it or a burn event after the slash has dried sufficiently. It may help the model user to design such a calendar. Figure 3.3 and Table 3.2 give an example of calendar of events for a hedgerow systems with Gliricidia as tree and maize - groundnut as crops. To help users in defining Julian days, we provide a list of Julian days in Wanulcas.xls – sheet ‘Julian Days’.

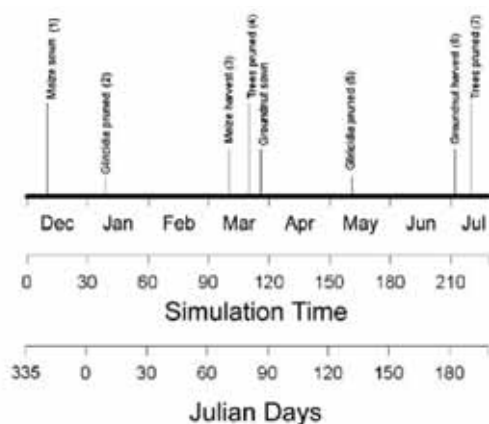


Figure 3.3. A schematic diagram of management activities of a hedgerow systems.

Table 3.2. An example of management activities record of a hedgerow systems.

No.	Activities	Date	Year in WaNuLCAS	Day in WaNuLCAS
1.	Planting maize	11 December 1994	0	345
2.	Pruning Gliricidia	8 January 1995	1	8
3.	Maize harvest	10 March 1995	1	69
4.	Pruning Gliricidia	20 March 1995	1	79
5.	Planting groundnut	27 March 1995	1	86
6.	Pruning gliricidia	14 June 1995	1	165
7.	Groundnut harvest	2 August 1995	1	214
8.	Pruning Gliricidia	7 August 1995	1	219

### 3.1.4. Crops, weeds and trees

The model user can schedule a sequence of crops (of different types) to be grown at one time for each zone, with specific fertilizer applications. For each simulation five crop types can be pre-selected from the database in the Wanulcas.xls spreadsheet. The crop type to be planted, in a given year and day (within year) can be specified for each zone by modifying the graphs Ca\_CType, Ca\_PlantYear and Ca\_PlantDoY. Similarly, subsequent fertilizer applications are specified by the graphs Ca\_FertOrExtOrgAmount, Ca\_FertOrExtOrgAppYear, Ca\_FertOrExtOrgAppDoY, Ca\_FertApply?, Ca\_OrExtOrgApply?.

There is no limit to the number of crops or fertilizer applications specified this way, as the x-axis of the graphs can be extended. A sequencing routine makes sure that crops which have been planted keep priority and new crops can only start after the current one has been harvested (as specified by the duration of its vegetative and generative phases set for the crop type). If a new crop should have been planted before the previous one is harvested, it is skipped from the sequence and the model will wait for the first new planting data specified.

Each crop has a maximum dry matter production rate per day, expressed in  $\text{kg m}^{-2} \text{day}^{-1}$ , Cq\_GroMax and a graphic input of Cq\_RelLUE[cr] giving the relative light use efficiency as a function of crop stage. These parameters may be derived for a given location from more specific models, such as the DSSAT family of crop growth models or WOFOST (see section 3.7 for further details).

Annual or perennial weeds can be simulated using the 'infrastructure' of the crop model, and a seed bank that allows weeds to regenerate whenever there is no crop cover is included. At the moment, however, no crop-weed interaction within a zone can be simulated (see 3.10.4).

Trees can be planted, pruned and harvested at set calendar dates, using either of the three copies of 'tree' available. Allometric equations, which can be derived from fractal branching rules in a separate spreadsheet, govern the allocation of growth resources over the various tree organs. Trees can be pruned in the model to a specified degree on the basis of a user-specified set of dates (T\_PruneY and T\_PruneDoY, similar to the crop sequence), or on the basis of one or two criteria: concurrence with a crop on the field and when the tree biomass exceeds a 'prune limit' (see section 3.10.7 for details). Prunings can be returned to the soil as organic input or (partially) removed from the field as fodder.

### 3.1.5. Animals and soil biota

The model does not at this stage include a livestock component, but it can be used to predict fodder production and the tree pruning rules can be used to describe fodder harvesting or grazing. In such a case external inputs of manure may have to be included. Soil biota are implicitly accounted for in the parameters of the decomposition model, in the parameters describing the degree of mixing of organic inputs between surface litter and the various soil layers, in the creation of soil macropores (influencing bypass flow) and in N fixation or P mobilization.



## 3.2. Soil and climate input data

### 3.2.1. Soil physical properties

For calculating water infiltration to the soil, a layer-specific estimate of the ‘field capacity’ (soil water content one day after heavy rain) is needed. For calculating potential water uptake a table of the soil’s ‘matric flux potential’ is needed, which integrates unsaturated hydraulic conductivity over soil water content. The model also needs the relationship between water potential and soil water content, to derive the soil water content equivalent to a certain root water potential. As these relationships are not generally measured for all soils where we may want to apply the WaNuLCAS model, ‘pedotransfer’ functions (Arah and Hodnett, 1997) are used. We derive parameters of the Van Genuchten equations of soil physical properties via a ‘pedotransfer’ function from soil texture, bulk density and soil organic matter content. The function selected was developed by Wösten *et al.* (1995, 1998). As this pedotransfer function is based on soils from temperate regions, one should be aware of its possible poor performance on soils with a low silt content, as the combination of clay + sand at low silt contents is much more common in the tropics than in temperate regions.

In WaNuLCAS versions up to 3.1 Van Genuchten equation developed by Woesten *et al.*, (1995, 1998) is the only option to generate soil hydraulic properties. Van Genuchten equation was developed based on temperate soils. By adding new algorithm (Tomasella and Hodnett, 2002), now WaNuLCAS more adaptable to generate soil hydraulic properties for tropical soils.

The pedotransfer function is included in the Excel file Wanulcas.xls and after the user has specified clay, silt and organic matter content and bulk density of the soil, all the tables are generated which WaNuLCAS needs. The user then has to copy these tables to the sheets representing each zone, replicating them for each layer. This way different soil physical parameters can be used for any layer and zone in the model. Further instructions are given in the spreadsheet itself.

Soil texture	=>	Van Genuchten	=>	Tabulated	=>	Soil by layer
Soil organic matter		parameters		water retention,		in WaNuLCAS.STM
Soil bulk density				matric flux potential		

Suprayogo (2003) produced a pedotransfer database for tropical soils containing 8915 data available worldwide. The data were then used to assess the performance of the pedotransfer function used in WaNuLCAS model in predicting soil physical relationships ( $\theta$ -h-K). The results appeared close to the field measurement. The largest deviations occurred on vertisols and mollisols, where bulk density and soil organic matter content diverged.

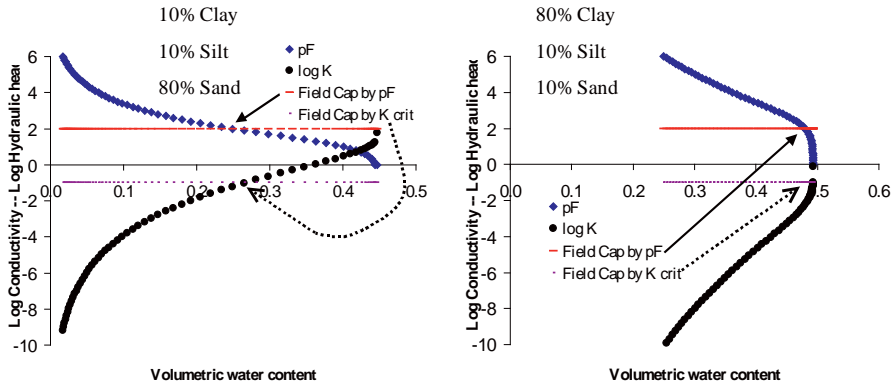


Figure 3.4. Relations between soil water content (X-axis), hydraulic head (expressed as pF or  $-\log(\text{head})$  -- positive Y axis) and unsaturated hydraulic conductivity (negative Y axis) for a dandy (left) and a clayey (right) soil, based on the pedotransfer function used in Wanulcas.xls; two definitions of 'field capacity' are indicated: one based on a user-defined limiting hydraulic conductivity, and one based on a depth above a groundwater table, defining a pF value; in the model the highest value of the two for each layer and zone will be used to determine maximum soil water content after a heavy rain event.

### 3.2.2. Temperature

Soil Temperature data are used to modify soil organic matter transformations. They can be entered as:

- A. [Temp\_AType = 1] a constant (Temp\_Const) ,
- B. [Temp\_AType = 2] as a table with monthly average values (Temp\_MonthAvg), or
- C. [Temp\_AType = 3] as a daily values (Temp\_DailyDat) linked to a sheet 'Temperature' in the Wanulcas.xls spreadsheet

Air temperature data through C\_Topt and C\_Tmin parameters are used to modified the length of cropping season. Current default values for air temperature ensure the length of cropping season = Cq\_TimeVeg + Cq\_TimeGen as specified on Wanulcas.xls.

### 3.2.3. Potential evapotranspiration

There are 2 options for the potential evapotranspiration rate: for Temp\_EvapPotConst? = 1 a constant value is used throughout the simulation (Temp\_EvapPotConst), while Temp\_EvapPotConst? = 0 a daily value (Temp\_EvapPotDailyData) is read from the excel spreadsheet. This can be calculated, for example from a (modified) Penman-Monteith equation or thornthwaite equation on the basis of climatological data for the site.

In this version 4.0, WaNuLCAS has elaborated estimation of daily potential evapotranspiration based on thornthwaite equation with air temperature and day length as its main inputs.

The potential rate of evapotranspiration is used to drive evaporation from canopy interception water (whenever present), trees and crops (but limited by plant water stress if present), dead wood piles on the soil after a slash event and finally by the soil (if any demand is unsatisfied as yet).

### 3.2.4. Rainfall

Rainfall data can be either generated within WaNuLCAS, or be obtained from an Excel spreadsheet. Setting the 'Rain\_AType' parameter makes the choice:

1 = Tabulated daily rainfall records from an external file.

2 = Random generator based on monthly data using rainfall simulator

3 = Random generator based on heavy and light rainfall data

4 = Monthly average tabulated data (with given probability of daily rainfall and normal random variation around the average values).

The four options are summarized in Table 3.3.

Table 3.3. Three options for deriving daily rainfall values.

Rain_AType	1 = Tabulated daily rainfall	2 = rainfall simulator	3 = Random generator	4 = Variation around monthly total
Probability of rain on a given day	not applicable	Probability for four rainfall occurrences (D D, D W, W W, W D)	Rain_DayP, split via Rain_HeavyP into 'light' (0.5-25) and 'heavy' (> 25 mm/day) rains	Rain_DayP
Amount of rain	Read from table	Probability distribution functions based on single- and multi-parameter models.	Normal distribution around Rain_Light and Rain_Heavy (truncated at zero)	Normal distribution around Rain_MonthTot / (Rain_DayP * 30) (truncated at zero)
Variability of rainfall	Implicit in data read from table		Rain_CoeffVar for heavy rain category, for light rain a standard deviation of 5 is used	Rain_CoeffVar

For choice 1, the data should be copied to sheet 'rainfall' to column 3 of a spreadsheet with name Wanulcas.xls. This spreadsheet has in column 1 real dates (optional), in column 2 days {1...end} and in column 3 {rainfall in mm/day}. Alternatively, a new STELLA link can be established between the 'Rain data' table in WaNuLCAS and another relevant spreadsheet. Missing data should be addressed outside of WaNuLCAS.

If the user would like to use a different rainfall generator, the easiest way would be to generate rainfall data outside of WaNuLCAS copy the results to the Wanulcas.xls spreadsheet and set Rain\_AType to 1.

For choice 2, number of parameters (Appendix 7) is needed to run this rainfall type. A help file to generate these parameters is available in excel file. This rainfall type generating daily rainfall data based on common 'Markov chain' way, which basically consists of two steps: i) simulating rainfall occurrence, i.e. determining whether or not a day is a rainy day or not, and ii) for rainy days, determine the amount of rainfall (Appendix 10).

For choice 3, six parameters are needed: the probability of rainfall on a given day ( $Rain_{DayP}$ ), the probability that rainfall is of type 'heavy' rather than 'light' ( $Rain_{HeavyP}$ ), the boundary value of heavy and light rains ( $Rain_{BoundHeaLi}$ ), the average value of 'light' and 'heavy' rains ( $Rain_{Light}$  and  $Rain_{Heavy}$ ) and a coefficient of variability for heavy rain ( $Rain_{CoefVar}$ ). Light rain is truncated from a normal distribution with 0.5 as minimum and  $Rain_{BoundHeaLi}$  (default 25 mm) as maximum value, heavy rain is truncated with  $Rain_{BoundHeaLi}$  as minimum. The standard deviation for light rains is as a standard input at 5 mm (but can be modified inside the equation for STELLA users).

For choice 4, tabulated monthly averages are entered in ' $Rain_{MonthlyTot}$ '. Daily rainfall is derived from a normal distribution around this average value, with a standard deviation defined as coefficient of variation.

$$Rain = \max(0, Rain_{Today}) \times Normal\left(\frac{Rain_{MonthTot}}{30 \times Rain_{DayP}}, \frac{Rain_{CoefVar} \times Rain_{MonthTot}}{30 \times Rain_{DayP}}, RainSeed\right) \quad [6]$$

The 'Normal' function in STELLA has three arguments: mean, standard deviation and seed. We protect against negative rainfall values for obvious reasons.

The linked data for option 1 and tabulated monthly data in option 4 may start at any 'day of year' before the simulation starts. They are read via 'Day of Year' variable  $Rain_{DOY} = \text{Mod}(\text{Time} + Cq_{DOYstart}, 365)$ . For option 1 one can start at any year of the climatic data set by specifying  $Cq_{YearStart}$  (one should be careful not to have the simulation start before or extend beyond the rainfall data set in such a case. It is possible to repeatedly use the rainfall data for a single year for a multiyear run ( $RainCycle? = 1$ ), or to read multi-year data from the Excel spreadsheet run ( $RainCycle? = 0$ ). One would normally start reading rainfall data at year 0; if one wants to start at a later point in the data set, the parameter  $Cq_{YearStart}$  has to be adjusted. The  $Rain_{DayP}$  values are given as a monthly tabulated function of Day of year.

### 3.2.5. Canopy interception of rainfall

Part of any rainfall event will not reach the soil surface because the tree or crop canopy intercepts it. This interception process has been included on the basis of a maximum water storage capacity of the tree + crop canopy, calculated as a thickness of water film times the leaf area index (ignoring water stored on stem surfaces). Water will evaporate from this intercepted layer at a speed equal to the potential evapotranspiration rate, with priority over crop and tree transpiration or soil evaporation.

### 3.2.6. Soil redistribution on slopes

Soil particles can get detached during rainfall events, move along with surface runoff water and may get entrenched or filtered out where the waterflow slows down on a rough surface or encounters a zone of high net infiltration rates. Soil particles can also be moved by soil tillage (section 3.10.8), especially by ploughing. The amount of soil particles leaving the border of any measurement area is a balance of the amount entering it from above, plus the amount of soil starting to move within the area, minus the amount filtered. A process level description

of such events should consider a time scale of minutes (or less) and deal with considerable heterogeneity in conditions at the soil surface. For WaNuLCAS we've chosen for a more aggregated description, in line with the daily time step, but maintain:

$$\text{Soil\_outflow} = (1 - \text{filterefficiency}) \times (\text{soil\_inflow} + \text{soil\_stirredup}) \quad [7]$$

where the filter efficiency is expressed as fraction of the soil moving. For a typical situation with contour hedgerows (or other vegetative filter strips), we can allocate most of the filter effect to 'Zone 1', while soil cover in all zones modifies the amount of soil stirred up.

A further simplification, although not strictly necessary for the model to function, is to assume that at any time the soil surface is approximately a plane within the zones considered. The main issues then are:

1. how does the soil slope change over time,
2. how much is the net outflow from one simulated land unit,
3. how are the properties of the topsoil modified in each zone due to the soil movement and filter effects.

### Change of slope

We want to derive the terrace height  $h_x$  and the final slope ( $h'/w$ ) from the initial\_slope ( $h/w$ ), the amount of soil moved and the amount lost. We first assume that the position of point A is fixed and that soil accumulation (terrace formation) can increase the level to point A' but not decrease the level. From Fig. 3.5 we can see that:

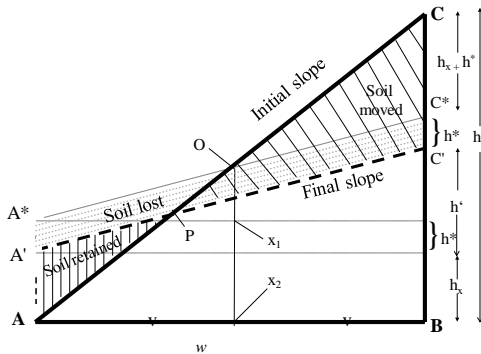


Figure 3.5. Terminology for describing change of slope: ignoring the soil below the boundary A-B which will not be affected by the changes and assuming that the bulk density of the soil is constant, the redistribution process modifies the triangle A-B-C (with a width  $w$ , a height  $h$  and a slope-length  $s$ ) into the polygon A-A'-C'-B (with height  $h'$  and slope length  $s'$ ), plus the soil loss which is proportional to  $AA^*C^*C'$ , or  $wh^*$ ; the triangle  $AA^*O$  is equal to  $OCC^*$

$$h = 2(h_x + h^*) + h' \quad [8]$$

$$\frac{\text{Soil\_lost}}{\text{bulkdensb}} = ABC - AA'C'B = A'A^*C^*C' = h^*w \quad [9]$$

$$\frac{\text{soilretained}}{\text{bulkdensb}} = \frac{(\text{Soil\_moved} - \text{Soil\_lost})}{\text{bulkdensb}} = AA'P = \left(\frac{h}{(h_x + h^*)}\right) AA'O = \left(\frac{h}{(h_x + h^*)}\right) (AA^*X_1X_2 + A^*OX_1 - AOX_2) = \left(\frac{h}{(h_x + h^*)}\right) \left(\frac{(h-h')w}{4} + \frac{h'w}{8} - \frac{hw}{8}\right) = \frac{\left(\frac{h_x}{(h_x + h^*)}\right) w(h-h')}{8} = \frac{wh_x}{4} \quad [10]$$

Hence,

$$Terrace\_height = h_x = \frac{4(Soil\_moved - Soil\_lost)}{(bulkdensbw)} \quad [11]$$

If Soil\_lost = Soil\_moved and thus Soil\_retained = 0, this leads to  $h_x = 0$ .  
Combining [\*x4], [\*x3], [\*x2] and [\*x1] we obtain:

$$Final\_slope = Initial\_slope - \frac{(8Soil\_moved - 6Soil\_lost)}{(Bulkdensbw^2)} \quad [12]$$

If Soil\_moved and Soil\_lost are expressed in Mg, w in m, the model is applied to a breadth b of 1 m and bulkdensity in  $Mg\ m^{-3}$ , the final slope in indeed dimensionless.

For the time being the effect of soil movement on the soil quality of the receiving zones (soil C, N and P contents, soil physical properties) are ignored, i.e. we assume the incoming soil to have the same properties as the average of the receiving zone. This may cause inconsistencies in the total C, N and P balance and will need further attention in a future release.

The situation where point A is not fixed, can lead (in the absence of filter functions) to a parallel decline of topsoil height, without change in slope angle.

### 3.2.7. Soil erosion

Soil erosion module applies to sloping land situation only. WaNuLCAS uses ROSE (physical equation) equations to estimate soil erosion. Tillage will affect soil erosion (see 3.10.8)

## 3.3. Water balance

### 3.3.1. Soil water storage infiltration and evaporation

For the description of the soil water balance in soil-plant models a number of processes should be combined which act on different time scales (Figure 3.6):

1. rainfall or irrigation (with additional run-on) and its allocation to infiltration and surface run-off (and/or ponding), on a seconds-to-minutes time scale,
2. infiltration into and drainage from the soil via a cascade of soil layers, and/or via 'bypass' flow, on a minutes-to-hours time scale,
3. subsequent drainage and gradual approach to hydrostatic equilibrium on a hour-to-days time scale,
4. transfers of solutes between soil layers with mass flow,
5. evaporation from surface soil layers on a hour-to-day time scale,
6. water uptake on a hour-to-days time scale, but mostly during daytime when stomata are open,
7. hydrostatic equilibration via root systems on a hour-to-days time scale, but mostly at night when plant transpiration is negligible,
8. hormonal controls ('drought signals') of transpiration on a hour-to-weeks time scale,
9. changes in macropore volume (and connectivity) based on swelling and shrinking of soils closing and opening cracks, and on creation and destruction of macropores by soil macrofauna and roots; this acts on a day-to-weeks time scale. Its main effect will be on bypass flow of water and retardation of nutrient leaching.

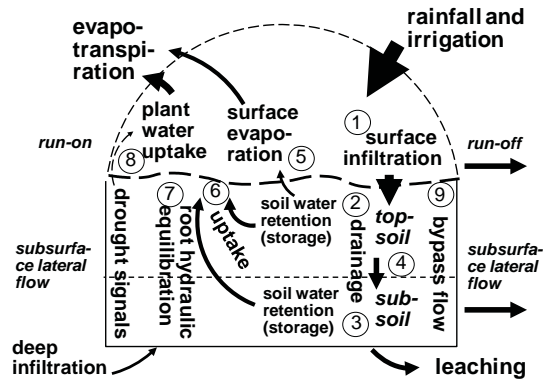


Figure 3.6. Elements of the water balance included in the WaNuLCAS model: 1. surface infiltration of rainfall, 2-4. Redistribution of water and solutes over the profile, recharging soil water content (2) and draining (leaching) excess water from the bottom of the profile, 5. surface evaporation, 6. water uptake by tree and crop roots, 7. hydraulic equilibration via tree roots, 8. drought signals influencing shoot:root allocation and 9. bypass flow of solutes.

The WaNuLCAS model currently incorporates point 1...7 and 9 of this list, but aggregates them to a daily time step; drainage to lower layers is effectuated on the same day as a rainfall event occurred. An empirical infiltration fraction (as a function of rainfall intensity, slope and soil water deficit) can be implemented at patch scale. Between the zones of the WaNuLCAS model, surface run-off and run-on resulting in redistribution among zones can be simulated on the basis of a user-specified weighing function for effective rainfall in the in the various zones.

Table 3.4. Water balance at patch level in WaNuLCAS

In	Out
Initial soil water content for all zones and layers	Final soil water content for all zones and layers
Patch-level run on	Patch-level run-off
Lateral inflow	Drainage from bottom of soil profile and lateral outflow
Rainfall	Soil evaporation
Irrigation (added as extra rainfall)	Evaporation of intercepted water
	Transpiration by tree
	Transpiration by crop
	Transpiration by weed

Upon infiltration a ‘tipping bucket’ model is followed for wetting subsequent layers of soil, filling a cascade of soil layers up till their effective ‘field capacity’. Field capacity is estimated from the water retention curve (see section SOIL above). In WaNuLCAS, *S\_SeepScalar* is an additional parameter (a constant value range 0 - 1) that also control the amount of water that infiltrate to the deeper soil layer.

Soil evaporation depends on ground cover (based on LAI of trees and crops) and soil water content of the topsoil; soil evaporation now stops when the top soil layer reaches a water potential of -16 000 cm.

A simple representation of by-pass flow is added, but only in its effects on nutrient leaching (see 3.4.3). Dynamics of macropore are described in section 3.3.7.

### 3.3.2. Water uptake

Water uptake by the plants is driven by their transpirational demand, within the possibilities determined by roots length density and soil water content in the various cells to which a plant has access.

The calculation procedure used by De Willigen and Van Noordwijk (1987, 1991) is based on an iterative procedure, solving the simultaneous equations for soil + plant resistance as a function of flow rate, and of flow rate as a function of the resistance's involved. As this routine can not be implemented as such in a STELLA environment, we chose for an approximate procedure, where some of the feed-back is included on an a-priori basis, and an other part is implemented in the next time step, by keeping track of the plant water status inherited from the previous day.

Plant water potential is calculated on the basis of soil water potential (weighted average over all zones and layers on the basis of local root length density, minus the potential to overcome root entry resistance if full transpirational demand is to be met, and a term to cater for expected soil resistance (estimated as 10% of soil water potential; a more precise value is calculated in step 5 of the daily procedure – see below)).

The sequence of events in modeling water uptake (Figure. 3.7), more detail equations are presented in Appendix 5 and 11:

1. Estimate potential transpirational demand  $E_p$  from potential dry matter production (an input to WaNuLCAS, derived from other models), diminished to account for the current shading and LAI, multiplied with a water use efficiency (CW\_TranspRatio, again a model input, reflecting climate and crop type),
2. Estimate plant water potential on the basis of the various resistances in the catenary process:
  - (a) soil water potential as perceived by the plant (weighted average over all zones and layers on the basis of local root length density),
  - (b) a term to cater for expected resistance between bulk soil in the voxel and the root surfaces (in the default situation initially estimated as 5% of soil water potential; a more precise value is calculated in step 5 of the daily procedure – see below)
  - (c) the potential gradient needed to overcome root entry resistance if full transpirational demand is to be met
  - (d) the potential gradient needed to overcome root axial transport resistance if full transpirational demand is to be met.
3. On the basis of this plant water potential, calculate the transpiration reduction factor  $f_p$  on the basis of a function proposed by Campbell (De Willigen *et al.*, 2000),
4. Use the reduced uptake demand  $f_p E_p$  to estimate the rhizosphere potential  $h_{rh}$  for all voxels  $i$  from the plant potential  $h_p$  minus the potential gradient needed to overcome the axial transport distance given the length of the pathway from voxel to stem base (Radersma and Ong, 2004),
5. Calculate potential water uptake rates for all layers  $i$  on the basis of  $h_{s,i}$  and  $h_{rh}$  and their equivalent matric flux potentials  $F$ ; the matrix flux potential is the integral over the unsaturated hydraulic conductivity and can be used to predict the maximum flow rates which can be maintained through a soil (De Willigen and Van Noordwijk, 1994), taking into account that the drier the soil the more difficult it is to move water through a reduced water-filled pore space



6. Calculate real uptake as the minimum of demand ( $f_p \cdot E_p$ ) and total supply (summed over all layers  $i$ ) and allocate it to layers on the basis of potential uptake rates,
7. Recalculate soil water contents in all layers  $i$  for the next time step.
8. Calculate a 'water stress factor' from real uptake as fraction of potential transpirational demand; real growth is based on the minimum of the 'water stress' and 'nutrient stress' factor and potential growth.

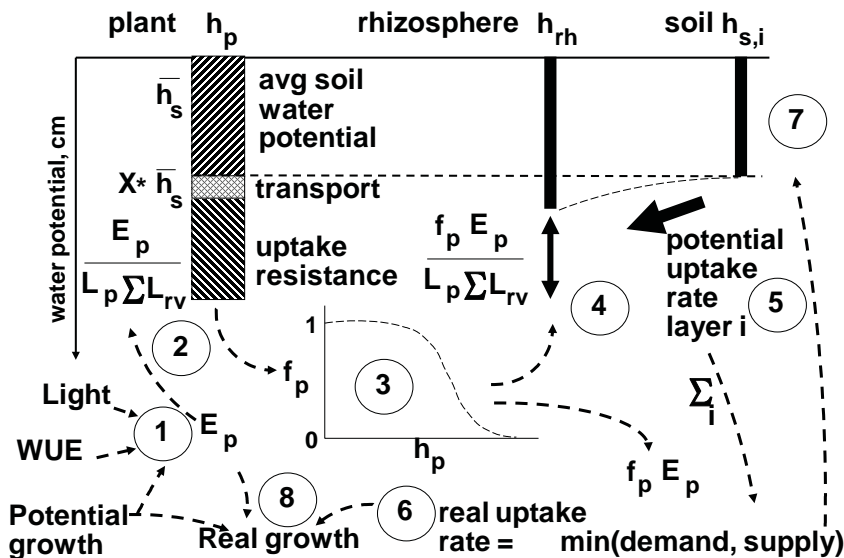


Figure 3.7. Steps (1...8) in daily cycle of calculations of water uptake; the interrupted arrows represent information flows.

The procedure for water uptake is similar to that for nutrient uptake (see below), but the transport equations are analogous in terms of 'matric flux potential' rather than soil water content. A further complication for allocating water uptake is that plant water potential may differ between roots of the various components in a given cell. In the model the highest (least negative) is used first to share out potential water uptake to all components, followed by additional uptake potential for components with a lower water potential (Figure 3.8).

The model in its current form does not include 'drought signals'. It may be possible to represent such direct effects of root-produced hormones on stomatal closure by adding a relation between  $CW\_PotSoil$  (the averaged water potential around the roots of a crop) and the  $CW\_DemandRedFac$ , beyond their current indirect relation via  $CW\_PotSuctCurr$ .

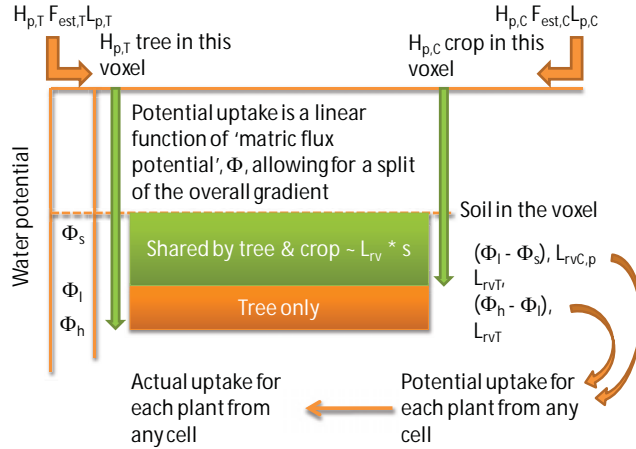


Figure 3.8. Diagram of sharing out available water by tree and crop.

### 3.3.3. Hydraulic lift and sink

An option exist to simulate hydraulic lift and hydraulic sink phenomena in tree roots, transferring water from relatively wet to relatively dry layers. The parameter  $W\_Hyd?$  determines whether or not this is included (0 = not, 1 = yes). Hydraulic continuity via root systems can lead to transfers of water between soil layers, on the basis of water potential and resistance. If the subsoil is wet and the surface layers are dry, this process is called hydraulic lift (Dawson, 1993). The reverse process, transfers from wet surface layers to dry subsoil is possible as well and has recently been observed in Machakos (Kenya) (Smith *et al.*, 1998; Burgess *et al.*, 1998). Although the total quantities involved in these water transfers may be relatively small, it can be important in the competition between shallow and deep-rooted plants. Hydraulic lift can re-wet nutrient-rich dry topsoil layers and thus facilitate nutrient uptake. The reverse process, deep water storage by deep rooted plants after moderate rainfall which only infiltrate into the topsoil, can increase their overall resource capture vis-a-vis shallow rooted plants.

A general solution for the flux  $F_i$  into or out of each cell  $i$  is:

$$F_i = \frac{\sum_{j=1}^n \frac{\Psi_i - \Psi_j}{r_i r_j}}{\sum_{j=1}^n r_j^{-1}} \quad [13]$$

where  $\Psi_i$  and  $\Psi_j$  refer to the root water potential in layer  $i$  and  $j$ , respectively and  $r_i$  and  $r_j$  to the resistance to water flow between the soil layer and stem base. This equation assumes a zero transpiration flux at night.

A more detailed account of hydraulic equilibration through root systems of crop or tree that connect relatively dry and relatively wet zones of the soil was incorporated into WaNuLCAS. The process of 'hydraulic equilibration' is driven by the existence of differences in water potential among the layers (and zones) of a soil profile, and the availability of a conductors in the form of root systems that are connected to the soil.

Implementation requires the following steps:

1. Estimation of equilibrium stem base water potential at zero flux, from the root-weighted average of the soil hydraulic potential in each cell; the proportionality factor consists of root length density and the volume of the cell as other proportionality factors cancel out in the equation.
2. Derivation of the equivalent equilibrium volumetric soil water content in each cell on the basis of this stem base potential for each tree or crop type and the parameters of the pedotransfer function.
3. Calculation of the amount of water involved in the difference between current and equilibrium soil water content (positive differences as 'potential supply' of water, negative ones as 'demand')
4. Derivation of the potential flux as the minimum of a 'cap' ('HydEq\_fraction that relates to soil transport constraints that may have to be calibrated to actual data -- default value is 0.1 day<sup>-1</sup>) of the difference between target and actual volumetric soil water content, and a potential flux that is in accordance with the potential difference, the hydraulic conductivity of the roots, root diameter and root length density and the period of time available (based on the fraction of day that stomata are expected to be closed)
5. Reduction on either the positive or the negative potential fluxes to be in accordance with a zero-sum net process, by calculating the minimum of the total potential supply and total potential demand, and scaling down the cell-specific differences such that total supply matches total demand.
6. Implementing the resulting flux in or out of each cell on a daily time step basis and checking the consistency of the water balance for errors or inconsistencies.

For a 'standard' case of parklands (with parameterization for parkland system in Burkina Faso as simulated by Jules Bayala) the implementation leads to:

1. A total hydraulic equilibration flux through tree roots that is 64% of the tree transpiration,
2. Slight increases for processes that depend on topsoil water content: runoff, soil evaporation
3. A 9% increase in crop water uptake
4. A 22% decrease of tree water uptake (and 10% decrease in canopy interception)
5. A 15% decrease in vertical drainage

These results are only moderately sensitive to the value (arbitrarily) selected for the HydEq\_Fraction; values above 0.5 may be unrealistic.

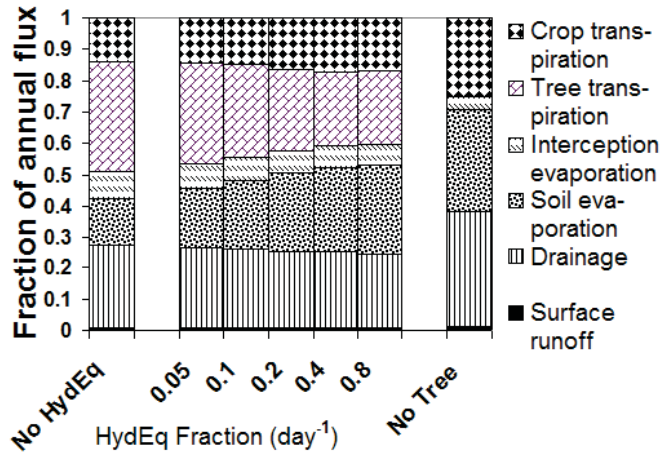


Figure 3.9. Impacts on the water balance of a parkland system with a rainfall of approximately 750 mm year<sup>-1</sup> of the presence of trees and inclusion of hydraulic equilibration in the model, for a range of values of the (arbitrarily set) HydEq\_Fraction parameter.

### 3.3.4 Implementing a lateral flow component into WaNuLCAS

Earlier versions of the model only considered vertical flow, but evidence from the field experiments in Lampung indicates that even on very mild slopes (4%) a lateral flow component is important (Suprayogo, 2000).

As the model operates at a daily time step, we can not give a detailed account of equilibration and some simplifying assumptions are required:

1. lateral flow is only supposed to occur when incoming water exceeds the 'field capacity' for a given cell in the model; during the lateral flow as well as vertical drainage we assume the soil to operate at saturated hydraulic conductivity,
2. the amount of water leaving a cell in the model, either vertically or horizontally, is equal to the amount of water coming in from above (infiltrating rain in layer 1 and drainage from the layer above in other layers) + lateral inflow from the up-hill neighbouring cell - the amount of water it takes to recharge the profile to field capacity
3. the amount of water flowing across any vertical or horizontal surface is the minimum of three quantities:
  - the amount available for flow (as defined above),
  - the amount that can cross the surface in a day, which depends on saturated hydraulic conductivity per unit area, the size of the surface area to be crossed, and the gradient (1 in the vertical direction, slope%/100 for the lateral flow), and
  - the maximum storage in, plus outflow out of the column below the cell (this is to avoid 'back logging' of water in a dynamic sense; the outflow in a lateral direction is ignored as it will normally be matched by incoming lateral flows)
4. the allocation of total drainage out of a cell over vertical and lateral outflow is based on the relative maximum outflows, but lateral flow can be greater than its nominal share if another constraint on vertical flow so allows; if there is (still) excess water coming into a cell (as lateral inflow exceeds lateral outflow), it is allocated to the water stock in the cell, which can

thus be above field capacity (the next day this will be reflected in a negative value of the potential recharge),

5. lateral flow normally has no influence on the soil water content after the rain event (as the soil will return to field capacity everywhere), but it can have a major impact on the redistribution of nutrients.

Implementing sub-surface lateral flow required the following steps:

1. Splitting the excess (incoming - recharge) water for each timestep into a vertical and a horizontal flow component (W1).

The amount of water leaving a cell is apportioned over one horizontal flow (to the left-hand neighbour) and one vertical one (to the lower neighbour), on the basis of saturated hydraulic conductivity, gradient in hydraulic head (difference in height of neighbouring cells divided by their distance) and surface area through which the flow occurs:

$$Fluxh_{ij} = \frac{Ksath_{ij}HydHeadHor_{ij}((depth_i - depth_{i-1})/2)}{Ksatv_{i4}xzonew_i + Ksath_{ij}HydHeadHor_{ij}((depth_i - depth_{i-1})/2)} \quad [14]$$

$$Fluxv_{ij} = \frac{Ksath_{ij}xzonew_i}{Ksatv_{ij}xzonew_i + \sum_i Ksath_{ij}HydHeadHor_{ij}((depth_i - depth_{i-1})/2)} \quad [15]$$

with:

$$HydHeadHor_{i1} = \frac{(depth_{i,1} - depth_{i-1,1})}{(zonew_i + zonew_{i-1})} + origslope \quad [16]$$

and for  $j > 1$   $HydHeadHor_{ij} = origslope$

2. Accounting for incoming water from above (rainfall in layer 1, vertical drainage from the layer above for the other zones), as well as laterally (W2)  
A 'circularity' problem arose when we tried to calculate the lateral flow out of zone 4 as input to zone 3 in the same soil layer. As a first approximation we made the assumption that the incoming lateral flow will **not** have an impact on the subsequent soil water content in a layer (which will return to field capacity if incoming rainfall is sufficient). This first estimate allows us to calculate an estimated drain volume from each cell, which is correct only for zone 4. In a next step, corrections are applied for zone 3, zone 2 and zone 1 in sequence, based on the knowledge of the real incoming lateral flows
3. Defining incoming lateral flow to the simulated zones for all layers (W3)  
We assume that the soil up-hill (beyond zone 4) of the simulated zones has similar properties to the soil in the 4 zones: it is assigned the average split over vertical and horizontal drainage found in the simulated zones (see W1), and the same rainfall per unit area. The total amount of water coming in is further set by the width of the area generating lateral flow, relative to the total width of the zones considered.
4. Calculating lateral flows of nutrients by multiplying amounts of water moving with the average concentration in soil solution, with an option for 'by-pass flow' of water without exchange with the soil matrix (N1)  
The equations followed the same logic as those for vertical leaching, but an option was provided that bypass flow may differ between nutrients already in the N stock of a cell ('matrix') and those in the current in-flow ('macropore'; this includes the fertilizer just added to the soil - if the first rain is mild it will get absorbed by the soil, if the first rainy day

is a heavy rain, it may leach down or out quickly depending on the value used for the two by-pass flow parameters).

5. Defining the incoming nutrient concentrations for the incoming subsurface flow (N2). The incoming nutrient concentrations for the incoming subsurface flow can be defined as a multiplier of the average concentration of drainage water within the simulated zones.

### 3.3.5. Run-on and run-off

Surface run-on and run-off are treated in a similar way, but here the conductivity is supposed to be non-limiting as soon as the slope exceeds 0. A RunonFrac parameter determines which fraction of the run-off generated uphill will actually enter the plot. The current routine replaces the old one where the run-off fraction was directly defined from the rainfall amount. In the new version a variable run-off fraction can be simulated, depending on the water content of the soil profile. Essentially two situations can lead to surface run-off:

- daily rainfall plus run-on exceed daily maximum infiltration rate (by setting these values one may try to compensate for typical rain duration per day),
- daily rainfall plus run-on exceed the potential water storage in and outflow from the soil column underneath the surface.

The first type of run-off is typically determined by properties of the soil surface (such as crusting and hydro-phobic properties) and the current infiltration capacity of the soil in the time available for infiltration. The time available for infiltration depends on the duration of the rainfall, the delayed delivery of rainfall to the soil via canopy interception and dripping of leaves (+ stemflow), and the rate at which water ponding on the surface will actually flow to a neighbouring zone or plot. The latter depends on slope. Formally:

$$Rain\_TimeAvForInf = \text{Min}(24, Rain\_Duration + Rain\_IntercDelay + Rain\_SurfPondDelay) \quad [17]$$

With

$$Rain\_Duration = \left( \frac{Rain}{Rain\_IntensMean} \right) \times \text{min} \left( \max(0, 1 - 3 \times Rain\_IntensCoefVar, \text{Normal}(1, Rain\_IntensCoefVar, Rain\_GenSeed + 11250)), 1 + 3 \times Rain\_IntensCoefVar \right) \quad [18]$$

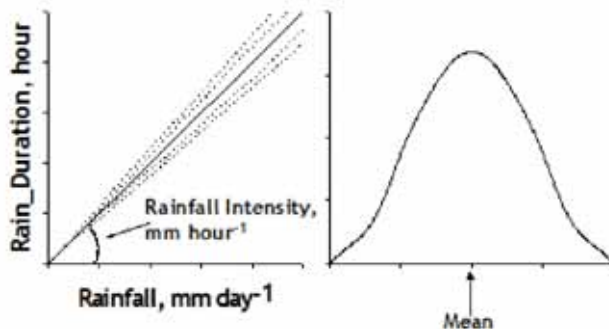


Figure 3.10. Rain Duration that determine the time available for water infiltrated to the soil. Rain duration calculated from rainfall and rain intensity.

$$Rain\_IntercDelay = \min \left( Rain\_Max\_IntDripDur, Rain\_IntMultx \frac{Rain\_Interception}{Rain\_IntercDripRt} \right) \quad [19]$$

where the factor IntercMultiplier indicates the maximum temporary storage of water on interception surfaces divided by the amount left at the end of the dripping stage, and the Drip\_Rate is expressed in mm hr<sup>-1</sup>. Default assumptions are Rain\_IntMult = 3, Rain\_IntercdripRt = 10 mm hr<sup>-1</sup>, Rain\_Max\_IntDripDur = 0.5 hr.

and

$$Rain\_SurfPondDelay = \frac{Rain\_PondStoreCp}{(AF\_SlopeCurr \times Rain\_PondFlwRt \times AF\_ZoneWidth)} \quad [20]$$

with default Rain\_PondStoreCp = 5 mm, and Rain\_FlwRt = 10 mm hr<sup>-1</sup> per m of AF\_ZoneWidth

The second type of run off is by the depth of the profile and the saturated hydraulic conductivity of the deep subsoil.

Intermediate situations with sub-surface run-off may build up from 'top down' (higher layers before deeper ones), or 'bottom up' (starting from the subsoil), depending on the specific profile in saturated hydraulic conductivities.

### 3.3.6. Subsurface inflows of water to plots on a sloping land

In WaNuLCAS 4.0 subsurface in-flows are derived from a 'virtual' soil column uphill (Figure 3.11). This process is only functioning during rainfall events, especially ones that saturate the soil and cause overland or subsurface lateral flow. These are the times, however, that the soil in the 4 zones is in similar 'overflow' mode. An important additional type of lateral inflow may occur during dry periods, when part of the horizontal groundwater flows may come within reach of the roots in the simulated zones. A simple representation of such flows makes use of a 'stock' of groundwater stored uphill, that depends on the 'number of plots uphill' as a scaling factor and the vertical drainage calculated (Figure 3.12).

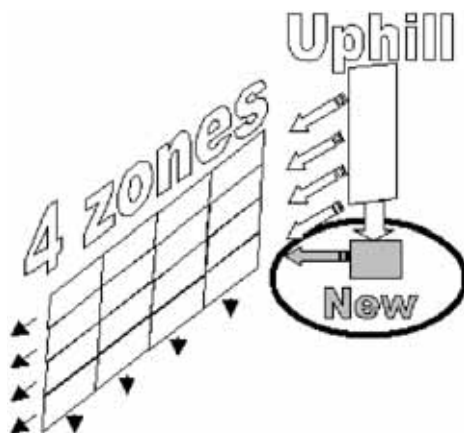


Figure 3.11. General lay out of soil column uphill in WaNuLCAS model.

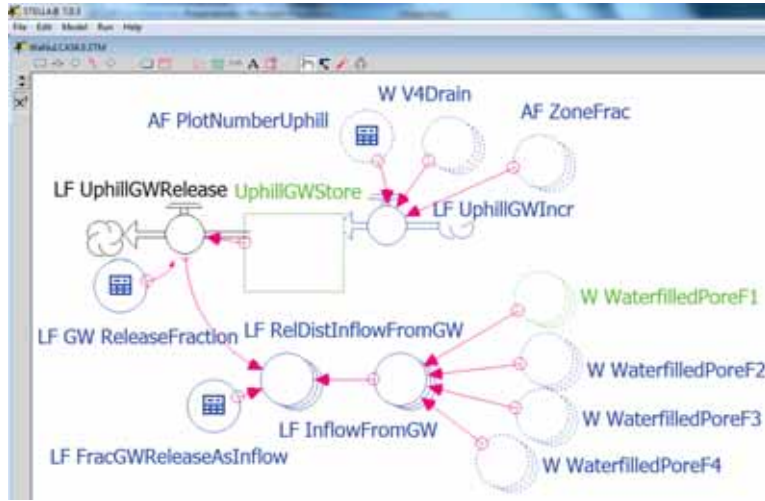


Figure 3.12. Show module of subsurface in-flows from uphill plot in WaNuLCAS.

### 3.3.7. Dynamics of macropore formation and decay

Formation and decay of macropores has consequences for the bulk density of the 'soil matrix', as the mass balance of soil solids has to be conserved. Compaction of the 'matrix' may increase the unsaturated hydraulic conductivity of the soil, while the macropores themselves greatly increase the saturated conductivity. If 'pedotransfer' functions are used, the change in bulk density (and possibly soil organic matter content) at constant texture can lead to predicted changes in water retention and the unsaturated hydraulic conductivity in a simple way, once the dynamics of macropores are predicted. Where macropores are dominated by cracking, a description of the swelling and shrinking properties is needed as function of soil water content. Where macropores are dominated by roots, earthworms and/or other soil macrofauna their population density and activity should be known, as well as the fraction of macropores temporarily blocked by roots and the rates at which macropores are back-filled by internal slaking of soils and/or bioperturbation.

In WaNuLCAS 4.0 the option is provided for a dynamic simulation of macropore structure. In the Wanulcas.xls spreadsheet, the user can define an initial saturated hydraulic conductivity value that differs (exceeds or is lower then) from the default value predicted by the pedotransfer value. The pedotransfer value reflects a surface infiltration rate in absence of soil biological activities. During the simulation the value will tend to return to this default value, at a rate determined by the  $S\_BDBDRefDecay$  parameter. The pedotransfer value is used as default, as it reflects measurements in small ring samples without much effect of soil structure. Depending on the 'foodforworms' provided by the structural and metabolic organic inputs (with conversions set by the parameters  $S\_WormsLikeLitStruc$ ,  $S\_WormsLikeSOMStruc$ ,  $S\_WormsLikeLitMetab$  and  $S\_WormsLikeSOMMetab$ , respectively), and the relative depth impact of the worms on the given location (the  $S\_RelWorm_{depth}$  parameters determine the relative impact for each soil layer and  $S\_RelWormSurf$  the impact on surface infiltration), earthworms can increase saturated conductivity above the default value, but this structure will gradually decay if not actively maintained. With root type 2 during the simulation, an amount of root decay allocated for



‘root channels’ by calculated root decay on a root biomass basis converted to root volume, and multiplied by an estimate of the fraction of roots that had formed new channels (as opposed to following existing channels, macropores or growing over aggregate surfaces) with conversions set by the parameters S\_T\_RootFormStrucFrac and S\_C\_RootFormStrucFrac for tree and crop root respectively.

With the current structures in place the model is sensitive to variations in saturated hydraulic conductivities (at least in certain parameter ranges, depending on rainfall regime and soil water storage parameters). It may be relatively easy now to make the saturated hydraulic conductivity a dynamic property, e.g. inheriting a system of old tree root channels from a preceding forest phase, with an exponential decay of such channels and a rate of new formation by (tree) root turnover and/or earthworm activity within the layers. Impacts of soil biota on macro-structure of the soil can now be explored.

## 3.4. Nutrient (nitrogen and phosphorus) balance

### 3.4.1. Nutrient inputs and outputs

WaNuLCAS release 1.1 only included a nitrogen balance. From release 1.2 onwards, an array ‘nutrients’ is used with nitrogen as first and phosphorus as second array element. The equations originally developed for nitrogen could be applied to the broader class nutrient, with a number of exceptions which will be noted in the text. In the model, interactions between N and P are only indirect, based on the interaction of both nutrients with plant dry matter production and/ or soil organic matter transformations.

Nutrient inputs to each cell can be based on leaching from higher layers (water flux multiplied with current concentration in soil solution, assuming no by-pass flow of water to occur). At the bottom of the soil profile nutrient losses by leaching become non-recoverable. For the top layer, inputs can consist of mineral fertilizer at specified times and rates, and from the mineralization of organic matter (on the basis of a process description similar to the Century model; Parton *et al.*, 1994). Total organic inputs are allocated to the various zones on the basis of user-specified weighing functions.

### 3.4.2. Nutrient inputs

Nutrient (nitrogen or phosphorus) inputs consist of initial amounts in mineral and organic N pools in the soil, initial stocks in the tree and crop seeds, and inputs during the simulation from fertilizer, organic inputs from outside and internal recycling of crop residues and tree litterfall and pruning.

For fertilizer inputs setting the parameters Ca\_FertAppYear, Ca\_FertAppDOY, Ca\_FertAppRate[Nutrient] can specify the dates and amounts. It is also possible to have two types of organic input as part of management during simulation, Ca\_ExtOrgInp. This would need additional parameters to defined the lignin, polyphenol, N and P content.

Table 3.5. Nutrient (nitrogen and phosphorus) balance at patch level.

In	Out
Initial inorganic N or P stock in soil	Final inorganic N or P stock in soil
Initial organic N or P in SOM-pools	Final organic N or P in SOM-pools
N & P in lateral inflow	N & P in lateral outflow
Fertilizer N or P input	N or P leached from bottom of soil profile
N or P in external inputs or organic material	N or P in harvested crop yield
Atmospheric N fixation (only for N)	N or P in harvested tree components
N or P in crop planting material	Final N or P in crop biomass
Initial N or P in tree biomass	Final N or P in tree biomass

### 3.4.3. Leaching

Leaching of N (and P) is driven by percolation of water through the soil and the average concentration in soil solution. The latter is derived from the inorganic nutrient stock, the soil water content and the apparent adsorption constant.

An option is provided for flow of water through macropores (e.g. earthworm or old tree root channels), bypassing the soil solution contained in the soil matrix. A multiplier  $N_{\text{BypassMacro}}/[\text{Zone}]$  is used in the leaching equation, which can get different values for each zone and or layer, e.g. to study the effect of earthworm activity mainly in the top layer of zone 1. Default value for  $N_{\text{BypassMacro}}/[\text{Zone}]$  is 1, values less than 1 lead to bypass flow (retardation of nutrient leaching), values above 1 to preferential flow (e.g. possible with rainfall directly after fertilization).

### 3.4.4. Nutrient (N or P) uptake

The nutrient uptake procedure includes 8 steps (the numbers refer to Figure 3.13):

**1) Target nutrient content.** The general flow of events starts with the current biomass (dry weight). First of all a 'target N content' is calculated from a generalized equation relating N uptake and dry matter production under unconstrained uptake conditions (De Willigen and Van Noordwijk, 1987; Van Noordwijk and Van der Geijn, 1996). The default equation used assumes a 5% and 0.5% (or  $Cq\_NconcYoung[\text{Nutrient}]$ ) N and P target in the young plant, up to a biomass of  $0.2 \text{ kg m}^{-2}$  ( $= 2 \text{ Mg ha}^{-1}$ ) (or  $Cq\_ClosedCanopy$ ) which may coincide with the closing of the crop canopy, and a subsequent dilution of N in the plant, resulting in additional N uptake at a concentration of 1% and 0.1% ( $Cq\_NConcOld[\text{nutrient}]$ ). The parameters in this equation can be modified for specific crops. Similarly, for the tree a nutrient target is derived by multiplying the biomass in leaves, twigs, wood and root fractions with a target N or P concentration ( $T\_NLFconc[\text{nutrient}]$ ,  $T\_NTwigConc[\text{nutrient}]$ ,  $T\_NWoodConc[\text{nutrient}]$ ,  $T\_NRtConc[\text{nutrient}]$ , respectively).

**2 & 3) Nutrient deficit.** The target N content is then contrasted with the current nutrient content, to derive the 'Nutrient deficit'. The N deficit can be met either by atmospheric N fixation, governed by a fraction of the deficit on a given day (3a).

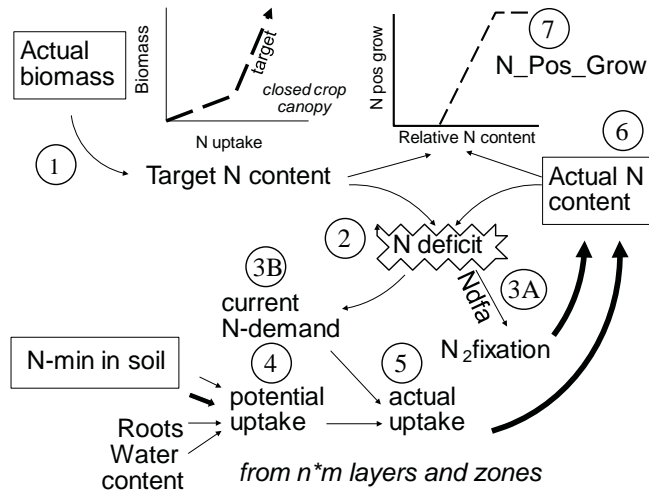


Figure 3.13. Major steps (explained in the text) in the daily cycle of calculating N uptake; a similar scheme applies to P uptake (without  $N_2$  fixation, but with additional options for ‘rhizosphere effects’).

$$CN\_Demand = CN\_Deficit * (1 - 0.5 * Cq\_Stage)^2 \quad [21]$$

The fraction is a user-defined value NDFA (if N supply from the soil is limiting the final percentage of N derived from fixation may be higher than the NDFA parameter chosen - some calibration may be needed to get realistic settings). The N-deficit not met by N fixation as well as the P-deficit lead to Nutrient demand (3b) for uptake from the soil. To avoid too drastic recoveries of uptake where nutrient supply increases after a ‘hunger’ period, not all of the nutrient deficit can be met within one day.

The fraction of the N deficit covered by the demand decreases with the physiological age of the crop; at flowering ( $Cq\_stage = 1$ ) only 25% of a deficit can be made up within one day and at full maturity ( $Cq\_stage = 2$ ) the uptake response has stopped. The parameters 0.5 and 2 used here have no solid empirical basis, but there is sufficient evidence to suggest that the responsiveness of uptake to past deficits does decrease with plant development.

**4) Potential uptake.** Potential nutrient uptake  $U_{ijk}$  from each cell  $ij$  by each component  $k$  is calculated from a general equation for zero-sink uptake (De Willigen and Van Noordwijk, 1994) on the basis of the total root length in that cell, and allocated to each component proportional to its effective root length:

$$U_{ijk} = \frac{Lrv_{ijk} \pi D_0 (a_1 \Theta_{ij} + a_0) \Theta_{ij} H_{ij} N_{stock,ij}}{\sum_k Lrv_{ijk} (K_a + \Theta_{ij}) \left[ -\frac{3}{8} + \frac{1}{2} \ln \frac{1}{R_0 \sqrt{\pi \sum_k Lrv_{ijk}}} \right]} \quad [22]$$

where  $Lrv$  is root length density ( $cm\ cm^{-3}$ ),  $D_0$  is the diffusion constant for the nutrient in water,  $\Theta$  is the volumetric soil water content,  $a_1$  and  $a_0$  are parameters relating effective diffusion

constant to  $\theta$ ,  $H$  is the depth of the soil layer,  $N_{stock}$  is the current amount of mineral N per volume of soil,  $K_a$  is the apparent adsorption constant and  $R_0$  is the root radius.

For P the same equation applies, but the apparent adsorption constant (the ratio of the desorbable pool and P concentration in soil solution) is not constant but depends on the concentration; parameters for a range of soils are included in the parameter spreadsheet,

**5) Actual uptake.** Actual uptake  $S_{ijk}$  is derived after summing all potential uptake rates for component  $k$  for all cells  $ij$  in which it has roots. Total uptake will not exceed plant demand. The effects of crop N and P content on dry matter production are effectuated via  $N\_pos\_grow[nutrient]$ .

$$S_{ijk} = U_{ijk} \frac{\min\left(demand_k, \sum_i \sum_j U_{ijk}\right)}{\sum_i \sum_j U_{ijk}} \quad [23]$$

**6 & 7) N\_Pos\_Gro[Nutrient].** Actual uptake and  $N_2$  fixation are both added to the actual N content (6) to complete the process for this timestep. Actual N content of the plant has a feedback on plant growth via N-PosGrow (7). The N-Pos-Grow parameter varies between 0 and 1. The actual N content can stay 20% behind on the N target before negative effects on dry matter production will occur (the N target thus includes 25% 'luxury consumption'); dry matter production will stop when the N content is only 40% of the N target; between 40 and 80% of the N target a linear function is assumed. The same function is used for tree and crop N-Pos-Grow.

### 3.4.5. Effective adsorption constants for ammonium and nitrate

Two forms of mineral N occur in most soils, ammonium and nitrate, which differ in effective adsorption to the soil and hence in leaching rate and movement to roots. Microbial transformation of ammonium to nitrate ('nitrification') depends on pH, and relatively slow nitrification may reduce N leaching from acid soils. Plant species differ in their relative preference for ammonium relative to nitrate in uptake, with only specialized plants able to survive on a pure ammonium supply; in the current model version such effects are ignored and it is assumed that the 'zero sink' solution for nitrate plus ammonium adequately describes the potential N uptake rate for both crop and tree. In the WaNuLCAS model a single pool of mineral N is simulated, but it can cover both forms if a weighted average adsorption constant is used. The potential uptake is inversely proportional to  $(K_a + W_{theta})$ , while the leaching rate is inversely proportional to  $(K_a + 1)$ . Both potential uptake and leaching are directly proportional to the  $N_{stock}$ , so the sum over nitrate and ammonium forms of mineral N can be obtained by adding  $N\_FracNO_3$  times the term with  $K_a$  for nitrate plus  $(1 - N\_FracNO_3)$  times the  $K_a$  for ammonium, where  $N\_FracNO_3$  is the fraction of mineral N in nitrate form.

An 'effective' apparent adsorption constant  $K_a$  for a nitrate + ammonium mixture can be calculated as:

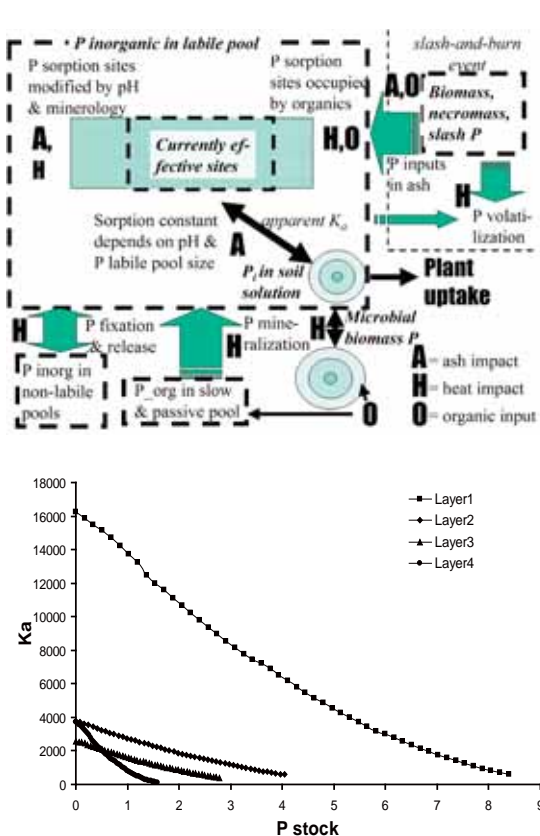
$$N\_Kaeff = -X + \frac{(N\_KaN O_3 + X)(N\_KaN H_4 + X)}{N\_KaN O_3 + N\_FracNO_3(N\_KaN H_4 - N\_KaN O_3) + X} \quad [24]$$

where X equals 1 for the leaching equation and WTheta for the uptake equation.

In the current version of the model  $N_{K_aNO_3}$  and  $N_{K_aNH_4}$  are user-defined inputs; in future they may be calculated from clay content and soil pH. The parameter  $N_{FracNO_3}$  is also treated as a user-defined constant for each soil layer; in future it may be linked to a further description of nitrification and be affected by the N form in incoming leachates in each layer and selective plant uptake.

### 3.4.6. P sorption

In the model the sorbed + soil solution P is treated as a single pool (Figure 3.14A), but at any time the concentration in soil solution can be calculated on the basis of the current apparent absorption constant  $K_a$ ; this way effects on  $K_a$  can be implemented separate from effects on total labile pool size.



A

B

Figure 3.14. A. Conceptual scheme of P pools in the soil as represented in the WaNuLCAS model and potential impacts of ash (A), heat (H) or addition of organics (O); B. Example of relations between apparent P sorption and total amount of mobile P in a soil, using data from the database of P sorption isotherms for acid upland soils in Indonesia (names refer to the location, in the absence of more functional pedotransfer functions for these properties).

For P the apparent sorption constant  $K_a$  is a function of the amount of mobile P in the soil. In the Wanulcas.xls spreadsheet examples of P sorption isotherms are given for Indonesian upland soils (Figure 3.14B) and Dutch soil types. The spreadsheet also gives a tentative interpretation to soil test data, such as  $P_{Bray}$ , and translates them into total amounts of mobile P, depending

on the sorption characteristics of the soil. This part of the model, however, is still rather speculative. It is based on the assumption that during a soil extraction (e.g. P\_Bray2 or P\_water) the effect of the extractant on sorption affinity and the soil:solution ratio determine the amount of P extracted from the soil, while non-labile pools do not interact with the measurements. Following this assumption, the relation between a soil test value such as P\_Bray2 and the size of the labile pool does depend on the sorption characteristics of the soil.

### 3.4.7. N<sub>2</sub> fixation from the atmosphere

The option exists for both crops and trees to represent atmospheric N<sub>2</sub> fixation as way of meeting the plant N requirement. The resultant fraction of N derived from the atmosphere (C\_Ndfa or T\_Ndfa) can be obtained as model output and equals  $N_{fix}/(N_{fix} + N_{uptake})$ .

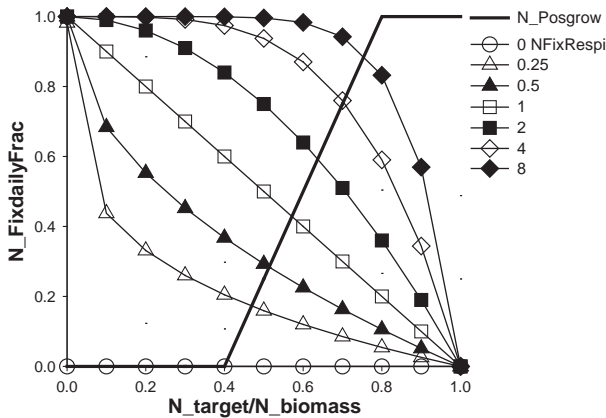


Figure 3.15. Relation between relative N content and daily N<sub>2</sub> fixation as part of plant N deficit, if the N\_fixVariable? parameter is set at 1.

N<sub>2</sub> fixation is calculated as a fraction of the current N deficit on any day. If the parameters C\_NfixVariable? or T\_NfixVariable? are set to 0 (= false), this fraction simply equals the C\_NfixDailyFrac or T\_NfixDailyFrac parameters set as model input and does not depend on N status of the plant, nor does N fixation have implications for the energy (C) balance of the plant. The part of the N deficit not covered by N<sub>2</sub> fixation drives the demand for uptake from the soil. If one wants to obtain a certain overall NDFA result, the NfixDailyFrac parameter has to be set at a lower (approximately half) value, depending on N supply from the soil, as parts of the deficit not met by uptake from soil on a given day will be included in the calculation for N<sub>2</sub> fixation on the next day (in the extreme case of no N uptake possibilities from the soil the overall NDFA will be 1 regardless of the NfixDailyFrac parameter setting, as long as this is > 0).

If the parameters C\_NfixVariable? or T\_NfixVariable? are set to 1 (= true), the fraction of the N deficit covered by N<sub>2</sub> fixation on any day does depend on the N status of the plant and can be constrained by the energy (C) balance of the plant via the 'growth reserves' pool (this may implicitly lead to effects of water stress on N<sub>2</sub> fixation). These parameter settings, however, are still in an experimental stage.

If the parameters  $C\_NfixVariable?$  or  $T\_NfixVariable?$  are set to 1,  $N_2$  fixation will use resources from the GroRes pools and can be constrained by the availability of these resources in the plant. A conversion factor ( $DWcost$  for  $Nfix$ ) is used to reflect the respiration costs associated with  $N_2$  fixation (roughly 0.01 kg DW per g N), and a maximum fraction of the GroRes pool to be used for  $N_2$  fixation ( $MaxDWUsefor\ Nfix$ ) is specified.

### 3.4.8. Special P mobilization mechanisms

Two further processes were added for P uptake:

- an 'immobile pool' was added to the model, reflecting the difference between total P and available P, and equations were added for a potential mobilizing effect of crop or tree roots on this pool; in the current version there is no (increased) reverse process when the roots disappear,
- roots may (temporarily) influence the adsorption constant in their local neighbourhood by modifying pH and/or excreting organic anions competing for P sorption sites; equations were added for such effects in proportion to the root length density of crop and tree roots; the benefits of a higher potential P uptake are shared over tree and crop on the basis of a 'root synlocation' parameter, reflecting whether the spatial distribution of crop roots in a soil compartment are such that they are mixed or occur in separate clusters. This determines the part of the benefits of rhizosphere modification that will accrue to the species directly influencing the adsorption constant.

The first process (which in principle could be used for nitrogen as well (certain forms of root-induced N mineralization might fall under such a description, although a further reconciliation with organic N pools would be needed), and is governed by:

- $N\_Nutmob[Nutrient]$  or relative rate of transfer from the 'immobile' pool of nutrients to the 'mobile' or sorbed pool, due to processes other than root activity ( $day^{-1}$ );
- $N\_CNutmob[Nutrient]$  and  $N\_TNutmob[Nutrient]$  Relative rate of transfer, per unit crop or tree root length density ( $cm\ cm^{-3}$ ), from the 'immobile' pool of nutrients to the 'mobile' or sorbed pool, due to root activity ( $day^{-1}\ cm^2$ )

The second process is governed by:

- $N\_CRhizEffKaP$  and  $N\_TRhizEffKaP$ , the proportional reduction of the apparent adsorption constant for P due to root activity of the crop, expressed as fraction of  $N\_KaPdef$  per unit crop root length density ( $day^{-1}\ cm^2$ ).
- $N\_RtSynloc$ , the root synlocation, or degree to which roots of the crop and tree are co-occurring within the various soil layers, affecting the way in which benefits of rhizosphere modification are shared.

### 3.4.9. $N_{15}$ labeling

The standard version of WaNuCAS no longer includes the sector that represents  $N_{15}$  labelling (earlier used by Edwin Rowe in the context of experiments in Lampung). On request, a new labelling sector was constructed that allows  $N_{15}$  in any of the 16 cells to be labelled and that tracks the N uptake of crop and tree, plus the relocation within the plant. The module does not yet include the vertical and lateral transfers of labelled N in the soil, nor the soil organic matter or litter layer pools.

### 3.4.10. Surface movement and incorporation of fertilizer

If there is heavy rainfall shortly after a fertilizer application, fertilizer can move along with overland flow of water, and can leave the plot in surface runoff. To simulate these processes (that can be quantitatively important under specific circumstances), WaNuLCAS now includes the process of dissolution of fertilizer grains and the lateral flow of the remaining fertilizer grains. Dissolved fertilizer will wash into the topsoil with rainfall, and/or can be mixed into the topsoil with a soil tillage operation (similar to the litter -> SOM transfer). Runoff loss from the plot occurs out of zone 1 (and may take two days with surface runoff if fertilizer is used in zone 2 but not in zone 1).

### 3.4.11. Green House Gas (GHG)

In a recent addition to the model, estimates of nitrogen oxide ( $N_2$ ,  $N_2O$ ,  $NO$ ) emissions are derived, on the basis of mineralization (the 'hole in the pipe' conceptual model; Verchot *et al.*, 2004) and denitrification. The form in which the gases emerge from the soil profile depends on the water-filled pore space.

Methane ( $CH_4$ ) absorption and emissions are closely linked to the available pore space, as the entry of methane from the air into the soil profile by diffusion tends to be the limiting step under dry conditions and wet conditions can lead to net emission from the soil.

The basic for predicting GHG emissions or absorption in WaNuLCAS model is:

1. the daily value of the water-filled pore space, that depends on the soil structure (as influenced by the soil biological activity if we switch the soil structure dynamics to 'on'), rainfall and water use by the vegetation,
2. for  $N_2O$  emissions, the dynamics of net nitrogen mineralization as it depends on organic inputs in interaction with mineral fertilizer.

#### Details for nitrogen oxides

Nitrogen oxide ( $NO_x$ ) emissions are estimated on the basis of the net N mineralization according to Verchot *et al.* (1999), on the basis of research on deep oxisols in Brasil. The partitioning over nitrous and nitric oxide depends on water-filled pore space. To make it a complete estimate of all gaseous N losses the  $N_2$  emissions are derived as multiplier on the nitrogen oxide emissions, again depending on water-filled pore space.

Verchot *et al.* (1998) derived:

$$NO_x \text{ flux (ng cm}^{-2} \text{ hr}^{-1}) = 0.954051 * \text{NetMineralization} - 0.093083 \quad [25]$$

with NetMineralization from disturbed samples of the topsoil (10 cm) in  $\text{mg kg}^{-1} \text{ day}^{-1}$

The intercept in the equation creates negative estimates for net mineralization rates less than  $0.098 \text{ mg kg}^{-1} \text{ day}^{-1}$ , or  $0.0098 \text{ g m}^{-2} \text{ day}^{-1}$  ( $35.8 \text{ kg ha}^{-1} \text{ year}^{-1}$ ). There were no data in this range in the original data set, and no negative flux estimates, so we can assign a zero value in this range,



or look for an alternative model, without intercept. Refitting the data, a power equation was derived that avoids the intercept and may be safer for use at low mineralization rates:

$$\text{NO}_x \text{ flux (ng cm}^{-2} \text{ hr}^{-1}) = 0.7212 * \text{NetMineralization}^{1.1699}$$

( $R^2 = 0.636$  versus  $R^2 = 0.751$  for the linear equation) [26]

In WaNuLCAS we have:

$$\text{NetMineralization} = \text{Mn2\_SomMin1Exch[Zone,N]} / (\text{AF\_DepthAct1[Zone]} * \text{W\_BDLayer[1]})$$
 [27]

but this is actual; the disturbed samples during incubation may be expected to be 1.5 times the actual.

From Verchot *et al.* (1999):

$$\begin{aligned} \text{N}_2\text{O fraction} &= (10^{(0.030001 * 100 * \text{W\_WaterfilledPoreF1[Zone]} - 1.446925)} / \\ & (1 + (10^{(0.030001 * 100 * \text{W\_WaterfilledPoreF1[Zone]} - 1.446925)}))) \\ \text{NO fraction} &= 1 - \text{N}_2\text{O fraction} \end{aligned}$$
 [28]

At higher water-filled pore fraction a substantial part of the gaseous emissions will occur as  $\text{N}_2$ , not measured in the GHG data set. As a first estimate, we can assume that at 100% water-filled pore space ( $\text{N}_2\text{O} + \text{NO}$ ) form 5% of total emissions, while at 50% water-filled pore space they are 95%. On this basis an  $\text{N}_2$  part is added.

The Verchot equation only uses the net mineralization of the topsoil, but was derived from whole-profile chamber measurements of emissions regressed on top 10 cm net mineralization measurements. It thus implies litter mineralization and deeper soil N mineralization and emission processes for ( $\text{N}_2\text{O} + \text{NO}$ ). The deeper layers may, however, contribute substantively to the overall  $\text{N}_2$  flux. As a first approximation we assume that the total  $\text{N}_2$  production from the layers below the topsoil has the same relationship with net mineralization as specified above, but that all comes out as  $\text{N}_2$ .

On this basis, a total gaseous N losses estimate is added to the N balance, while data for predicted  $\text{N}_2\text{O}$  and NO emissions are available for each of the zones in the model.

### Details for methane

A midrange estimate for the methane oxidation rate in aerated upland soils is  $4 \text{ kg ha}^{-1} \text{ y}^{-1}$  (equivalent to  $0.011 \text{ kg ha}^{-1} \text{ day}^{-1}$  or  $0.0011 \text{ g m}^{-2} \text{ day}^{-1}$ ), while emissions under wet conditions can reach a similar level (Verchot *et al.*, 2004). For the model we need one additional parameter that defines the shape of the relationship between water-filled pore space and net emission. Figure 3.16 provides examples for a range of values of the Km parameter.

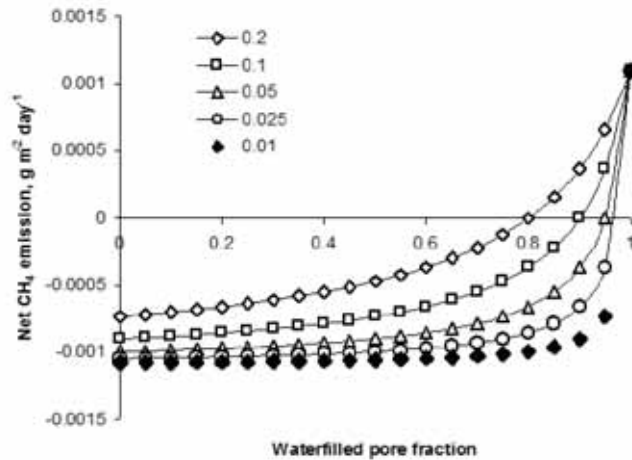


Figure 3.16. Methane flux (negative values indicate consumption, positive ones emission) as a function of the water-filled pore space, for a range of values of the GHG\_CH4\_Km parameter (a dimension parameter relating to the difference in water-filled pore space (by decrease from fully saturated soil) that causes a 50% change in net emission, within the range defined by highest and lowest flux.

### An example

For a simulation on a degraded soil with cassava production and a local tree, we find the following response of gaseous N losses to modifications of the measured rainfall (Figure 3.17):

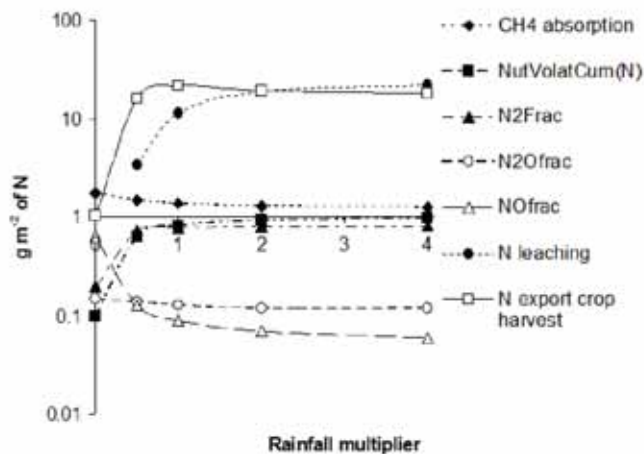


Figure 3.17. Effect of total rainfall, as simulated by using multiplier on daily rainfall amounts, on the gaseous N emissions from a soil (specified over NO and N<sub>2</sub>O), leaching and N export from the plot in crop harvests over a 5 year period.