WaNuLCAS 2.0

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

INTERNATIONAL CENTRE FOR RESEARCH IN AGROFORESTRY

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Copies of the software available freely from the web:
http://www.icsea.or.id/wanulcas/

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Chapter 1
Introduction and Objectives

This background document is written for two groups of readers:

1. Agroforestry researchers who are not very familiar with modeling 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. Modelers 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 modeling 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

Chapter 5: describes current ideas about further development of the model.

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 modeling framework is desirable in which they are endpoints of a continuum.

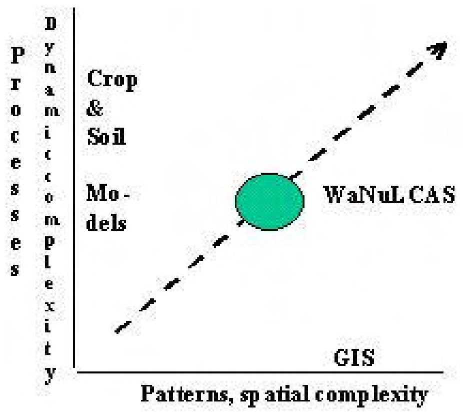


Figure 1.1 Schematic classification of the way crop growth models deal with spatial and temporal complexity; agroforestry models should explore the diagonal, rather than try to introduce spatial patterns in complex process based models

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

1.

$Y_c =$ 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-levelunderstanding		Litter quality, mineralization rates	Functional SOM fractions (Ludox)	Canopy shape, light profiles	Root architecture (fractal branching analysis)	
3. Synthesis model		W A N U L C A S				

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

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

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

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

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

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

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

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

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.

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

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

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

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

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

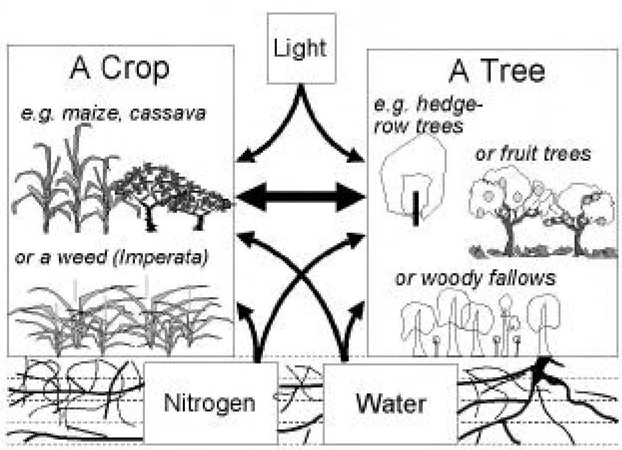


Figure 1.2 Components of the WaNuLCAS model

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

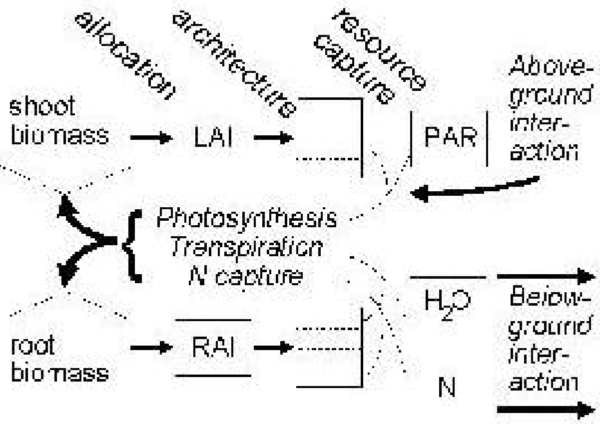


Figure 1.3 Resource capture framework for modeling plant growth, based on shoot and root biomass, allocation to leaf and root area index (LAI and RAI, respectively) and its spatial distribution (based on 'architecture') and capture of light, water and nutrients; aboveground plant-plant interactions modify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

1.4 Objectives of the WaNuLCAS model

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

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

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

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

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

http://www.nbu.ac.uk/hypar for the HYPAR model

http://www.nmw.ac.uk/ite/edin/agro/ for results of the DFID-sponsored Agroforestry Modeling Project

http://meranti.ierm.ed.ac.uk/ame for AME

http://www.icsea.or.id/wanulcas/ for WaNulCAS

http://www.icsea.or.id/models/cdfu.htm for 'crop down, fallow up' a model of crop-fallow rotations

Chapter 2
Overview of the model

Before we give a detailed description of model assumptions and formulation in chapter 3, we'll give an overview of the model here (Fig. 1.2).

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.

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.

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:

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

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 (e.g. 5% N in dry matter up to a closed crop canopy is reached at an aboveground biomass of about 2 Mg ha^{-1}, 1%N in new dry matter after that point; target N:P ratio = 10), a 'luxury uptake' (stating that growth will not be reduced until N content falls below 80% of demand), 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:

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

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

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 a representing an established tree system with equilibrium of root growth and root decay or can follow dynamic rules roots similar to those for crop.

A three-pool model, following the terminology and concepts of the Century model represents decomposition of **Soil Organic Matter**.

Light capture. 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 (Fig. 2.1A) and output can be obtained in the form of graphs and tables (Fig. 2.1B),
2. On the middle layer (Fig. 2.2), 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 5.

In Stella multiple representations of similar structures can be obtained by using arrays (indexed variables). In WaNuLCAS we use arrays for the ‘zones’, but not for the different soil layers, as this would imply a 1-time step delay in each transfer between layers in the profile in the process of leaching. For a daily time step this may not be acceptable. In future, we may use arrays for nutrients other than N, 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 3.1.3).

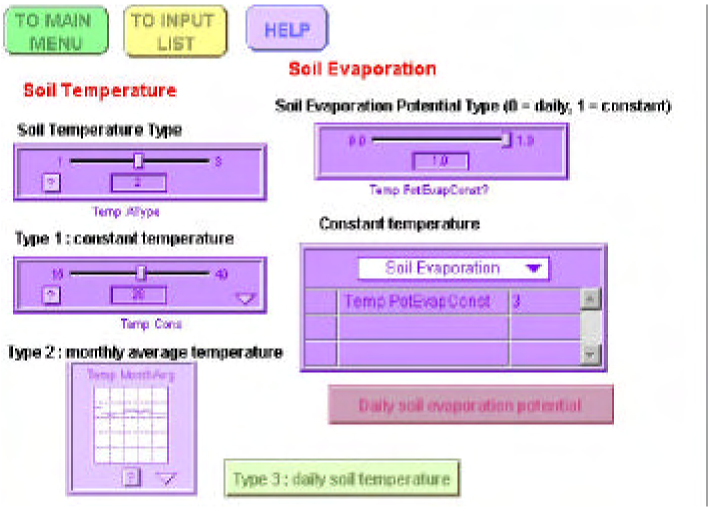


Figure 2.1A Upper level view on the WaNuLCAS model options for setting input values numerically or in graph (table) form; the buttons 'to main menu' and 'to input list' allow one to navigate through the input section

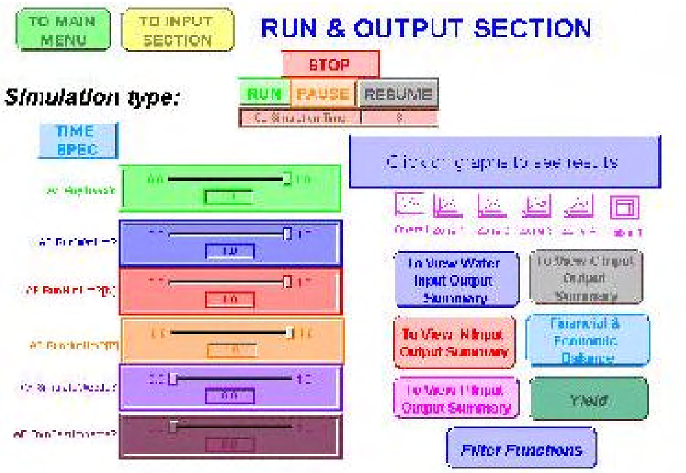


Figure 2.1B Upper level view on the WaNuLCAS model with example of output graphs and tables

Figure 2.2A A Middle level overview of the WaNuLCAS model in version 1.2

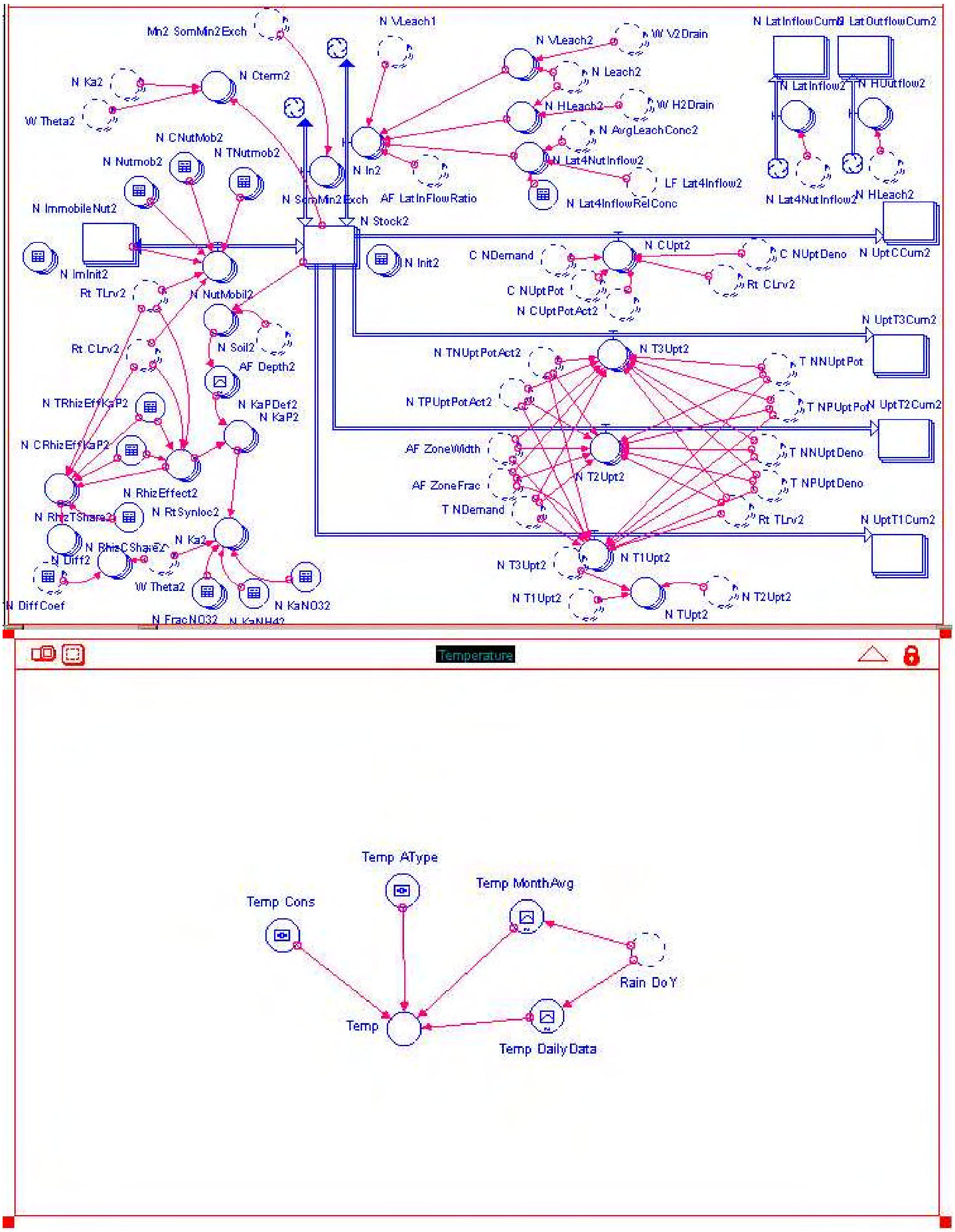
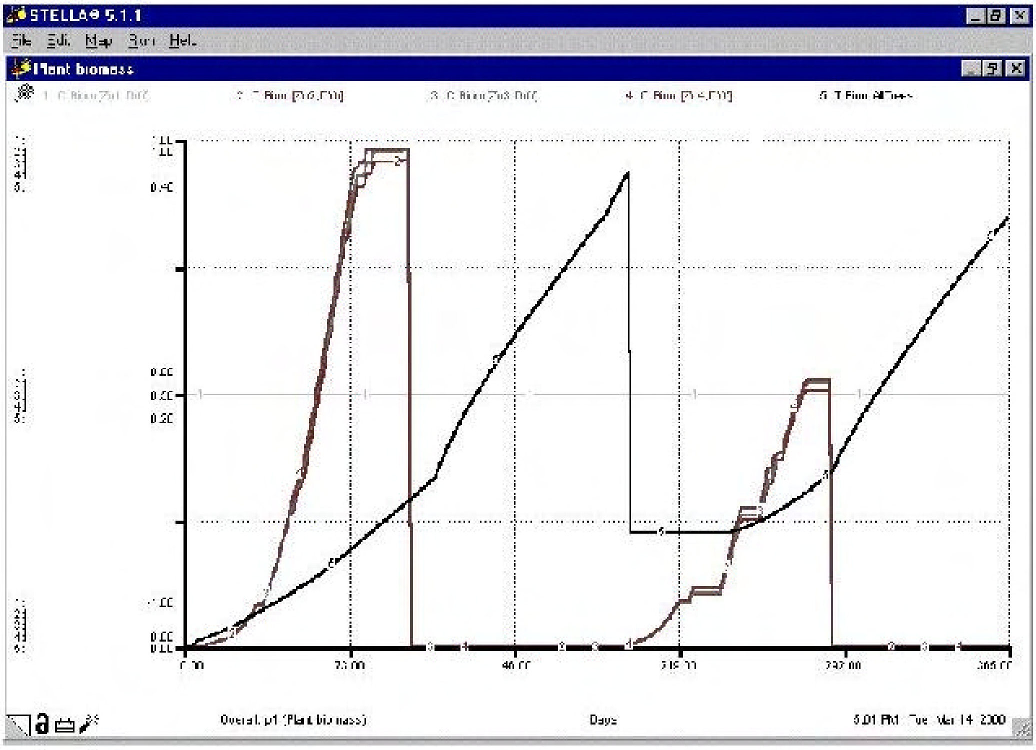


Figure 2.2B Middle level view on the WaNuLCAS model with examples of 2 sectors



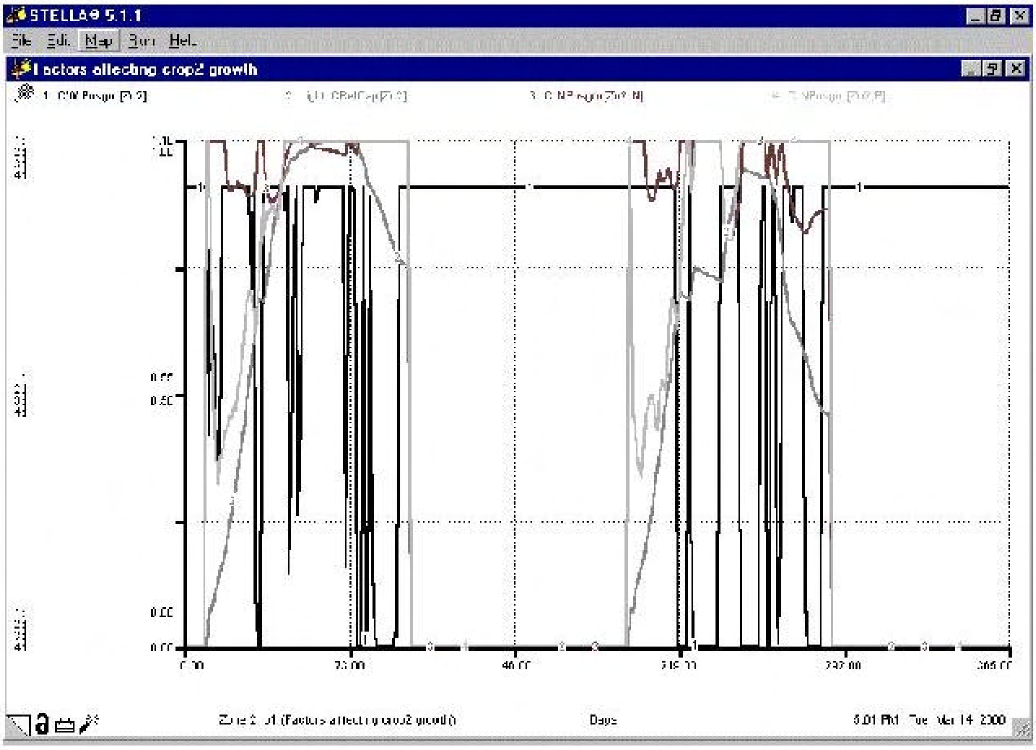


Figure 2.3 Example of output graphs

Chapter 3
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

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. Normally the intensity of interactions will decrease from zone 2 to 4.

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 4-1	Gradient	Heterogeneous (-runoff + run-on)	Continuous (soil redis- tribution can be simulated)
Taungya transition into tree crops	Linear	Zone 1 + 4 Zone 1-4	Homogeneous	Homogeneous, except for canopy interception	Continuous
Agroforestation of *Imperata* grasslands	Linear, start with *Imperata* 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

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^2) 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 i] 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:

$$AF\_ZoneFrac[Zn1] = \frac{AF\_Zone[Zn1]}{AF\_ZoneTot} \qquad \textbf{[4]}$$

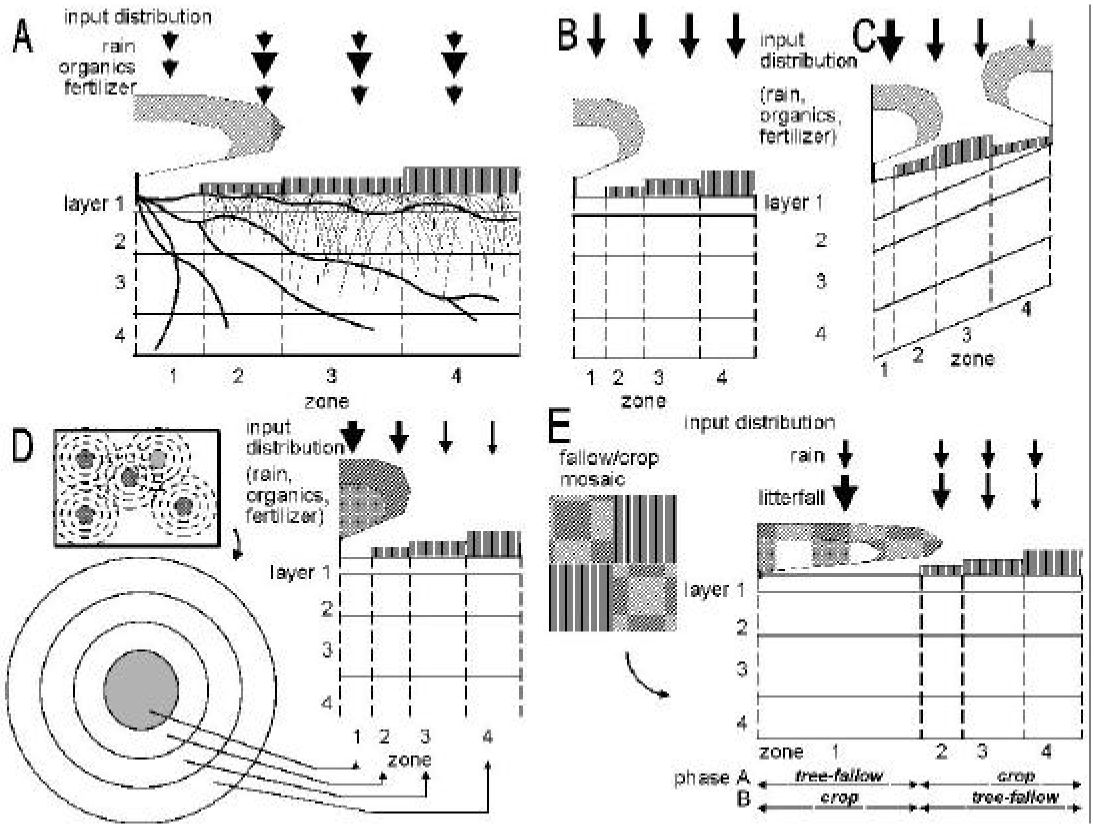


Figure 3.1 General lay out of zones and layers in the WaNuLCAS model (A) and applications to four types of agroforestry system: B. Alley cropping, C. Contour hedgerows on slopes, with variable topsoil depth, D. Parkland systems, with a circular geometry around individual trees, E. Fallow-crop mosaics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

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 sixteen depths (thickness) of layers (four zones, four layers each) under the parameter name AF_Depth_i [Zn j]

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 surface runoff of rainfall in one zone and its infiltration in another. The model expects four input values 'Rain_Weight[Zn i]' and calculates effective weights from:

$$RainWeightAct[Zni] = \frac{RainWeight[Zn1]}{\sum_{1}^{4} AFZoneFrac[Zni] * RainWeight[Zni]} \quad \textbf{[5]}$$

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_PrunWeight, Cq_FertWeight, Cr_ResidWeight for allocating tree litterfall, tree prunings, N fertilizer and crop residues 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

Before a simulation, the user can specify a number of events that will take place at a given calendar date (Table 3.2), usually by specifying the Year and Day-of-Year (DOY) in which they will occur. Other 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 before parameters are modified. The starting day of the simulation can be specified at any time after DOY 1 of Year 1, while climatic data are entered by calendar date.

Table 3.2 Calendar of events during a WaNuLCAS simulation that can be specified by the model user

Time			Climate			Fert g/m^2		Tree (s = start, p = prune, h = harvest)			S&B	Plow	Crop type in zone			
Simul Time	Year	DOY	Rain mm	Temp ºC	Epot mm	N	P	1	2	3			1	2	3	4
	1	1	..	..	..											
	1	2	..	..	..											
	1	3	..	..	..											
		..	..	..	..											
1	1	65	..	..	..											
2	1	66	..	..	..	6	3									
	1	..	..	..	..								1	1	1	1
	1	..	..	..	..			s								
299	1	364	..	..	..	3										
300	1	365	..	..	..											
301	2	1	..	..	..			p								
302	2	2	..	..	..									2	3	2
303	2	3	..	..	..						*					
	2	..	..	..	..											
664	2	364	..	..	..											
665	2	365	..	..	..											
666	3	1	..	..	..	6		p								
667	3	2	..	..	..									4	1	4
		..	..	..	..											
1029	3	364	..	..	..											
1030	3	365	..	..	..											
1031	4	1	..	..	..											
1032	4	2	..	..	..	6		p				*				
1033	4	3	..	..	..									2	3	2
		..	..	..	..											
1397	4	364	..	..	..			h								
1398	4	365	..	..	..											

3.1.4 Crops, weeds and trees

The model user can schedule a sequence of crops (of different types) to be grown in 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_FertAppRate, Ca_FertAppYear, Ca FertAppDoY. The Cq_Weight parameter, however, is a constant and applied throughout the simulation (in the current version).

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 kg m^{-2} day^{-1}, Cq_GroMax and a graphic input of Cq_RelLUE[cr i] 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 3.6 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_PrunY and T_PrunDoY, 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 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.

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 zone and layer
Soil organic matter		parameters		water retention,		in WaNuLCAS.STM
Soil bulk density				matric flux potential		

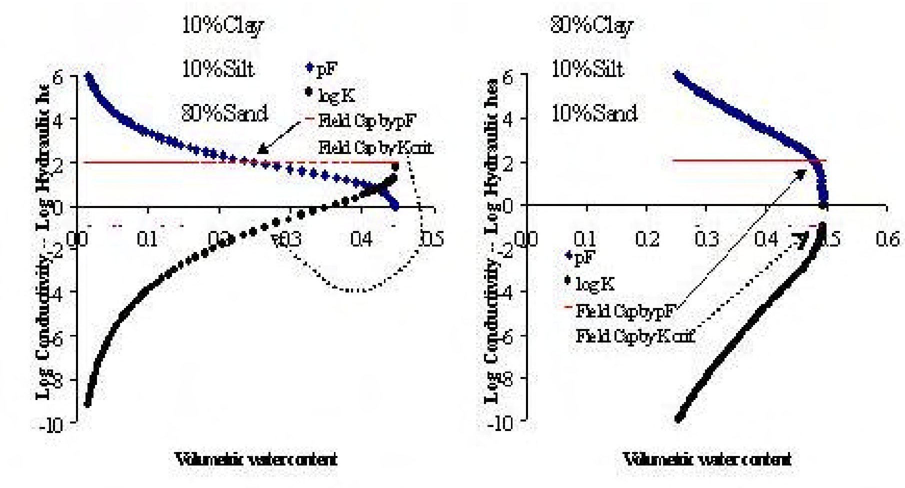


Figure 3.2 Relations between soil water content (X-axis), hydraulic head (expressed as pF or -log(head) -- positive Y axis) and unsaturated hydraulic conductivity (negative Y axis) for a dandy (left) and a clayey (right) soil, based on the pedotransfer function used in WaNuLCAS.XLS; two definitions of '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

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

A. [Temp_AType = 1] as a daily values (Temp_DailyDat) linked to a sheet 'Temperature' in the WaNuLCAS.XLS spreadsheet.
B. [Temp_AType = 2] a constant (Temp_Cons), or
C. [Temp_AType = 3] as a table with monthly average values (Temp_MonthAvg)

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 on the basis of climatological data for the site.

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

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

The three options are summarized in Table 3.3.

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, six parameters are needed: the probability of rainfall on a given day RainPday), the probability that rainfall is of type 'heavy' rather than 'light' (Rain_HeavyP), the boundary value of heavy and lighrt rains (Rain_BounHeaLi), 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).

Table 3.3 Three options for deriving daily rainfall values

Rain_AType	1 = Tabulated daily rainfall	2 = Random generator	3 = Variation around monthly total
Probability of rain on a given day	- not applicable	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	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 3, 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.

$$Rain = \max(0, Rain\_Today) * Normal\left\langle \frac{Rain\_MonthTot}{30 * Rain\_DayP}, \frac{Rain\_CoefVar * Rain\_MonthTot}{30 * Rain\_DayP}, Rainseed \right\rangle \quad \textbf{[6]}$$

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 3 may start at any 'day of year' before the simulation starts. They are read via Day of Year' variable Rain_DOY = Mod(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. In WaNuLCAS 2.0 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, 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:

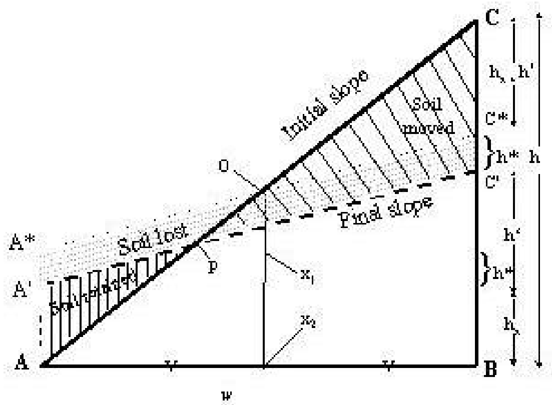
$$soil\_outflow = (1 - filterefficiency)(soil\_inflow + soil\_stirredup) \quad \textbf{[7]}$$

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:

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

Figure 3.3 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 A'A*C*C', or wh*; the triangle AA*O is equal to OCC*



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. 3.3 we can see that:

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

$$Soil\_lost/(bulkdens\ b) = ABC - AA'C'B = A'A^*C^*C' = h^*w \quad \textbf{[9]}$$

$$\begin{aligned} Soil\ retained/(bulkdens\ b) &= (Soil\_moved - Soil\_lost)/(bulkdens\ b) = AA'P = (h_x/(h_x+h^*))AA^*O = \\ &= (h_x/(h_x+h^*))(AA^*X_1X_2 + A^*OX_1 - AOX_2) = (h_x/(h_x+h^*))((h-h')w/4 + h'w/8 - hw/8) = \\ &= (h_x/(h_x+h^*))w(h-h')/8 = wh_x/4 \end{aligned} \quad \textbf{[10]}$$

Hence,

$$Terrace\_height = h_x = 4(Soil\_moved - Soil\_lost)/(bulkdens\ b\ w) \quad \textbf{[11]}$$

If Soil_lost = Soil_moved and thus Soil_retained = 0, this leads to $h_x = 0$.

Combining [*x4], [*x3], [*x2] and [*x1] we obtain:

$$Final\_slope = Initial\_slope - (8Soil\_moved - 6Soil\_lost)/(Bulkdens\ b\ w^2) \quad \textbf{[12]}$$

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. (In WaNuLCAS 2.0 this has not yet been incorporated as an option).

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 3.4):

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. It’s main effect will be on bypass flow of water and retardation of nutrient leaching.

The WaNuLCAS model currently incorporates point 1...7 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.

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).

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 3.3.6.

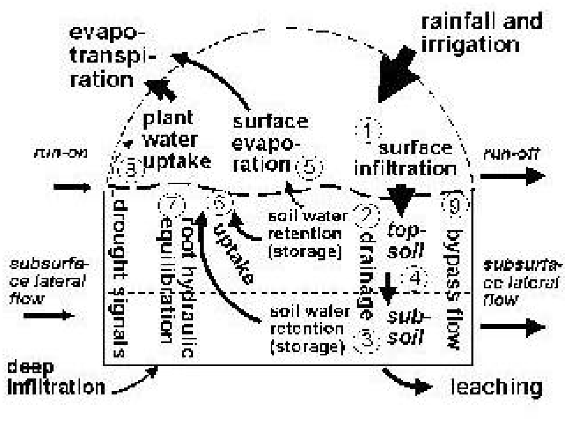


Figure 3.4 Elements of the water balance included in the WaNuLCAS model: 1. surface infiltration of rainfall, 2-4. Redistribution of water and solutes over the profile, recharging soil water content (2) and draining (leaching) excess water from the bottom of the profile, 5. surface evaporation, 6. water 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.

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

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 (Fig. 3.5):

1. Estimate potential transpirational demand Ep 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 h_p from average (weighted by root length) soil water potential h_s minus pressure differences to overcome transport and uptake resistance; uptake resistance is estimated to meet the full transpirational demand E_p, transport resistance is taken as proportional to soil water potential,
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 - see De Willigen *et al.* in prep.),
4. Use the reduced uptake demand f_p E_p to estimate the rhizosphere potential h_{rh} for all layers i from the plant potential h_p
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 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.

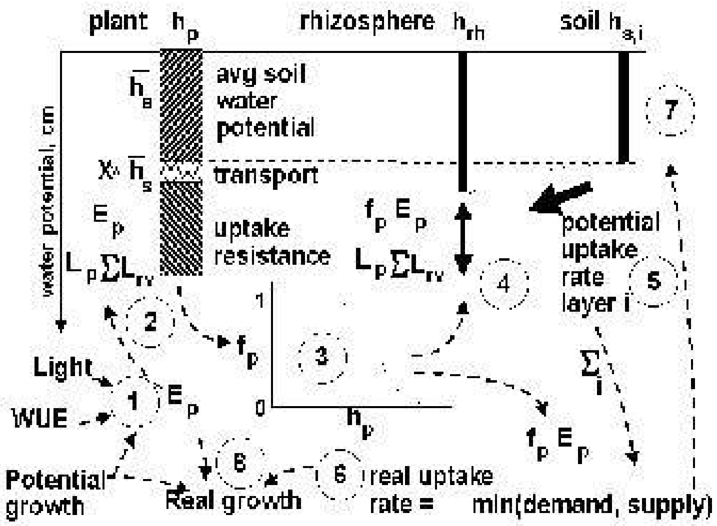


Figure 3.5 Steps (1...8) in daily cycle of calculations of water uptake; the interrupted arrows represent information flows

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.

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.

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:

$$F_i = \frac{\sum_{j=i}^{n} \frac{(y_i - y_2)}{r_i r_j}}{\sum_{j=1}^{n} r_j^{-1}} \qquad [13]$$

where ψ_i and ψ_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.

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 and Rowe, *in prep.*).

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

- 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,
- 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
- the amount of water flowing across any vertical or horizontal surface is the minimum of three quantities:
  1. the amount available for flow (as defined above),
  2. the amount that can cross the surface in a day (depending 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
  3. 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)
- 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),
- 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:

- W1 - Splitting the excess (incoming - recharge) water for each timestep into a vertical and a horizontal flow component,
- W2 - Accounting for incoming water from above (rainfall in layer 1, vertical drainage from the layer above for the other zones), as well as laterally,
- W3 - Defining incoming lateral flow to the simulated zones for all layers,
- N1 - 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,
- N2 - Defining the incoming nutrient concentrations for the incoming subsurface flow.

Ad 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:

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

$$Fluxv_i = \frac{Ksatv_{i4} * zonew_i}{Ksatv_{i4} * zonew_i + \sum_i Ksath_{ij} HydHeadHor_{ij}\left(\left(depth_i - depth_{i-1}\right)/2\right)} \quad \textbf{[15]}$$

with:

$$HydHeadHor_{i1} = \left(depth_{i,1} - depth_{i-1,1}\right)/\left(zonew_i + zonew_{I-1}\right) + origslope \quad \textbf{[16]}$$

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

Ad 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

Ad 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.

Ad 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).

Ad 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). The second 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 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 2.0 the option is provided for a dynamic simulation of macropore structure. The user can (in the Wanulcas.xls spreadsheet) define an initial saturatd hydraulic conductivity value that differs (exceeds or is lower then) the default value predicted by the pedotransfer value.During the simulation the value will tend to return to this default value (at a rate determined by the S_KStructDecay parameter). The pedotransfer value is used as default, as it reflects measurements in small ring samples without much effects of soil structure. Depending on the 'foodforworms' provided by the structural and metabolic organic inputs (with conversions set by the parameters S_WormsLikeStruct and S_WormsLikeMetab, 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 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 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 transfomations.

Nutrient inputs to each cell can be based on leaching from higher layers (water flux multiplied with current concentration in soil solution, assuming no bye-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.

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

3.4.2 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 litter fall and pruning.

For fertilizer inputs setting the parameters Ca_FertAppYear, Ca_FertAppDOY, Ca_FertAppRate[Nutrient] can specify the dates and amounts.

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_BypassMacro*i*[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_BypassMacro*i* [Zone] is 1, values less then 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 Fig. 3.6)

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[Nutrient]) N and P target in the young plant, up to a biomass of 0.2 kg m^{-2} (= 2 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[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[nutrient], T_NTwigConc[nutrient], T_NWoodConc[nutrient], T_NRtConc[nutrient], respectively.

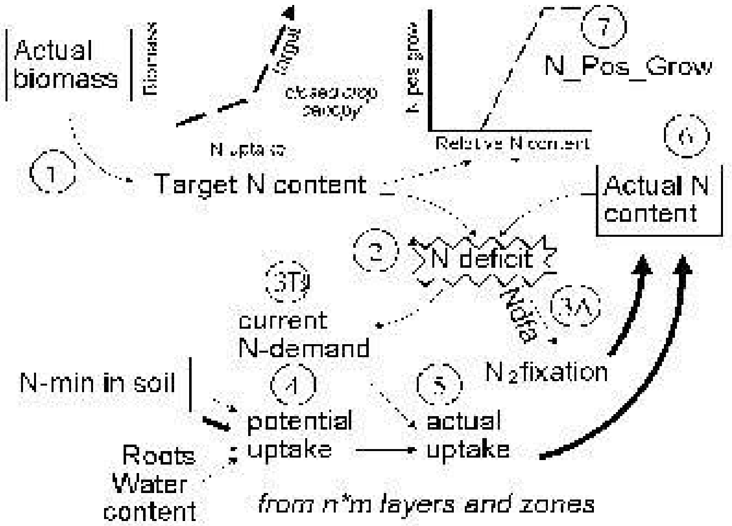


Figure 3.6 Major steps (explained in the text) in the daily cycle of calculating N uptake; a similar scheme applies to P uptake (without N_2 fixation, but with additional options for 'rhizosphere effects'

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).

$$CN\_Demand = CN\_Deficit * (1 - 0.5 * Cq\_Stage)^2 \qquad \textbf{[17]}$$

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 then 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:

$$U_{ijk} = \frac{Lrv_{ijk}\, pD_0 \left(a_1 \Theta_{ij} + a_0\right) \Theta_{ij} H_{ij} N_{stock,ij}}{\sum_k Lrv_{ijk} \left(K_a + \Theta_{ij}\right) \left[-\frac{3}{8} + \frac{1}{2} \ln \frac{1}{R_0 \sqrt{p \sum_k Lrv_{ijk}}} \right]} \qquad \textbf{[18]}$$

where L_{rv} is root length density (cm cm^{-3}), D_0 is the diffusion constant for the nutrient in water, θ is the volumetric soil water content, a_1 and a_0 are parameters relating effective diffusion constant to θ, 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].

$$S_{ijk} = U_{ijk} \frac{\min\left(demand_k , \sum_1 \sum_j U_{ijk} \right)}{\sum_i \sum_j U_{ijk}} \qquad \textbf{[19]}$$

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 + Wtheta), while the leaching rate is inversely proportional to (K_a + 1). Both potential uptake and leaching are dirctly proportional to the Nstock, so the sum over nitrate and ammonium forms of mineral N can be obtained by adding N_FracNO3 times the term with K_a for nitrate plus (1 - N_FracNO3) times the K_a for ammonium, where N_FracNO3 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:

$$N\_Kaeff = -X + \frac{(N\_KaNO_3 + X)(N\_KaNH_4 + X)}{N\_KaNO_3 + N\_FracNO_3(N\_KaNH_4 - N\_KaNO_3) + X} \qquad \textbf{[20]}$$

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

In the current version of the model N_KaNO3 and N_KaNH4 are user-defined inputs; in future they may be calculated form clay content and soil pH. The parameter N_FracNO3 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 (Fig. 3.7A), 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.

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 (Fig. 3.7B) 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.

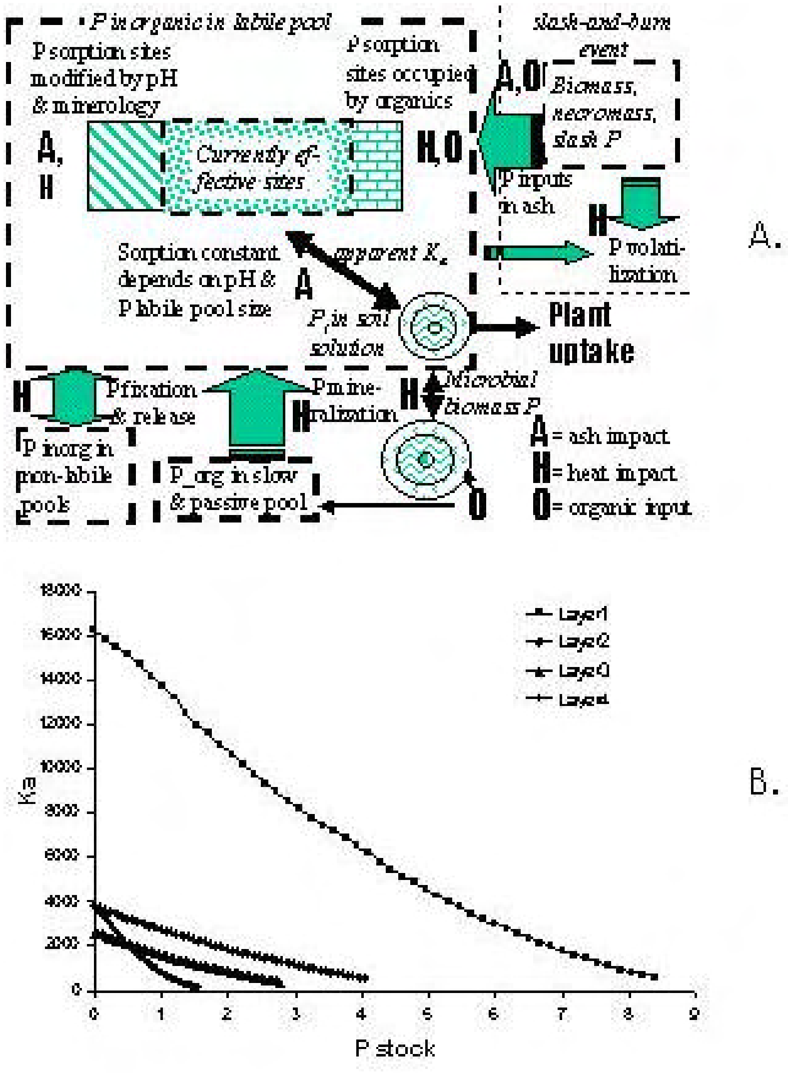


Figure 3.7 A. Conceptual scheme of P pools in the soil as represented in the WaNuLCAS model and potential impacts of ash (A), heat (H) or addition of organics (O); **B** Example of relations between apparent P sorption and total amount of mobile P in a soil, using data from the database of P sorption isotherms for acid upland soils in Indonesia (names refer to the location, in the absence of more functional pedotransfer functions for these properties...)

3.4.7 N_2 fixation from the atmosphere

The option exists for both crops and trees to represent atmospheric N_2 fixation as way of meeting the plant N requirement. The resultant fraction of N derived from the atmopsphere (C_Ndfa or T_Ndfa) can be obtained as model output and equals Nfix/(Nfix + N_uptake).

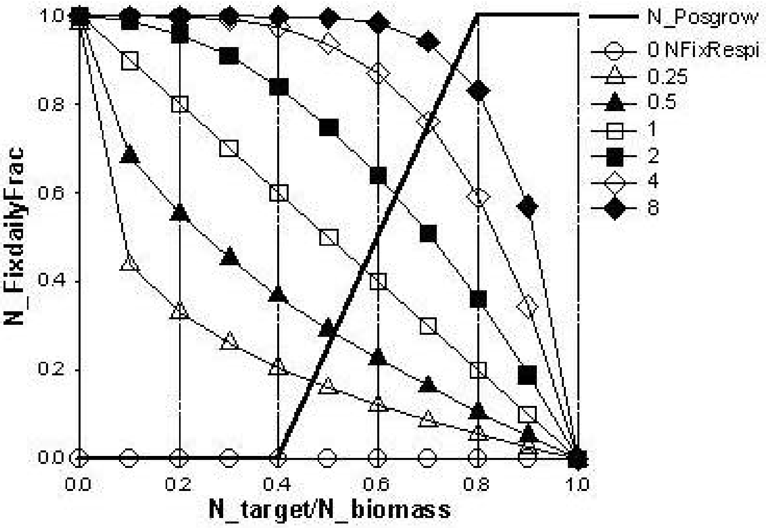


Figure 3.8 Relation between relative N content and daily N_2 fixation as part of plant N deficit, if the N_fixVariable? parameter is set at 1

N_2 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_2 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_2 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_2 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_2 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.

3.5 Root distribution

3.5.1 Crop root length density

Three options exist for deriving the maximum root length density in each cell:

Rt_ACType = 0 user input of maximum root length density for each layer *i* of zone *j*. Crop roots can grow and decay following a predetermined pattern, by multiplying a tabulated function [0,1] with this layer-specific maximum value. The maximum value may for example be based on the amount of roots at time of flowering, with a tabulated function describing root growth and decay as a function of crop stage reaching a value of 1 for Cq_Stage = 1 and declining for 1< Cq_Stage <2). Users can modify the form of the graph which (in version 1.1) applies to all crops. Information on the relative root presence during a crop growing season can be ontained from minirhizotron data and analysis of sequential images.

Rt_ACType = 1 crop root length density within each zone decreases exponentially with depth:

$$LrvC\ (i,j) = Lra\ (i) DecWDepthC \quad e^{\left(-DecWDepthC\ \ 0.5\left(Depth_{(i,j)}\right) + Depth_{j}\right)} \qquad \textbf{[21]}$$

This function has two parameters:

Rt_CLra(i) = total root length per unit area (cm cm^{-2}), which may depend on zone *i* ;

Rt_CDecDepth = parameter (m^{-1}) governing the decrease with depth of root length density (at a depth of 0.699/RtCDecDepth the root length density has half of its value at the soil surface). The RtCDecDepth parameter depends on the crop type, and may differ between zones *i*.

Table 3.6 Options for deriving crop root distribution; in WaNuLCAS 2.0

Rt_AC Type	Distribution of roots over soil layers	Dynamics of root growth and decay
0	User input value of Lrvmax	RelRoot... as function of crop stage
1	Exponential function (root diffusion into homogeneous soil);RtCDecDepth and maximum Lra(I) as inputs	As in 0
2	As in 1, but Rt_CLra(i) derived from root biomass; Rt_CDecDepth can be modified from the initial input values based on 'local response', modified by Rt_CdistRespFor Rt_CDistResp :0 => no response0-1 mild response1 => change in Rt_CDecDepth proportional to inverse of relative depth of uptake> 1 strong response of root distribution to uneven uptake success of the most limiting resource	Driven by total crop biomass, root weight ratio as a function of crop stage (Cr_RtAlloc), specific root length (Cr _RtSRL) and mean root longevity (Cr_RtHalfLife, in exponential decay); The degree of 'functional equilibrium' response in root/shoot allocation is determined by Cr_RtAllocResp: 0 => no response, => fairly late response to stress, => proportional increase of root allocation with stress, 1 => rapid response to stress

The function is evaluated for the half depth of each layer (average of total depth of current and previous layer). The Rt_CLra(i) values as a function of crop stage can be obtained by multiplying a maximum value with a crop-stage dependent ratio (as for Rt_ACType = 0).

Rt_ACType = 2 Uses the same exponential root distribution, but involves a 'functional equilibrium' response (Van Noordwijk and Van de Geijn, 1996), allowing the relative allocation of growth to roots to increase when water and/or nitrogen limit plant growth. A simple representation is included of 'local response' by which the vertical distribution of roots is influenced by the relative success of roots in taking up the most limiting resource in upper or lower layers of the profile. Both responses are regulated by a parameter (Cr_RtAllocResp and Rt_CDistResp, respectively) determining the degree of response. These parameter are, however, not easily measured independently and the user may have to explore a range of values. Functional as well as local response can be 'turned off' by setting the responsiveness parameters at 0.

For Rt_AcType = 2, the value of Rt_CLra(i) is derived from root biomass multiplied with C_SRL, the specific root length or root length per unit dry weight (m g^{-1}). Root biomass is derived from daily increments in plant biomass, multiplied with the root allocation fraction Cr_RtAllocAct. The latter is calculated from a base-line value Cr_RtAlloc, multiplied with a tabulated function of Cq_stage, and potentially modified to account for functional equilibrium and local response.Cr_RtAllocAct can be modified from Cr_RtAlloc by the minimum of the current water and nitrogen stress in the plant, modified by the parameter Cr_RtAllocResp, as indicated in Table 3.6.

Root decay is implemented by daily removing a fraction of –0.69/Cr_RtHalfLife, where the latter is measured in days and can e.g. be derived from sequential observations with minirhizotrons. In version 1.2 root turnover is **not** influenced by water or nitrogen stress, but such a feedback may be included in future versions.

For Rt_ACType 2 it is also possible to modify the Rt_CDecDepth parameter on the basis of current uptake distribution. The response is based on N uptake if C_NPosGro < CW_PosGro, and otherwise by water uptake. We first calculated the relative depth of uptake, by the weighted sum of depth of layer multiplied by uptake per unit root length. For relatively high uptake success in deep layers Rt_CDecDepth will decrease, for success of shallow roots it will increase. The degree of response is regulated by Rt_CDistResp, as indicated in Table 3.6. When high values of this responsiveness are chosen, the calculated change in root length of an individual layer could exceed the total change in root length from decay and new root growth. We prevent this, by capping off the change based on the proportional change in total root length.

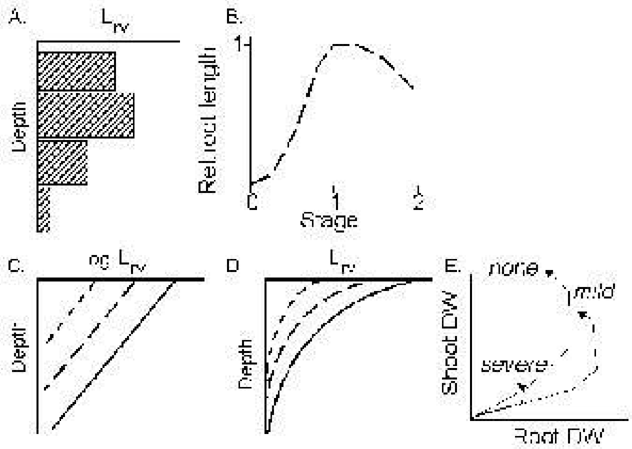


Figure 3.9 Distribution and development of crop root length density; A. Arbitrarily set values of maximum L_{rv} per depth interval (Rt_ACType = 0); B. multiplier to derive daily actual L_{rv} from maximum values per layer (Rt_ACType = 0 and 1); C Exponential decrease of L_{rv} with depth (on log scale), D. *idem* (linear scale) (Rt_ACType = 1); E. Relationship between shoot and root dry weight under no, mild and severe water or N stress (Rt_ACType = 2)

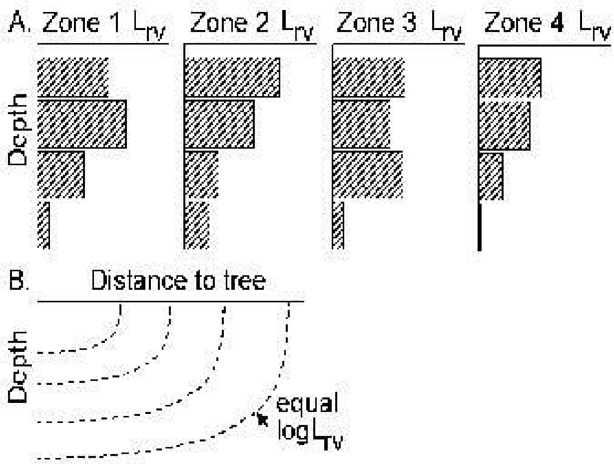


Figure 3.10 Root length density distribution for tree; A. (Rt_ATType = 0) user input of root length density for each cell *ij*; B. (Rt_ATType = 1) tree roots distributed according to an elliptical function

3.5.2 Tree root length density

Three options exist for obtaining its value for each cell (zone * depth):

Rt_ATType = 0 user input of root length density for each cell *ij*, and

Rt_ATType = 1 tree roots distributed according to an elliptical function:

$$Lrv(i,j) = LraX0 * RtTDecDepth * e^{-RtTDecDepth\sqrt{Depth_j^2 + (RtDistShapeHorDist_i)^2}} \quad [22]$$

This function has three parameters:

T_LraX0 = total root length per unit area (cm cm^{-2}) at a distance X of 0 from the tree stem

Rt_TDecDepth = parameter (m^{-1}) governing the decrease with depth of root length density (for X = 0, at a depth of 0.699/DecWDepth the root length density has half of its value at the soil surface),

Rt_TDistShape = dimensionless parameter governing the shape of the tree root system; values less than 1 indicate shallow-but-wide root systems, values of 1 give a circular symmetry, and values > 1 indicate deep-but-narrow root systems.

The function is evaluated for all four corners of each cell and a logarithmic average is determined.

where the Lrv_{00} .. Lrv_{11} refer to the four corners. (In fact the function is just evaluated once for an elliptically averaged position).

$$Lrv = e^{0.25(\ln(Lrv_{00}) + \ln(Lrv_{01}) + \ln(Lrv_{10}) + \ln(Lrv_{11}))} \quad [23]$$

For **Rt_ATType = 2** a functional equilibrium and local response are implemented, as for crop roots, regulated by T_RtAllocResp and Rt_TDistResp. The main difference is that there is no dependence on crop stage, and that the local response has a vertical (Rt_DecDepth) as well as a horizontal (Rt_DistShape) component. Both are regulated by the same Rt_TDistResp parameter.

3.5.3 Specific root length of tree root systems

For Rt_ATType = 2 we use (inverse) allometric equations to relate proximal root diameters to total root biomass, and drive the specific root length (length per unit biomass) as a function of this diameter (compare section 3.8.4 for aboveground allometric equations.

For a single branched root we can formulate for biomass and length, respectively:

$$T\_Root = Rt\_TWghtDiam1\ Rt\_TProxDiam^{Rt\_TWghtDiamSlope} \quad [24]$$

$$Rt\_TLength = Rt\_TLengDiam1\ Rt\_TProxDiam^{Rt\_TLengDiamSlope} \quad [25]$$

For a root system consisting of a number of roots of different diameters, we assume that the cumulative frequency distribution of proximal root diameters can be approximated by:

$$CumFreq = (TProxDiam / TProxDiam_{max})^{TProxGini} \quad [26]$$

where TProxGini is a parameter equivalent to a Gini coefficient as used in studies of income distribution, and hence (using D in stead of TProxDiam, a1 for Rt_TWghtDiam1, b1 for Rt_TWghtDiamSlope, a2 for Rt_TLengDiam1 and b2 for Rt_TLengDiamSlope):

$$Freq(D) = d\ Cumfreq / dD = D_{max}^{-TProxGini} D^{(TProxGini-1)} \quad [27]$$

We can derive the total dry weight T_Root as:

$$T\_Root = \int_0^{D_{max}} Freq\ W\ dD = a_1 n\ D_{max}^{-n} \int_0^{D_{max}} D^{b1+n-1} dD = a_1 n D_{max}^{b1} / (b_1 + n) \quad [28]$$

Similarly, for the sum of proximal root diameter squares, we obtain:

$$SumD_r^2 = nD_{max}^2 / (2 + n) \quad [29]$$

and the equivalent single proximal root diameter as the square root of $SumD_r^2$.

Equations (28) and (29) can be used to derive the maximum proximal root diameter D_{max}:

$$D_{max} = \left(W_t\left(b_1+n\right)/\left(a_1 n\right)\right)^{1/b1} = \left(Sum_r^2\left(2+n\right)/n\right)^{0.5} \quad \textbf{[30]}$$

Relations between Wt and SumDr2 can now be obtained as:

$$W_t = \left(\left(a_1 n\right)/\left(b_1+n\right)\right)\left\{SumD_r^2\left(2+n\right)/n\right\}^{b1/2} \quad \textbf{[31]}$$

and

$$SumD_r^2 = n/\left(2+n\right)\left\{W_t\left(b_1+n\right)/\left(a_1 n\right)\right\}^{2/b1} \quad \textbf{[32]}$$

Similarly, from (25) and (26) we obtain

$$L_t = \left(a_2 n\right)/\left(b_2+n\right)\left\{SumD_r^2\left(n+2\right)/n\right\}^{b2/2} \quad \textbf{[33]}$$

and $$L_t = \left(a_2 n\right)/\left(b_2+n\right)\left\{W_t\left(b_1+n\right)/\left(a_1 n\right)\right\}^{b2/b1} \quad \textbf{[34]}$$

Finally, the specific root length SRL is obtained as function of W_t

$$SRL\left(W_t\right) = L_t/W_t = \left(a_2 n\right)/\left(b_2+n\right)\left\{\left(b_1+n\right)/\left(a_1 n\right)\right\}^{b2/b1} W_t^{b2/b1-1} \quad \textbf{[35]}$$

Equation (35) is used in the model.

3.5.4 Root diameter and mycorrhiza

Tree and crop are likely to differ in root diameter. As root diameter has an effect on the potential uptake rate, an 'average' root diameter in each layer and zone is needed for the uptake functin and a way to estimate the equivalent effective root length of each component at such a diameter. A simple approach is used in WaNuLCAS, based on De Willigen and Van Noordwijk (1987) and Van Noordwijk and Brouwer (1997), comparing roots of different diameter on the basis of the product of root length and SQRT(root diameter); this method of averaging makes the uptake function least sensitive to diameter (see Van Noordwijk and Brouwer, 1997; Figure 3.11)

$$RtDiamAV_{ij} = \left[\frac{Rt\_CLrv_{ij}\sqrt{Rt\_CDiam} + Rt\_TLrv_{ij}\sqrt{Rt\_TDiam}}{Rt\_CLrv_{ij} + Rt\_TLrv}\right]^2 \quad \textbf{[36]}$$

Based on this rule for adding roots of different diameter on the basis of the square root of their diameter, we can also get a first approach to the effects of mycorrhizal hyphae. The total length of hyphae can be derived from the fraction of roots that is mycorrhizal (Rt_MCInfFrac or Rt_MTInfFrac), and the length of hyphae per unit length of mycorrhizal root (Rt_MCHypL or Rt_MTHypL).

The effective root length then can be derived as:

which effectively converts the mycorrhizal hyphae into an equivalent length at the diameter of the roots. This option is provided for both crop and tree.

$$EffLrvC_{ij} = LrvC_{ij}\left[1+\frac{Inffrac\ .HypLeng\ .\sqrt{HypDiam}}{\sqrt{RtDiamC}}\right] \quad \textbf{[37]}$$

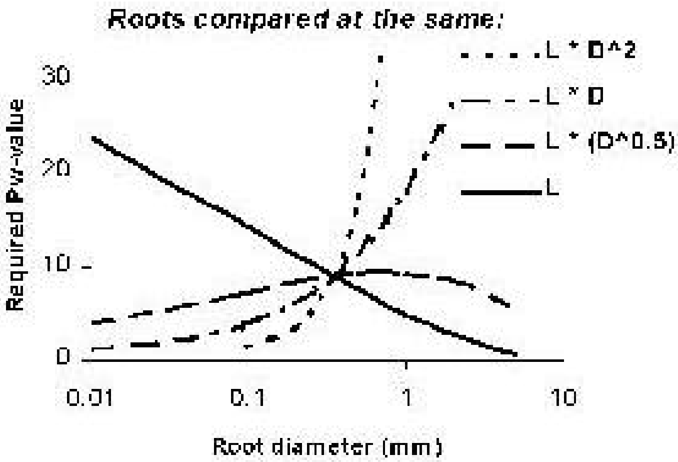


Figure 3.11 Effect of root diameter on potential uptake when root systems of different diameter are compared at equal length, root surface area or volume (weight); the smallest effect of root diameter exists when root length times the square root of the root diameter is used (Van Noordwijk and Brouwer, 1997)

3.6 Light capture

Light capture is calculated on the basis of the leaf area index of the tree(s) and crop (T_LAI[tree] and C_LAI) for each zone, and their relative heights. In each zone the parameters T_CanLow[tree], T_CanUp[tree], C_CanLow, C_CanUp indicate lower and upper boundaries of crop and tree canopy, respectively. LAI is assumed to be homogeneously distributed between these boundaries.

Light capture by the trees is separated in light captured by branches (based on their vertical projection area in the 'branch area index' or BAI) and leaves (based on leaf area index, LAI), while only the LAI part of total capture is used by the plants. This option allows to account for shading by trees when they are leafless, as *Faidherbia albida* is during the crop growing season. The ratio of BAI and LAI depends on the canopy architecture, leaf size and age of the tree. For older trees with small leaf sizes BAI can be similar to LAI (Van Noordwijk and Ong, 1999).

The current approach has evolved from that in WaNuLCAS 1. where only a single tree plus crop component was simulated. In that case, three strata were distinguished in the canopy: an upper one (with only one type of leaves), a mixed one (with both types of leaves present) and a lower one (with one only) (Fig. 3.12).

If light capture of ***n*** plants is to be accounted for in the same way, a total of ***2n-1*** canopy layers should be distinguished, with all boundaries determined by either an upper or a lower boundary of one of the components. In WaNuLCAS 2.0 we chose, however, to use only ***n*** canopy layers, using only the upper bounds of the component canopies as determinants. This choice means that for any plant type the light capture above its canopy is correctly calculated, but in the sharing of light within a canopy layer the calculations assume that all plant types present in that layer have leaves spread evenly within that layer.

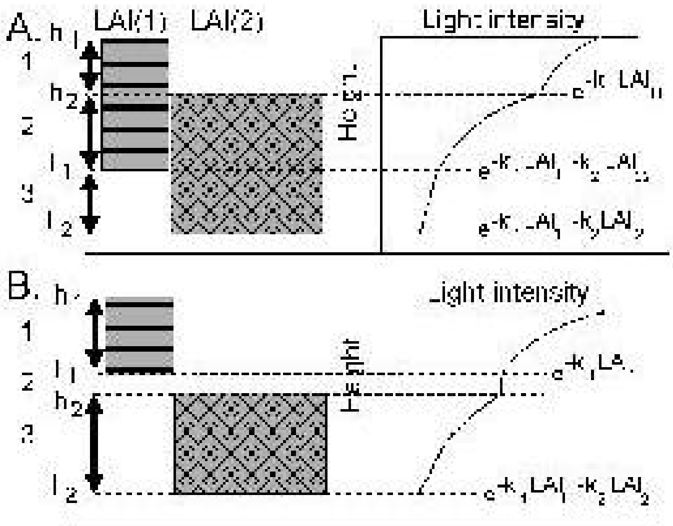


Figure 3.12 Light capture in a two-component leaf canopy, as used in WaNuLCAS 1.0; three zones can be distinguished: an upper zone with only one species, a middle one with both and a lower one with only one (usually not the same as in the upper zone); total light capture in the shared zone may be apportioned relative to the leaf area index of both species in that zone (compare Kropff and Van Laar, 1993)

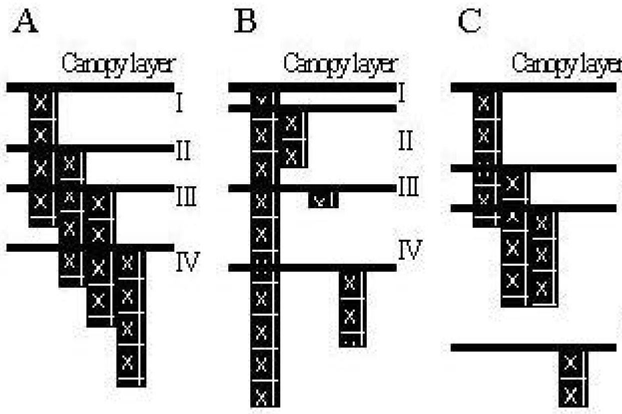
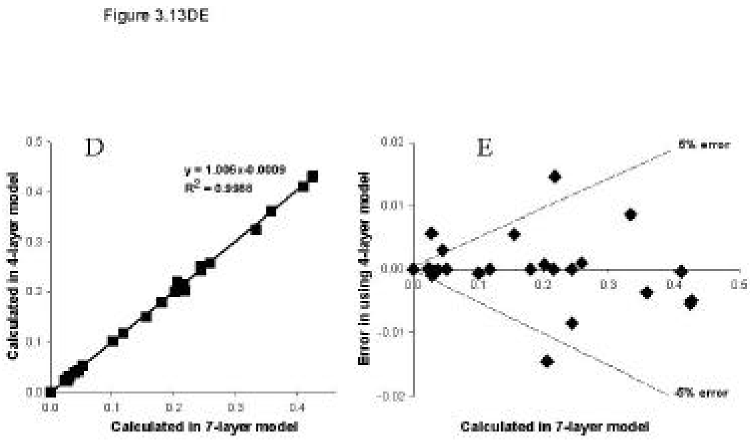


Figure 3.13 A, B and C Three examples of canopy distribution of four plant types within a given zone and the way they are represented in the canopy layers for calculating light capture; D and E Comparison of light capture calculations per component (tree or crop) according to the 4-layer canopy model used in WaNuLCAS 2 and that in a theoretically more correct 7-layer model



The errors made in this approximation are generally less than 1% of incoming radiation, but under specific parameter conditions light capture by a component can have a relative error of up to 25% (Fig. 3.13)

Specifically, the following steps are taken in WaNuLCAS 2.0 in the daily calculations per zone:

1. sort the four values (three trees plus crop) of upper canopy boundary (CanUpi),
2. calculate the canopy boundary values CanBoundj from these ranked values (for j = 1 take the highest, for j = 4 the lowest CanUp value)
3. calculate the LAI of each plant component i in each canopy layer j by assuming the leaf area to be evenly distributed within its canopy:

$$LAI_{ij} = LAI_i \left(MIN\left(CanUp_i, CanBound_j\right) - MAX\left(CanLow_i, CanBound_{j+1}\right)\right) / \left(CanUp_i - CanLow_i\right) \quad \textbf{[38]}$$

CanBound5 is assumed to be zero (any value smaller or equal to min(CanLowi) will give the same result).

4. calculate total light capture in each canopy layer on the basis of Beer's law for all components, starting at the top and accounting for light captured above the layer:

$$TotLightCap_j = 1 - \sum_{k=1}^{j-1} TotLightCap_k - e^{-\sum_i \left(kLLight_i * LAI_i - kBLight_i * BAL_i\right)} \quad \textbf{[39]}$$

where the kLLighti and kBLighti values represent the light extinction coefficients for leaves and branches, respectively.

5. share the light captured in a layer over the contributing components,

$$LightCap_{ij} = TotLightCap_j \frac{kLLight_i LAI_{ij}}{\sum_i \left(kLLight_i * LAI_i - kBLight_i * BAI_i\right)} \quad \textbf{[40]}$$

6. accumulate the light captured by each tree or crop over the various canopy layers.

Our choice for n rather than 2n-1 layers introduces an inaccuracy in step 5 in as far as the lower canopy boundaries of the various components within a layer do not coincide.

3.7 Crop growth

3.7.1. Basic Relations

Major relationships in the daily cycle of calculating crop biomass accumulation (Fig. 3.14) are:

1. calculation of crop leaf area index on the basis of shoot biomass, leaf weight ratio (LWR, leaf weight as fraction of total shoot weight) and specific leaf area (SLA, $m^2\ g^{-1}$),
2. calculation of canopy height on the basis of biomass and physiological stage (assuming height growth to stop at flowering),
3. calculation of the relative light capture on the basis of LAI of both tree and crop (see section 3.5),
4. calculation of the potential growth rate of the crop for that day, by multiplying relative light capture with the light use efficiency (dry matter production per unit light captured) and maximum net growth rate (kg m^{-2} day^{-1}), which is an input to the model and can be derived from more physiologically explicit models of potential crop growth under the given climate. The maximum net growth rate is supposed to include respiration losses for maintenance of existing tissues as well as for the formation of new ones. It may be desirable to split this term in its components, but we chose at this stage to take these values from existing calibrated crop models rather than duplicating these inside WaNuLCAS,
5. calculation of transpirational demand on the basis of this light-limited potential growth rate and a potential water use efficiency (dry matter production per unit water transpired), which will depend on the crop species,
6. calculation of whether actual water uptake can meet this transpirational demand (see section 3.3); the factor CW_PotGro is determined as the ratio of actual water use and transpirational demand,
7. calculation of the N limitations on growth on the basis of CN_PotGro (see section 3.4),
8. calculation of real dry matter production as the product of C_PotGroRed and the minimum of CN_PosGro and CW_PosGro.

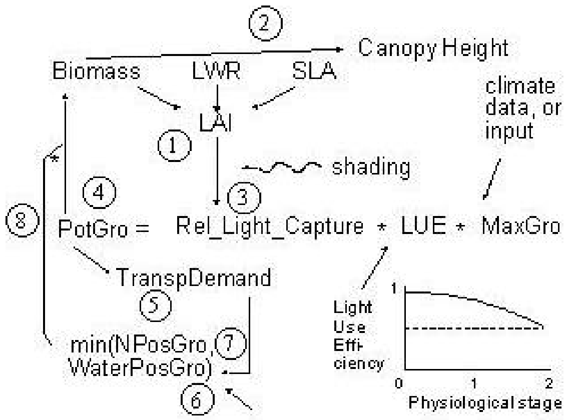


Figure 3.14. Major relationships in the daily cycle of calculating crop biomass accumulation

The model thus assumes that under N deficiency crops keep their potential transpiration rate, but have a reduced actual water use efficiency (dry matter production per unit water use). Under water stress, N uptake will be reduced as biomass accumulation slows down and thus demand is decreasing.

3.7.2 Deriving stage-dependent potential growth rates and allocation to harvested organs for situations without shading, water or nitrogen deficiency

A number of the allocation functions depends on the 'physiological age' of the crop. A basic length of the vegetative and generative stage is given as model input (Cq_TimeVeg[season] and Cq_TimeGen[season], respectively) for each crop. These values are used to re-scale time into 'crop-age'; for environments where temperature is a major variable, crop development can be driven by a temperature sum rather than by time.

In WaNuLCAS 1.2 the following allocation functions depend on crop stage:

- harvest allocation (Cq_HarvAlloc),
- specific leaf area (Cq_SLA),
- leaf weight ratio (Cq_LWR),
- relative light use efficiency (Cq_RelLUE).

These functions can be user-defined from experimental data of crops growing in full sunlight in the local climate with adequate supply of nitrogen and water, or from more detailed physiological models. Figure 3.15 and 3.16 give examples of basic allocation functions derived from the Wofost model (data provided by Dr. P. de Willigen, AB-DLO Haren the Netherlands), using climate data for Lampung (Indonesia) and 'standard' parameter settings for cassava, (upland) rice, maize, groundnut and cowpea. From data such as this taking the ratio of green leave and total biomass can directly derive LWR. To obtain RelLUE the growth rate (dW/dt) is divided by the estimated light capture (on the basis of LAI - this calculation requires parameter values for SLA and light extinction coefficient)

The sheet 'Deriving Crop Gowth' in the WaNuLCAS.xls spreadsheet takes the following steps in converting output of a potential crop growth simulation (daily predicted biomass in leaves, stems and storage organ(or grain)), into the input parameters which are used in the 'Crop Growth' spreadsheet .

Input columns:

DwLv[time], DwSt[time],DwSo[time], all expressed in kg ha^{-1} day^{-1}, and SLA[time] in m^2 g^{-1}

Cq_kLight as fixed value

Derivations:

DwTot = DwLv + DwSt + DwSo

Maximum daily increment in aboveground plant biomass: GroMax = max(DwTot) (kg ha^{-1} day^{-1})

LWR[time] = DwLv[time]/(DwLv[time] + DwSt[time])

TimeVeg = time of flowering (or last day before first value of DwSt is recorded)

TimeGen = time to harvest - TimeVeg

Stage = time/TimeVeg for time<TimeVeg and else (1 + (time - TimeVeg)/TimeGen)

Deriving apparent light use efficiency

Daily increment in total dry weight (logarithmic average over preceding and subsequent period): exp(0.5*(ln $(dDwTot/dt)_{preceding}$ + ln $(dDwTot/dt)_{subseuent}$)

Daily relative light capture: RelLightCap[time] = 1 - exp(-k * DwLv * SLA/10000) (the factor 10 000 converts from ha to m^2)

Relative daily growth per unit light capture (relative to the maximum growth rate, which implicitly reflects the radiation level): RelLUE[time] = (dDwTot/dt)/(GroMax* RelLightCap)

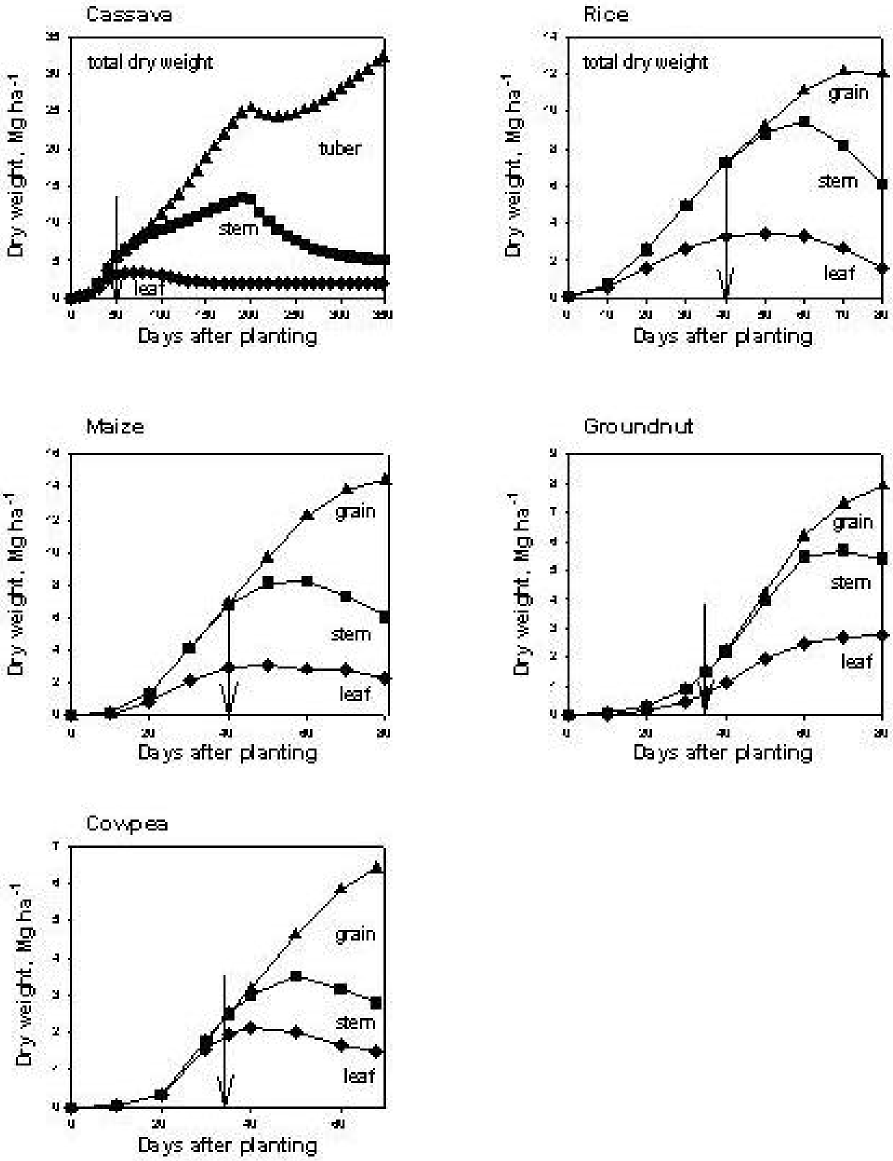


Figure 3.15 Examples of basic allocation functions derived from the Wofost model using climate data from Lampung (Indonesia) and 'standard' parameter settings for cassave, (upland) rice, maize, groundnut and cowpea (data provided by Dr. P. de Willigen, AB-DLO Haren the Netherlands). Arrows denote the starts of generative stage (Cq_Stage=1)

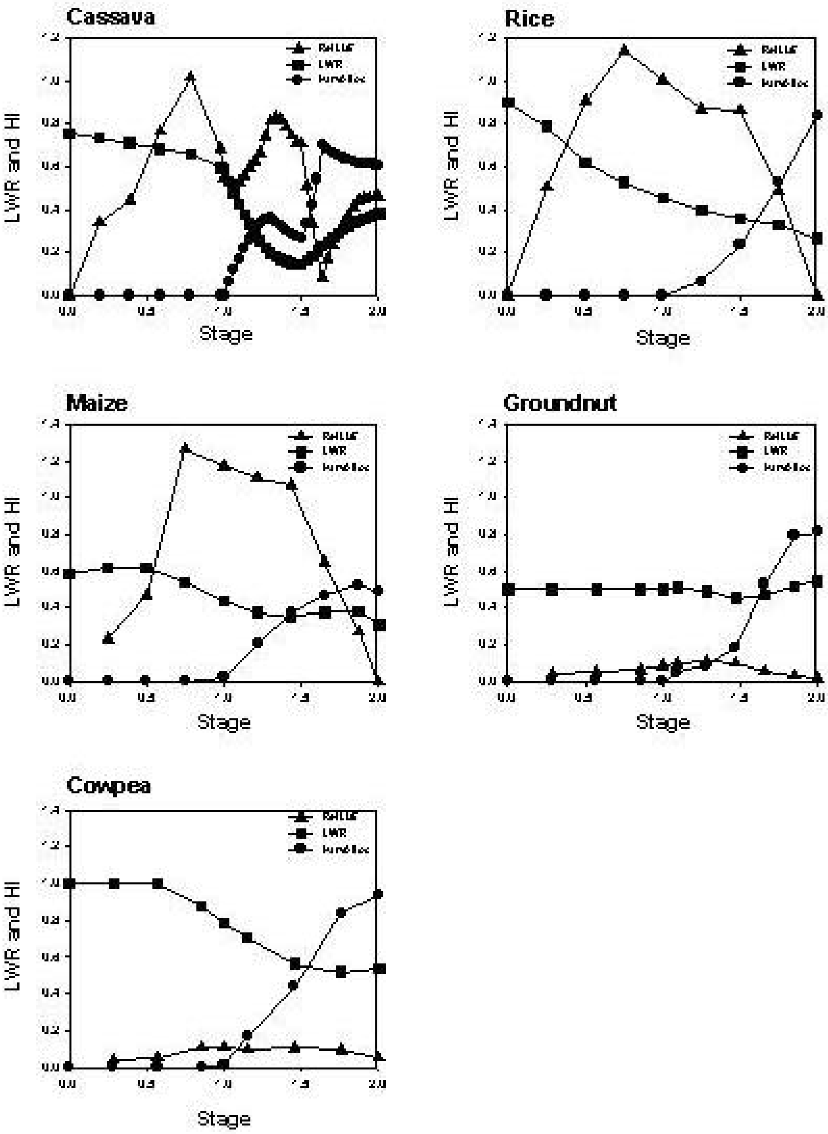


Figure 3.16 Leaf weight ratio, harvest allocation and relative light use efficiency rate as a function of time for the model output of figure 3.15

Deriving apparent remobilization from stems and leaves and allocation to storage organs

Daily increment in storage organ: dDwSo/dt

Apparent remobilization from leaf and stem dry weight during generative stage Remobfrac[time]: (dDwSo/dt - dDwTot/dt)/(DwLv + DwSt)

Value of Remobfrac which can be used for the whole growing season as max(Remobfrac[time])

Daily allocation to storage organs: HarvAlloc[time] = (dDwSo/dt)/((dDwTot/dt) + Remobfrac * (DwLv + DwSt))

Converting time-dependent variates into crop stage dependent ones

The derived parameters LWR[time], SLA[time], RelLUE[time] and HarvAlloc[time] are now converted to crop-stage dependent equivalents:

To convert the data which may have unequal intervals into the equal-interval format expected by Stella, the stage dependent variates are plotted in a graph with stage as X-axis. Manually we read in values at constant intervals (helped by grid-lines in the graph) into the columns Cq_CLWR[stage], Cq_CSLA[stage], Cq_CRelLUE[stage] andCqCHarvAlloc[stage], respectively.

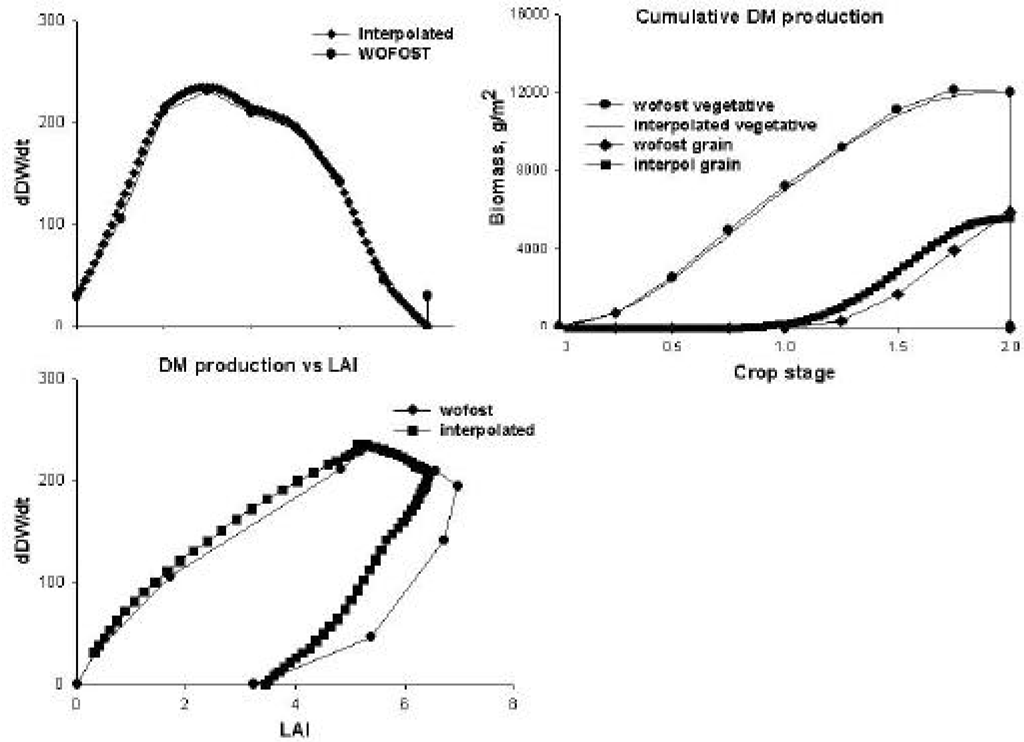


Figure 3.17 Comparison of potential production as derived per 10-day interval from the WOFOST model, and the daily interpolated values derived in the Wanulcas.xls spreadsheet: A. daily growth rates, B. accumulative dry matter production, C. trajectory of the relation between growth rate and LAI

As illustrated in Fig. 3.17 for maize, the daily interpolation does not exactly match the Wofost input (based on 10 day recording intervals), but errors in daily rates as well as cumulative amounts stay within generally acceptable limits (5%); towards the end of the crop development, however, the Wofost model (as well as proper field data) show a decline in total dry weight as respiration exceeds photosynthesis; in Wanulcas we do not explicitly represent respiration losses or account for negative growth rates, but the losses are accounted for by assuming a lower net growth rate in the preceding period. This approach, however, leads to deviations in the harvest index.

In Wanulcas a reverse procedure is used to derive the daily potential growth rate (Cq_from the actual relative light capture (based on crop LAI as well as shading) multiplied by Cq_RelLUE and Cq_GrowMax. [This assumes that potential growth rates are proportional to light capture]

Effectively we allow the user to use this simulated data for modified crop phenology (changes in TimeVeg and TimeGen) as well as modified maximum growth rates, as simple ways to apply it to modified climatic conditions. If large modifications are made it would be safer to derive fresh inputs from a potential crop growth model for the new situation.

If no potential growth simulations are available, the user may enter other types of estimates of the biomass of leaves, stems and storage organs into the spreadsheet and otherwise follow the procedure outlined.

3.8 Tree growth

3.8.1 Tree growth stage

For the trees a physiological growth stage is defined in the [0 - 1] range for the vegetative stage up to the first flowering event, and in the [1 - 2] range for flowering and fruit ripening. After fruit ripeness the tree returns to stage 1 (rather than dies, as is the case for 'annuals'). The parameters governing tree growth stage are:

T_TimeVeg - duration [days] of initial vegetative period before first flowering

T_InitStage - tree growth stage at start of simulation

T_StageAfterPrun - growth stage to which trees are returned after a pruning event

T_TimeGenCycle - duration [days] of a flowering - fruit ripeness cycle

T_FlowerDOYbeg - first day of year at which flowering can occur (provided stage = 1.0)

T_FlowerDOYends - last day of year at which flowering can occur

T_FruitAllocFrac - fraction of current growth resources in the tree allocated to developing fruits

T_FruitHarvFrac - fraction of ripe fruit biomass and nutrients harvested from the plot

When the trees are pruned, all fruit biomass is removed from the tree and may be partly harvested from the plot, along with vegetative pruned biomass, as governed by the T_PrunHarvFrac.

When the growth stage reaches 2.0, all fruit biomass is removed from the tree, and the T_FruitHarvFrac part of it is harvested from the plot, the remainder returned as mulch.

On a daily basis a fraction of the T_Fruit biomass pool can be removed by frugivory and fruit abortion, as governed by T_frugivory&abortionFrac, and returned to the soil as mulch.

3.8.2 Canopy and support structure

WaNuLCAS includes a simple description of canopy shape, aboveground biomass production and litterfall; these rules are applied if the T_ApplyFBARules? switch is put at 0. In the model, the calculated aboveground tree biomass increment is first of all allocated to a buffer of 'carbohydrate reserves' and is allocated from there to make:

- a canopy, consisting of leaves and small branches (<2 cm diameter),
- a support structure, consisting of supporting branches and a trunk,
- replacement of leaves and branches transferred to 'litterfall'

$$\Delta Biom = \Delta Canopy + \Delta Support + \Delta Litterfall \qquad [41]$$

The allocation over canopy and support structures depends on the size of the tree. while litterfall is related to the development of 'bare branches' in the support structure.

Within the canopy, the increment in leaf biomass is calculated from:

- LWR (leaf weight as fraction of total biomass in the canopy),
- SLA (specific leaf area, or leaf area per unit leaf weight).

$$\Delta Leafarea = \Delta Canopy * LWR * SLA \qquad [42]$$

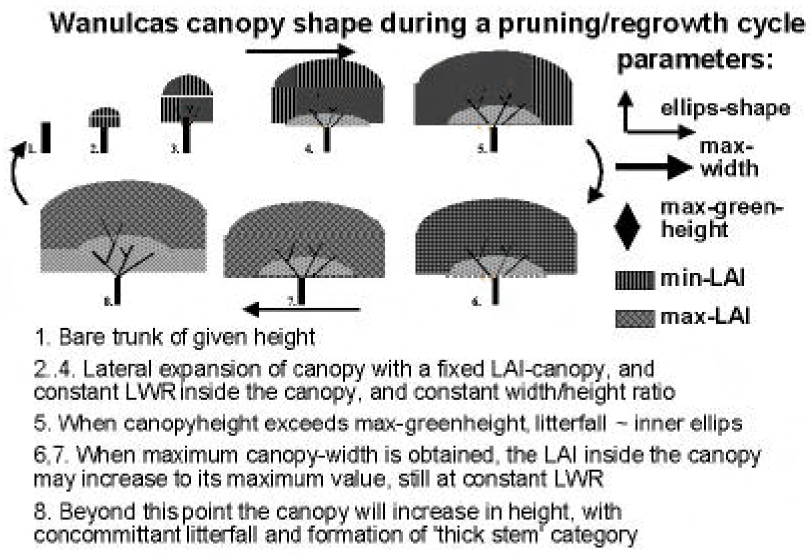


Figure 3.18 Tree canopy shape during a pruning - regrowth cycle

A half ellipse on a stick (forming an ‘umbrella’ approximates tree canopy shapes, with as parameters:

- R, radius (half of the width),
- H, height (measured above the bare stem section); the canopy height consists of a green part and, above a certain total height, a bare section,
- S, shape, or ratio of radius and height of the half ellipse (or of width and total height of a full ellipse; S = R/H; S = 1 indicates a circle),
- LAI-canopy (leaf area index within the canopy), which can vary between LAI_{min} and LAI_{max}.
- An alternative formulation that is activated when T_ApplyFBARules? = 1 is described in section 3.8.4.

3.8.3 Daily cycle of calculations

The sequence of events during a pruning/regrowth cycle is illustrated in Fig. 3.18

In the first stages of regrowth after pruning, growth is based on the carbohydrate reserves in the bare trunk which remained after pruning and is thus dominated by the fraction which can be converted daily. Once green leaves start to function, the carbohydrate reserve pool can be replenished and growth rates can increase. At first the canopy extends with a minimum LAI within the canopy, LAI_{min}. Both width and height can be calculated from the total leaf area, LAI_{min} and the shape of the ellipse (which is assumed to be constant, but could be made size-dependent if more specific data are available).

$$R = Leafarea / LAI_{min} \quad \textbf{[43]}$$

$$H = R / S \quad \textbf{[44]}$$

By the time the calculated canopy height exceeds the 'green-canopy height', litterfall is supposed to start. New biomass production continues to be allocated to leaves (T_LWR) and stems (1 – T_LWTR), but only the stems is added to tree biomass and the new leaves are simply replacing litterfall. If the maximum canopy width is reached, the canopy can gradually increase in LAI from LAI_{min} to LAI_{max}.

$$\Delta height = leafgrowth / (LAI_{max} * Maxwidth) \quad \textbf{[45]}$$

If LAI_{can} reaches LAI_{max}, the canopy will gradually move upwards. All new leaf growth is offset by litterfall. The increment of tree-height follows from: For the 'support structure' a tabulated function can be used to allocate dry weight. Alternatively, allometric equations based on fractal branching properties can be used (not yet)

Pruning events are described in section 3.10.

3.8.4 Tree diameter and allometric biomass allocation rules

A number of allometric biomass equations (of the general form: $Y = a\ D^b$) is commonly used to relate biomass in specific fractions (total aboveground, leaves+twigs, branches, total belowground) or total root length to the diameter of the main stem, or the equivalent diameter of all proximal roots (for belowground application see section 3.5.3). The spreadsheet 'Functional BranchAnalsysis' (FBA) that is released as a companion to WaNuLCAS provides a way to derive parameters of these allometric equations on the basis of parameters that can be relatively easily observed (without large scale destructive sampling).

In WaNuLCAS we use the general biomass - stem diameter relation in inverse form to derive stem diameter from the total tree biomass as it develops on the basis of the growth rules. The relation

$$T\_BiomAG = T\_BiomDiam1\ T\_StemDiam^{T\_BiomDiamSlope} \quad \textbf{[46]}$$

can be inverted to obtain

$$T\_StemDiam = (T\_BiomAG / T\_BiomDiam1)^{1/T\_BiomDiamSlope} \quad \textbf{[47]}$$

Aboveground biomass of a tree may decrease, e.g. due to litterfall or pruning, without causing a direct reduction in stem diameter. In WaNuLCAS we therefore keep track of the stem diameter via the maximum aboveground biomass obtained so far in the simulation. The T_StemDiam parameter is used as indicator for the readiness for tapping latex in rubber trees, and to drive allometric equations for other properties:

$$T\_TargetLeafTwig = T\_LeafTwigDiam1\, T\_StemDiam^{T\_LeafTwigDiamSlope} \quad [48]$$

$$T\_BiomBranch = T\_BranchDiam1\, T\_StemDiam^{T\_BranchDiamSlope} \quad [49]$$

$$T\_LargeWood = T\_Wood - T\_BiomBranch \quad [50]$$

If the T_ApplyFBARules? switch is on (value = 1), the transfer of dry weight and nutrient resources from the canopy biomass to the T_Wood pool is driven by the difference between T_TargetLeafTwig and current T_CanBiom.

3.8.5 Cumulative litter fall

If the initial length of a link (section of stem or branch between two branching points) is L_{min}, and its initial diameter D_{min}, a linear increase of expected link length with diameter can be described as:

$$L(D) = L_{\min} + a_1 (D - D_{\min}) \quad [51]$$

If we may assume that the distance between branching points does not vary with time or growth stage of the tree, an increase in distance reflects branches being dropped. If L(D) = 2 L_{min} one branch will have dropped, for L(D) = 3 L_{min} two branches etc.; from equation [51] we can expect that for a diameter increment from D_x to $D_{x+\delta}$ an additional number of branches of $\delta\ a_l\ /L_{min}$ will be dropped (ignoring the discrete character of these events and describing their expected means for a population of branches). We may assume that the branch dropped was the smaller one of the two branches at that branching point, so it had a diameter of:

$$D_{x2} = \left((1-q)D_x^2 / a\right)^{0.5} \quad [52]$$

where a and q are parameters of the fractal branching process.

The biomass of the dropped branches can be estimated from the overall biomass equation Biom = BiomD1 D^b and the total biomass dropped can now be derived by integrating from D = D_{min} to D = D_{max}:

$$CumLittfall(D0) = \int_{D\,min}^{D\,max} (a_l / L_{min})\, BiomD1 \left\{\sqrt{(1-q)}D^2 / a\right\}^b dD =$$
$$= \frac{a_l\ BiomD1\left((1-q)/a\right)^{0.5b}}{L_{min}(b+1)} \left(D_{max}^{b+1} - D_{min}^{b+1}\right) \quad [53]$$

For any D_{max} value more then 2.4 D_{min} the error made when ignoring the D_{min} term in the equation is ignored is less than 5% and for D_{max} > 3.7 D_{min} it is less than 1%. For cumulative litter fall based on dropped branches with the leaves they originally carried, we thus derive an approximate allometric equation with power b+1, if the D_{min} term can be ignored. As the power of the cumulative litterfall equation is higher that that for standing biomass, cumulative litterfall will exceed standing biomass beyond a certain stem diameter (Fig. 3.18A); the position of the cross-over point is (again, if the D_{min} term can be ignored):

$$D = \frac{L_{min}(b+1)}{a_l\left((1-q)/a\right)^{0.5b}} \quad [54]$$

and is this independent of BiomD1 and decreases with increasing slope of the link length diameter relationship a_l (if a_l = 0 there is no litterfall).

From equation [54] we can derive the current litterfall for a small diameter increment above D_0 as:

$$AllocLit(D) = \frac{dCumLittFall}{dD} = \frac{a_l BiomD1\left((1-q)/a\right)^{0.5b}}{L_{\min}} \quad [55]$$

while allocation to the Biomass pool will be:

$$AllocBiom\ (D) = \frac{dBiom}{dD} = bBiomD\ 1\ D^{b-1} \qquad [56]$$

Thus, the relative allocation of new photosynthate to litterfall will increase with D_0 according to:

The relative allocation to litterfall thus approaches 1, posing a limit to the maximum size of a tree (Fig. 3.18 B).

$$RelLitFallAloc(D) = \frac{a_l((1-q)/a)^{0.5b} D}{a_l((1-q)/a)^{0.5b} D + bL_{min}} \qquad [57]$$

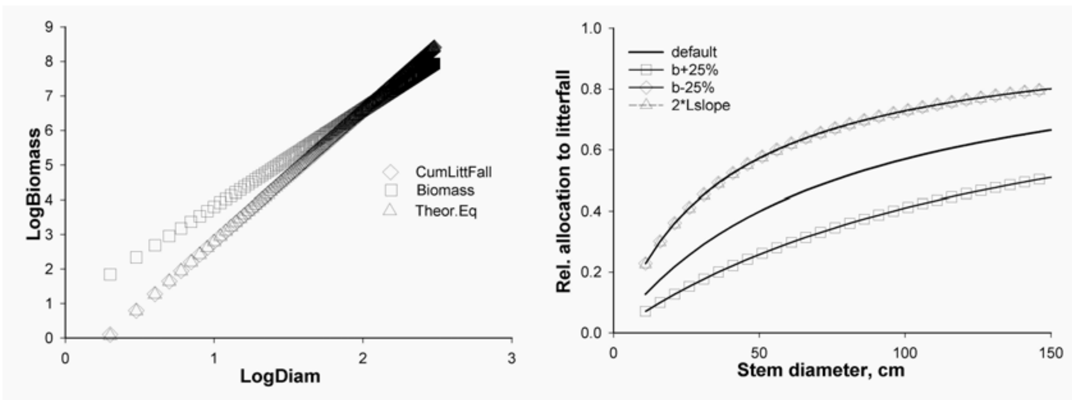


Figure 3.19. A. Comparison of biomass and cumulative litterfall as a function of stem diameter comparing a numerical integration with results of eq.[54]; B. Relative allocation of current biomass production to litterfall as a function of stem diameter for a default parameter set and in situations where the slope of the biomass allometric equation is increased or decreased by 25%

In the actual implementation of litterfall according to these allometric rules, we take into account that actual litterfall e.g. due to drought stress, can be ahead of the amount due according to equation [54]. If so, new leaves and twigs can grow unimpeded until the former canopy biomass is regained.

3.8.6 Tree products

A number of tree products can be harvested and removed from the plot:

- tree prunings (e.g. for use as fodder), governed by T_PrunHarvestFrac
- fruits, governed by d T_FruitHarvIndex, fruiting itself governed by tree stage (see Tree Growth Stage)
- latex, coming directly from the T_GroRes pool; the model user can define a minimum tree diameter required for tapping and the fraction of growth resources harvested on a tapping day
- wood, governed by T_WoodHarvestFrac and T_WoodHarvDay

3.9 Carbon Balance

3.9.1 Soil organic matter

Total soil organic matter is supposed to consist of 'metabolic' and 'structural' pools in the recently added organic materials, an 'active' (= microbial biomass), 'slow' and 'passive' pool. This terminology is derived from the Century model. This part of the model was developed in discussions with Dr. Georg Cadisch (Wye College, UK) and Dr. Andy Whitmore (AB-DLO, the Netherlands).

In agro-ecosystems without soil tillage, a distinct litter layer develops where much of the organic inputs decompose with little contact with the mineral soil layers. The dynamics of C and N here can differ substantially from that in the soil layers, as the 'physical protection' mechanisms based on soil texture are absent, and temperature and water dynamics differ. Incorporation of surface litter into the soil can be the result of specific groups of the soil fauna, as well as of mechanical tillage operations. Starting from version 2, WaNuLCAS therefore represents the C, N & P pool dynamics for the litter layer separate from SOM dynamics, using the Century pool descriptions for both (all parameter names MC_... and MN_... refer to the litter layer, names MC2_.. and MN2_...

to the SOM pools). The texture, water and (potentially) temperature controls differ between these layers. For N immobilisation the litter layer has limited access to soil layer 1, while all mineralization products arte delivered to layer 1. For the SOM pools, a weighted averaged is made of layer 1...4 for all its relations with soil water and N pools (including immobilization and mineralization). The weighing factors for the soil layers are set at the start of the model (but can be made dynamic if one wants).

Input streams of organic matter from crop residues, tree litterfall, prunings and/or external organic sources supply 'metabolic' and 'structural' pools, by adding all C, N, lignin and polyphenolic contents of all inputs on a given day. Century's distribution equation is then applied to allocate these streams to metabolic and structural litter pools. This represents a 'simple mixing' algorithm, without specific interactions between residues.

Before the Century equations are applied, however, the total polyphenolic content is supposed to immobilize N from the current organic inputs and (if necessary) soil Nmin pool, into the 'slow' pool of C and N. This equation can account for some of the non-linear effects when residues with low and high polyphenolic content are mixed. (Polyphenolics are not yet implemented in WaNuLCAS 2.0).

Immobilization of mineral N can occur where metabolic and especially structural SOM pools are utilized by microbial biomass to make 'active SOM', with a low C/N ratio and (for structural litter) 'slow SOM'. Modifications were made here to the model (if we understand what the Century handles this situation). The flow of C is driven by the preceding C pool size and the relevant decomposition parameter k. This C flow induces a parallel N flow on the basis of the C/N ratio of the preceding and subsequent SOM pool.

If there is sufficient Nmin in the soil layer, this will be used to meet the 'target' C/N ratio of the subsequent pool. If there is not enough mineral N, however, to (fully) meet this demand the C/N ratio of the subsequent pool will increase. This will have two effects:

1. further transformations of SOM will slow down, and reach a halt where the microbial biomass has a CN ratio of 1.75 times the 'target' value. The value 1.75 was suggested by Dr. Georg Cadisch.
2. the SOM pools remain 'hungry' for mineral N and will re-stock their N content to meet the 'target' whenever mineral N becomes available in the soil again.

These modifications to the Century model are mainly relevant at relatively small time scales (less than the yearly time steps for which Century was designed). The model can now potentially account for the rapid disappearance of mineral N into the soil after fertilizer N additions, while such fertilizer may become available to subsequent crops.

Apart from the freedom to set parameters, a number of options on model structure was built into WaNuLCAS:

The k values driving the SOM-C and SOM-N transformations are a function of clay content and soil temperature as in the Century model, and an additional reduction based on soil water content. For example, for the active pool the k value is calculated as:

$$k = 0.14 * (1 - .75 * Mc\_SiltClay) * Mc\_TempLim * Mc\_TethaLim[Zone] \quad \textbf{[58]}$$

where the 0.14 and 0.75 are the parameter values for the active pool (other pools use different values but the same reduction factors). Make sure that the value of silt and clay content used should be consistent with the value used in deriving soil hydraulic properties.

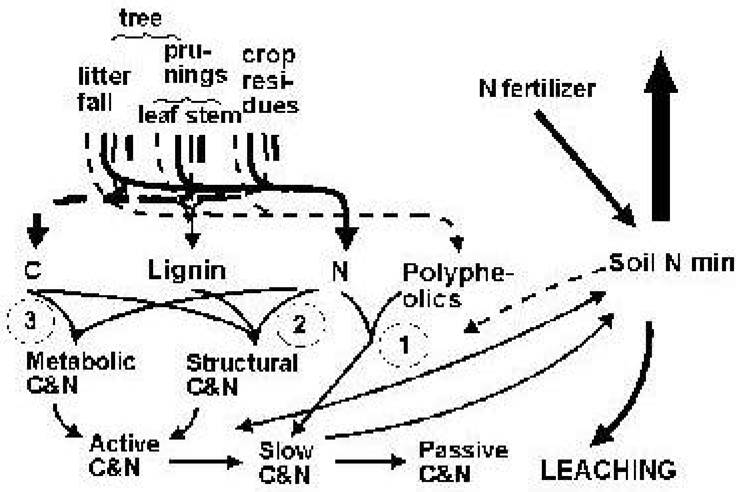


Figure 3.20 Major relationships in N immobilization and N mineralization from organic residues; the basic C and N pools are similar to the Century model, but plant polyphenolics are added as litter quality parameter

3.9.2 Carbon stocks

An output table is provided which summarizes the carbon balance, similar to the water, nitrogen and phosphorus balance sheets.

On the left hand side it includes all initial carbon stocks in soil, crop and tree (with plant biomass converted into carbon units) and all net daily photosynthesis by crop and tree. On the right hand side it lists all final carbon stocks in soil, crop and tree, all carbon in products removed from the plot and all carbon lost as CO_2 in soil organic matter transformations. Plant respiration is implicit in the net photosysnthesis and thus does not appear on the C balance sheet.

3.10 Management options

3.10.1 Options for strategic and tactic management

The WaNuLCAS model can evaluate a number of farmer management options. These can be grouped in strategic decisions, to be made by a farmer before crops are planted and by a modeler at the start of a simulation and tactic management during a growing season, in response to actual crop performance.

Strategic options include

- Plot size and tree spacing,
- Choice of tree species as reflected in their functional parameters of canopy shape and branch allocation, root distribution under given soil conditions),
- Cropping cycle: crop types and planting dates.
- Predetermined pruning events
- Pre-determined tree final harvest and/or tree mortality
- Slash-and-burn events, including options to remove part of the wood before the burn,
- Building a fence around the plot

Tactical options represented in the model are:

- Tree pruning based on current tree and crop status,
- Use of fertilizer and organic inputs and their distribution over the zones,
- Crop residue removal,
- Maintaining the fence.

At this stage only two types of plants are considered and thus we imply that there are no weeds. The equations for resource sharing and competition are set up in such a way that the model can be extended to an n-plant interaction and different plants can share a zone in the model, above as well as belowground.

3.10.2 Slash-and-burn events

A number of 'Slash' events can be defined in the event calendar, by specifying the S&B_SlashYear and S&B_SlashDOY tables. Slash events transfer all current aboveground biomass in tree, weed or crop pools to the S&B_Necromass pool. This refers to the dryweight, N and P contents of these pools. From the S&B_Necromass a fraction can be transferred daily to the surface litter pool, as set by the S&B_DailyNecromLittTransf parameter, where it will follow century-model based transformations of C, N and P pools. The S&B_Necromass pool will intercept part of any rainfall events, replacing the role played previously by tree and crop biomass, and the subsequent evaporation from the 'Rain_CanopyWater' pool will determine the moisture content of the necromass. When this is below a set value ('S&B_CritWatContent') the switch 'S&B_IsSlashDry?' will be turned on, allowing burn events to take place, otherwise it is turned off.

Burn events are defined by specifying a minimum and maximum number of days after the most recent 'slash' event. A fire event will be implemented on the first day in this period that the signal 'S&B_IsSlashDry?' is on. During a burn event, the temperature increase at the soil surface is calculated from the necromass + structural part of surface litter, with corrections for their respective moisture contents based on 'Rain_CanopyWater' and 'W_Theta1[Zone]'. Temperature calculations need two parameters: 'S&B_ FuelLoadFactor' and 'S&B_TempWetnessCorr'. The temperature increase in the topsoil is derived from the temperature increase at the soil surface, modified by soil water content of the topsoil.

Burn events can have impacts on a number of pools in the model, either via the temperature at the soil surface or that in the top soil:

- reduction of surface necromass, surface litter and SOM pools, by S&B_NecromassBurnFrac, S&B_SurfLitBurnFrac and S&B_SOMBurnFrac, respectively,
- allocating all C of the burnt necromass to CO2, and 1 - S&B_NutVolatFrac of its N and P content to mineral nutrients at the soil surface,
- induce a (one-off) transfer from the immobile P fraction in the topsoil via S&B_FirIndPMobiliz
- induce a semi-permanent relative change of the effective P sorption via S&B_FirImpPSorption; a gradual return to the original P sorption value will be governed by S&B_PsorpRecFrac
- release cations into the topsoil from burnt necromass, leading to an increase of topsoil pH; this change of pH will modify the P sorption properties as well, with the overall effect obtained by multiplying the two factors,
- evaporate all soil water from the topsoil if the temperature exceeds 100oC via S&B_FireWEvap
- modify soil water retention properties via S&B_FireImpactonWatRet, with a gradual return to the original values governed by S&B_WatRetRecFrac.
- induce tree mortality switch S&B_FireTreeMort? if the temperature exceeds the S&B_TreeTempTol[tree]
- induce mortality in the weed seed bank via S&B_FireMortSeedBank

Most of the above impacts is related to temperature via a graphical input; impacts can be set to zero by modifying these graphs.

3.10.3 Tree mortality

Trees can die due to fire (see 3.10.2) or at a set date (T_KillYear and T_KillDOY). If Rt_ATType = 2 is used, any remaining root biomass at that time is treated as input to the soil organic matter module.

3.10.4 Weed growth

An option is provided to include weed growth in the simulations, outside of the cropping periods. If the switch C_SimulateWeeds? is set at 1 (in stead of 0), weeds will start growing whenever crops are absent, based on a fraction C_WeedGermFrac of the current seedbank of live weed seeds. The seed bank (dry weight) is initialized at C-WeedSeedBankInit kg m-2 for all zones, with nutrient contents based on C_SeedConc. Daily influx of weed seeds from outside of the plot equals C_WeedExtInflux, while a fraction C_DailyWeedSeedDecay is transferred to the litter layer. During fire, additional decay of viable seeds will be accounted for, depending on the temperature on the topsoil.

Growth of the weed biomass follows the rules for crop growth, with a parameter set chosen on the basis of Cq_WeedType (default = 10). The weed can have a perennial or annual growth habit, depending on the value of Cq_SingleCycle? for crop type 10.

3.10.5 Pests and diseases

Leaves, roots, fruits and wood of crops and trees can be eaten by herbivores, rhizovores, frugivores and lignivores, respectively. The user can define a constant daily fraction to be removed from each plant organ types by such events. This is a skeleton on whicg the user can build, e.g. by making the impacts dependent on crop stage and/or the amount of alternative food for the organims involoved. A simple version of a pest population dynamics module is included, that allows pest organisms (nasties) to enter the plot from the surroundings of the simulated area. A fence can be build around the plot and the various categories of pest can either jump the fence or be deterred by the fence if it is in a good enough condition (PD_FenceQ >= 1). Again, this is a skeleton of a module only, and the user who is interested in this type of interactions and lateral flows will have to provide more detail.

3.10.6 Fence

Fence quality is supposed to be related to initial labour time investment according to Q = M * L/(K + L), where M is the maximum quality (PD_FenceFullQuality) and K the amount of labour to reach half of this maximum (PD_HalfFenceTime). To calculate the change in fence quality due to subsequent labour investment, we can first express the current condition in an equivalent time (t = K Q/(M - Q) and then calculate the new quality based on this time t plus the new labour time investment. The change in fence quality due to a new time investment Lcurr becomes:

$$\Delta FenceQuality = Lcurr(M-Q)^2 / \left(KM + Lcurr(M-Q)\right) \quad \textbf{[59]}$$

In WaNuLCAS two options are provided for fence building and maintenance: if PD_FenceMaint? = 1 a certain amount of labour is spent (PD_FenceMUnit * PD_HalfFenceTime) whenever there is a crop on the field (in any of the zones) and the current quality of the fence is below the threshold (PD_FenceQThresh. If PD_FenceMaint? = 0, fence building responds to a calendar of events specified by PDFeceBuildY, PD_FenceBuildDOY and PD_FenceBuildLabSeq (the latter in units relative to PD_HalfFenceTime).

Fence quality decays by a fraction PD_FenceDecK per day. Costs for fence building and maintenance are taken to be proportional to the amount of labour spent, and the P_FenceMatCost[PriceType] value is supposed to be spent when the amount of labour used equals PD_HalfFenceTime.

3.10.7 Tree pruning

For tree pruning the following options are provided:

T_PrunY and **T_PrunDoY** allow the user to specify pruning dates, similar to the cropping calendar. This option may be especially useful if simulations are to be compared to actual data sets. If the user does not want this type of pruning events, the T_PrunY for the first event should be after the simulation run ends.

T_PrunPlant? Determines whether or not the tree will be pruned every time a new crop is planted (0 = not, 1 = yes)

T_PrunLimit specifies a critical total LAI of tree canopy above which trees will be pruned, if and only if there is a crop in one of the zones

T_PrunStageLimit will ensure that no tree pruning is implemented in the later part of the crop (after this stage in crop development), to avoid tree pruning just before crop harvest.

For each pruning event, the parameter **T_PrunFrac** specifies the fraction of tree canopy biomass removed. This can be specified as constant for every pruning event or changes for every event.

T_PrunHarvFrac specifies the fraction of prunings that is removed (harvested) from the field, e.g. for use as fodder. This can also be specified as constant or dynamic.

3.11 Model output

3.11.1 General

A number of graphs and tables is provided for viewing output of a WaNuLCAS simulation, but the Stella environment allows a user to interrogate the model for the value of any parameter at any time step desired.

On the 'Output menu' one has a choice between viewing graphs of biomass and elements of water and nutrient balance for the system as a whole, or specific by zone. An overview of the balance of inputs and outputs is given for N, P, C, water and money. The 'yields' screen translates the dry weights of the model to the moisture contents conventionally used for agronomic yields (as governed by the .C_AgronYMoistFrac parameter in crop type).

3.11.2 Financial analysis

The WaNuLCAS model can predict the outcome of patch-level performance of agroforestry systems under a range of management choices. In version 2 a simple financial analysis is provided in the form of a Net Present Value calculation. Dr. Thomas P. Tomich and Mr. Suseno Budidarsono (ICRAF SE Asia) advised on the development of this section. The basic equation is:

$$NPV = \sum \frac{-cost + return}{\{1 + DiscountRate/365\}^{Time}} \qquad [60]$$

Two types of prices can be used simultaneously, social and private, so as to allow an analysis of the impacts of economic policies and market imperfections on the profitability of the agroforestry system simulated. As we do a daily accounting of costs and returns, no separate category of 'working capital' is needed as one would use for an annual accounting system. Costs and returns included in WaNuLCAS 2.0 are listed in Table 3.7.

Table 3.7 Costs and returns included in the calculation of net present value in WaNuLCAS 2.0

Costs	Returns
Planting material for crop and tree	Harvested crop yields
N and P fertilizer or pesticides used	Harvested tree products (wood, fruit, latex, prunings used as fodder)
Organic inputs	
Labour for tree planting, management and harvesting	
Labour for crop planting, management and harvesting	
Labour and input costs for field protection (incl. fence building and maintenance)	

3.11.3 Filter functions

Tree and crop roots can exert 'safety-net' or 'filter' functions by intercepting nutrients from various depths of the soil, and thus preventing them from losses by vertical leaching or horizontal lateral flow. The ratio of uptake to (uptake + loss) can be used to indicated the local filter function (Cadisch *et al*. 1997, Rowe *et al*., 1999):

$$N\_LocFF_{ij}[Nutrient] = Upt_{ij}[Nut]/(Upt_{ij}[Nut] + Loss_{ij}[Nut]). \qquad [61]$$

$$N\_LocFF_{ij}[Nutrient] = Upt_{ij}[Nut]/(Upt_{ij}[Nut] + Loss_{ij}[Nut]). \qquad [62]$$

$$N\_TotFF[Nut] = TotUpt[Nut]/(TotUpt[Nut] + TotLoss[Nut]) \qquad [63]$$

where the TotLoss is accounted for at the boundary of the system, ignoring internal transfers within the system. The total filter function by this definition is not equal to the sum (or average) of the local filter functions, as the divisors of the ratio differ. The total filter efficiency can, however, be split into the contributions of each cell:

$$N\_TotFF[Nut] = S_i S_j N\_TotFF_{ij}[Nut] = \\ = S_i S_j Upt_{ij}[Nut]/(UptTot[Nut] + LossTot[Nut]) \qquad [64]$$

The N_TotFF_{ij} values can be added up to obtain the total filter function of a certain layer or column. Of particular interest may be the filter function of the bottom layer and that of the lowermost column.

A third type of filter function can be defined for the 'edge' of the system., i.e. layer 4 + zone 1 (but avoiding a double count of cell 1.4):

$$N\_EdgeFF[Nut] = S_{k=edge} UptEdge_k[Nut]/(UptTotEdge[Nut] + LossTotEdge[Nut]) \qquad [65]$$

This edge filter function can be partitioned in a horizontal (zone 1) N_EdgeFFH[Nut] and vertical (layer 4) N_EdgeFFV[Nut] component, by sharing the uptake from cell 1.4 over the two in proportion to the cumulative loss in horizontal and vertical direction from this cell.

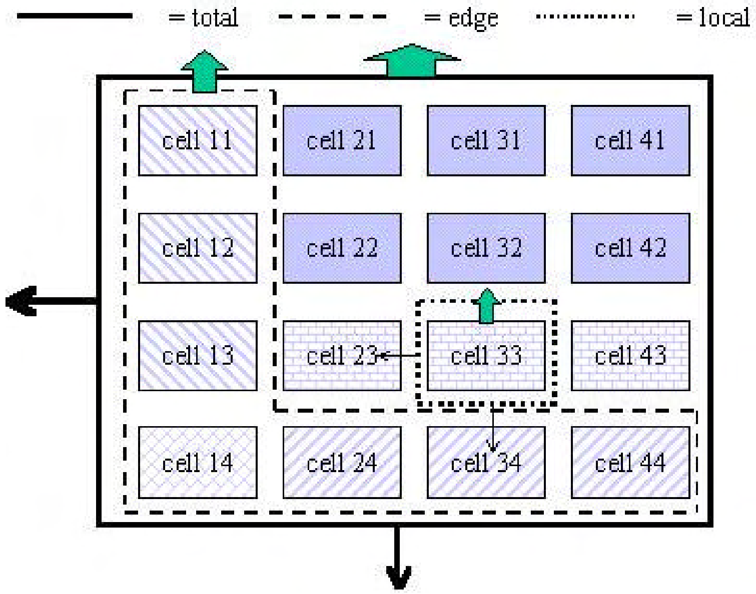


Figure 3.21 Filter functions (or safetynet functions) are defined as uptake/(uptake +loss) at three scales: local (as example here for cell 3.3), edge (uptake from zone1+layer4, net losses from the edge equal net losses from system as a whole) or system as a whole

Chapter 4
Examples of model applications

We first explore a simulation based on the 'default' parameters and see how crops, trees and weed interact and compete for N, P, water and light on a fairly rich soil, recently derived from forest with high rainfall but limited rooting depth due to subsoil acidity.

After that, five examples of model (made with version 1.2) applications are presented here, to test the objective that the model can be applied to a wide range of agroforestry research questions.

Results are not compared to specific data sets and no parameter fitting has occurred. Examples are presented for simulation runs of a simple soil-crop system at different N fertilizer regimes, hedgerow intercropping systems at different hedgerow spacing and pruning regime, a test of the safetynet function of deep tree roots, lateral interactions in crop-fallow mosaics and a first exploration for parkland systems with a circular geometry across a rainfall gradient.

In each example, a list of input parameter changes is provided. These changes are relative to default values. If you have made recent changes in WaNuLCAS and would like to return to default values for a group of parameters, click on undo button (U) at the top of list input device. If you want to reset all parameters to their default values, you can use a button in the "Input" section

4.1 Simulation based on default parameter settings

For a start, the default parameter settings can be used to become familiar with the various types of model output that can be obtained. Figure 4.1 gives the biomass production results for a 'default' run of 2 years duration in which two crops of maize per year are grown in an 'alley cropping' system with trees that are pruned whenever their biomass exceeds a set threshold value. Obviously the second crop in each year produces less biomass than the first crop. In between the cropping periods the hedgerow trees develop a total biomass that reaches about a half that of the crops at about 0.5 kg m^{-2} (= 10 Mg ha^{-1}). There is a little difference between crop growth in zone 2, 3 and 4.

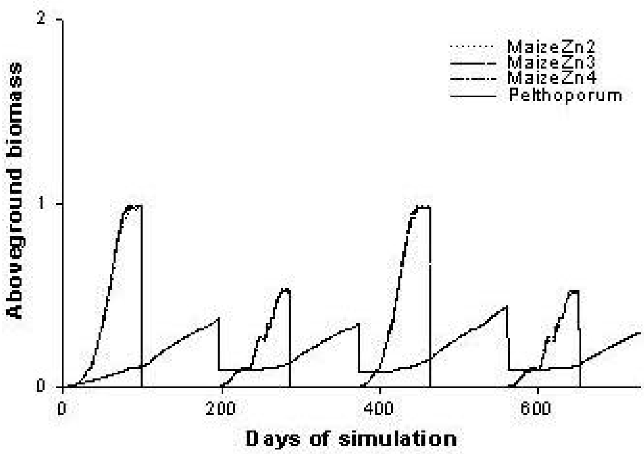


Figure 4.1 Biomass development of crop and tree for a WaNuLCAS 2.0 simulation using 'default' parameter settings

If you click on 'View Water Input Output Summary' you will see results of the water balance. The only inputs of water were due to rainfall directly on the simulated area, as the default slope of 0% stops any Run-On or Lateral Inflow (but not the option of Run-Off). Out of a cumulative rainfall of 4618 mm (i.e. 2309 mm $year^{-1}$), 242 mm was used to recharge the soil (which was initialized below field capacity), 1130 mm drained from the soil profile, 336 mm became surface run-off, 392 mm evaporated from the soil surface, 375 mm evaporated from interception by crop and tree canopy, 875 mm was transpired by the crop and 1269 mm by the tree. The BW_NetBal result of 7 10^{-12} indicates that the error in accounting for all inputs and outputs of water is negligible.

The N balance shows that there has been a considerable net mineralization of N during the simulation, with the SOM_N pools decreasing from 255 to 201 g m^{-2}. Neither crop nor tree fixed atmospheric N_2 and no N fertilizer was applied. The stock of mineral N has increased from 1.1 to 15.2 g m^{-2}, while 20 g m^{-2} was lost through leaching and 16 g m^{-2} was exported with crop harvest products. At the end of the run the tree biomass 5.1 g m^{-2}. The error term of the N balance was -6 10^{-14}.

In the P balance we again see that mineralization of organic P has been the major supply of P to the crop and tree, with the organic P stock decreasing from 25.5 to 20.1 g m^{-2}. In contrast to N, however, leaching losses have been very small, while there has been slight a build-up of mineral P in the sorbed pool, and export in crop products was. The error term of 0.0000 again indicates that there are no problems of consistency.

The 'Filter Function' output sector indicates that overall the agroforestry system has been quite effective in capturing the N and P released from the soil organic matter before it leached out of the profile, with an overall filter efficiency of 70 and 99% for N and P, respectively. A substantial part of this overall filter function was located in the 'Edge': uptake in the fourth layer was 28 and 48% of total output from the 'Edge' for N and P respectively and uptake in first zone 13 and 28%, for N and P respectively, leading to a combined filter effect of 41% for N and 95% for P. The local filter efficiency in layer 3 (relative to leaching and lateral flow losses from each cell) clearly decreased from zone 2 to zone 4, with decreasing root length density of the tree. The filter functions are higher for P than they are for N as the lower mobility of P (relative to N) retards the leaching and increases the P residence time, giving more opportunity for uptake; this effect apparently exceeds the impacts on uptake of a larger diffusive resistance.

The C balance shows again the decrease in soil C during the simulation (2775 to 2230 g m^{-2} or 27.8 to 22.3 Mg ha^{-1}), while total photosynthesis of the tree is half of that by the crop (505 and 1072 g m^{-2}, respectively), most of which was lost in respiration. At the end of the two year simulation, 664 g m^{-2} has been exported from the field in crop products, while the current tree biomass is 125 g m^{-2}.

The error term of the C balance is negligibly small at 2 10^{-12}, while the 'time-averaged C stock' is 2584 g m^{-2} (or 25.8 Mg ha^{-1}).

The 'Yields' sheet specifies the agronomic yields obtained from the system as a whole. Only the maize crops ('Type 2') are counted, as the trees did not (yet) produce any directly usable products. The maize grain yield of 1.86 kg m^{-2} or 18.6 Mg ha^{-1} (5.9, 3.4, 5.9 and 3.4 Mg ha^{-1} per crop, respectively) is quite good.

The financial and economic balance output gives results for the costs (labour and inputs), benefits (crop yields) and net present value of the simulated agroforestry system accumulated over 4 crops of maize for default cost and labour parameters. The profitability of the system tested shows a positive net present value of 3.9 M Rp ha^{-1}. The assumed costs of establishing and pruning the trees is less than half of those directly costed to the crop. For the default parameter settings in the excel sheet, the difference (divergence) between the private and social net present value is small, showing that there is little net impact of taxation and subsidies on the plot level profitability.

4.2 The use of the main switches and changes in crop or tree type

A number of ways exist to further explore the backgrounds of these results and the way limitations by water, N, P and light interact. One method is to inspect the graphs of current limitations in each zone, as provided in the 'Output' section of the model. A second method is to use the main switches on the 'Output' level and try the various combinations of 'no trees', 'no water, N or P' limitations and 'presence of weeds' for the default setting of all other parameters

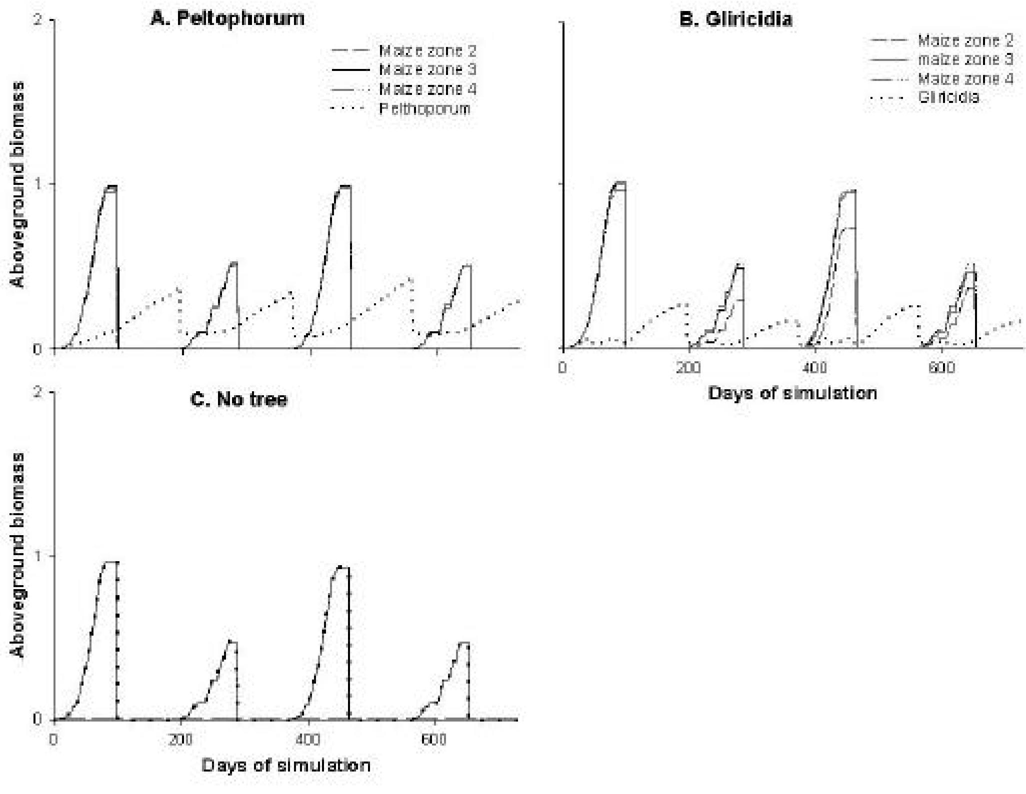


Figure 4.2A...C. Aboveground biomass for a simulation based on default parameters in Wanulcas 2.0 using tree type D(=Peltophorum) or E(=Gliricidia) or none (setting T_GroResInit[Sp1] to 0

Figure 4.2A-K show the biomass results for such runs. Leaving out the tree (comparing Fig 4.2.A and C) does not make much difference for the crop, but changing the tree type from Peltophorum to Gliricidia in the Excel sheet 'Tree parameters' (compare Fig. 4.2.A and B) affects crop growth esp. in zone 2 and 3, while the tree biomass itself shows a different pattern in time. The decrease of total tree biomass during a cropping period is due to pruning and use of internal reserves in the tree.

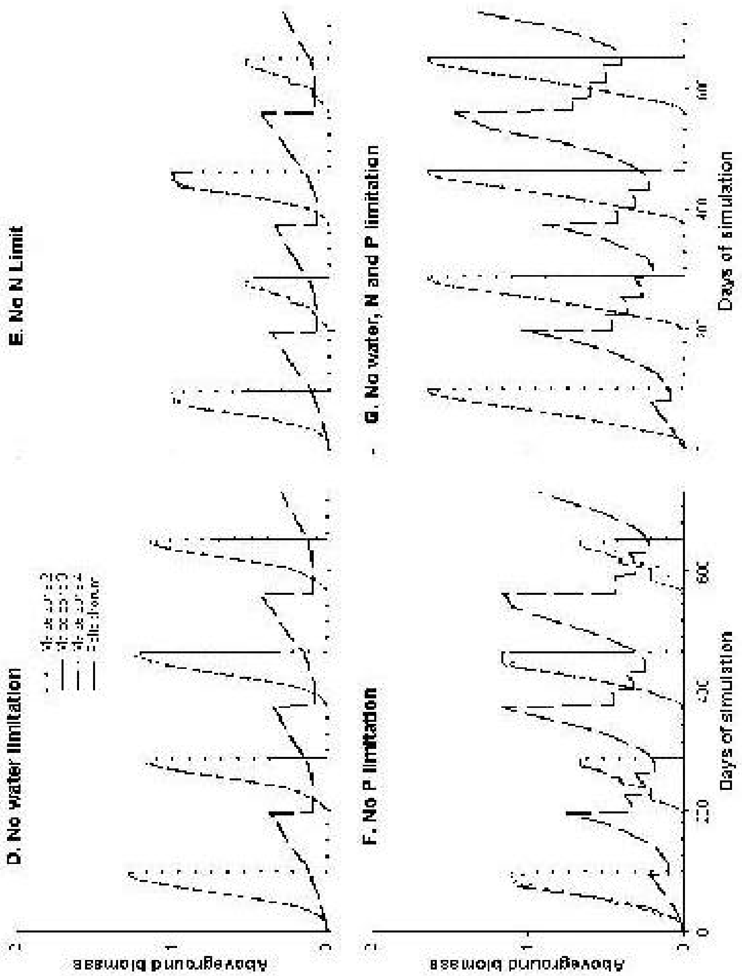


Figure 4.2 D-G indicate that removing the impacts of water limitation has by far the strongest impact on crop growth. Removing the impacts of P limitation has a strong impact on tree growth and of the crops of zone 2 during the second year.

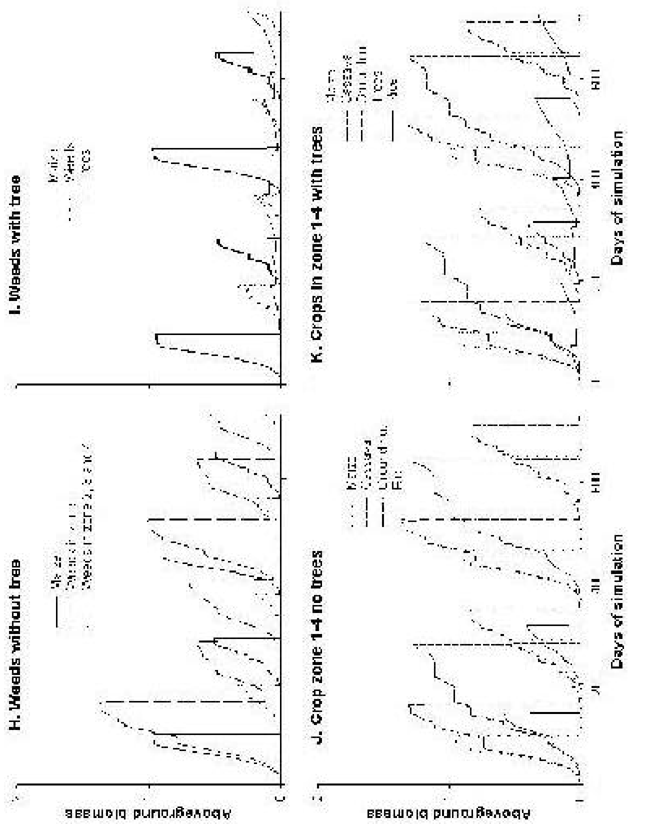


Figure 4.2.D....K. Aboveground biomass for the simple modifications (less than 5 mouse clicks) of the default parameter settings in Wanulcas 2.0; for explanations, see text

Figure 4.2 H and I show the impact of 'weed growth' in default situation with or without a tree. The pattern starts to become fairly complex, as the Cr_Biom output in zone 2...4 alternately refers to a crop and weed, while the weed growth in zone 1 is out of phase with the weed growth in zone 2...4. In Figure 4.2.I, a tree is added to this pattern; note that the tree is not pruned when weeds rather than crops occupy zone 2…4; the tree has some impact on weeds in zone 2, but apparently is not very effective in reducing weed growth, except for those in zone 1.

Figure 4.2 J compare the results for four crop types, each grown in separate zones and each following their own phenological cycle. To obtain this run, return to 'default' settings, set the tree biomass at 0 and change the crop types by zone on the 'crop management' sheet of the excel file. Note that when a tree is added now (Fig. 4.2.K) it will be pruned nearly continuously, as at least one crop will be present in the alleys all the time.

4.3 Crop-only controls with N and P fertilizer

We will normally want to compare agroforestry options with a crop only and/or tree only run for the same soil and climate. As an example we use data for maize growth in Lampung (Indonesia) as inspiration for the default case.

On flat land, in the absence of a tree there is no interaction between the crop zones, so we can simultaneously make runs for three N fertilizer regimes (0, 60 and 120 kg N ha^{-1} $crop^{-1}$), by specifying Cq_Fertweight as 0, 0, 1 and 2 for zone 1, 2, 3 and 4, respectively. The average amount of N fertilizer (in kg m^{-2}) equals (for our zone width of 0.5, 1, 1 and 1 m in zone 1...4, respectively) 3.5/(0 * 0.5 + 0 * 1 + 1 * 1 + 1 * 2) = 1.17 Napp. So to get the target nominal amount of fertilizer applied in zone 3 and twice that in zone 4, we specify Cq_FertAppRate as 3/1.17 = 2.6 kg m^{-2}. For simplicity, we used the same dates and amounts for P fertilizer.

The simulation (Fig. 4.3) was extended to two years, with four consecutive crops of maize. For unfertilized plots, crop biomass development started with a good initial crop (with a total biomass of over 1 kg m^{-2} (= 10 Mg ha^{-1}) and a grain yield of nearly half that value, but yields declined to 20% of the first year's value in year 2. The third crop performed less than one might expect from the soil fertility, but recorded rainfall for the second year of our data series was less than in the other growing seasons (this effect can also be seen in all subsequent runs for agroforestry systems with this data set).

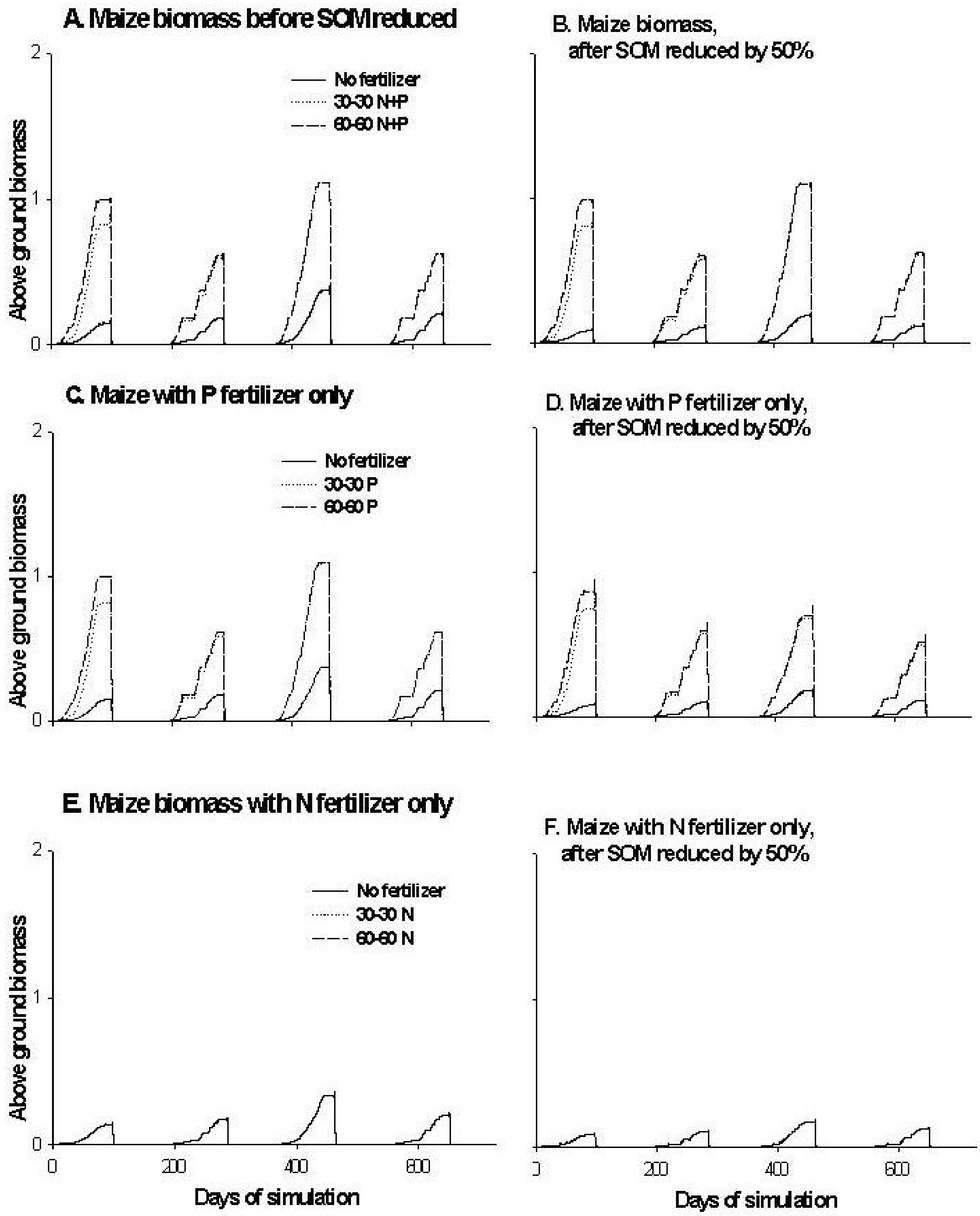


Figure 4.3A...F. Simulated crop development (total aboveground biomass) for maize with a Lampung climate and default parameters (for changes in parameter settings from the default values, see Table 4.1), with or without N fertilizer (at 60 or 120 kg N ha^{-1} $crop^{-1}$, with split application (50% at planting, 50% 30 days later)

Table 4.1 Input parameter modifications from default to generate example 4.3.

Parameter		Location on WaNuLCASInput / Output Section
INPUT New Value		
T_GroResInit	0	Tree Parameters / Initialization
Ca_FertWeight[Zn1] Ca_FertWeight[Zn2] Ca_FertWeight[Zn3] Ca_FertWeight[Zn4]	0 0 1 2	Fertilizer Application
Ca_FertY x axis (Ca_PastFertApp) = 0 1 2 3 4 5 6 7	 0 0 1 1 1 1 2 2	Excel sheet Crop Management
Ca_FertDOY	317, 347, 140, 170, 317, 347, 140, 170	Excel sheet Crop Management
Ca_FertAppRate	2.6, 2.6, 2.6, 2.6, 2.6, 2.6, 2.6, 2.6	Excel sheet Crop Management
Mn2_InitAct[Zn1], …, …[Zn4]	0.074	Soil Organic Mattre / Intial N in SOM Pool
Mn2_InitSlw[Zn1], …, …[Zn4]	0.371	Soil Organic Mattre / Intial N in SOM Pool
Mn2_InitPass[Zn1], …, …[Zn4]	1.45	Soil Organic Mattre / Intial N in SOM Pool

For runs with 50% reduced SOM, Mn_InitAct, Mn_InitPass and Mn_InitSlw were reduced by 50%.

The results show that for these parameter settings crops respond positively to medium (60 kg N ha^{-1} $crop^{-1}$) fertilizer rates from the second crop onwards, but not to higher fertilizer rates. Figure 4.3 C...F shows that some crop response is obtained when P fertilizer applied separately but not for N. The following examples for agroforestry systems are based on this soil+crop system: it starts with a good initial crop, but becomes deficient in N due to leaching losses and crop harvest in subsequent crops. There is thus scope for trees in agroforestry configurations to increase crop yields, in as far as there beneficial effects are not outweighed by competition.

4.4 Hedgerow intercropping: pruning regime and hedgerow spacing

The WaNuLCAS model can predict crop yields in different strips (zones) within the alleys in a hedgerow intercropping system, by making modifications from the default settings as indicated in Table 4.2. The simulations presented here were made will version 1.1 as a first approximation of long term hedgerow intercropping experiments in Lampung (Indonesia); details of the experiments which form the inspiration for these simulations can be found in Van Noordwijk *et al.* (1998a). The 'P trees' have some characteristics in common with *Peltophorum* as we know that in Lampung experiments, while the 'G-tree' simulates *Gliricidia.* (Van Noordwijk, 1996a).

Based on different tree characteristics ('P' and 'G' in Figure. 4.4), the model predicts different pruning frequencies to be applied (one or twice per crop for P and two to three times per crop for G). Compared to the unfertilized Maize series of Fig. 4.1 which we include as 'control', both the P and the G trees can partly alleviate the yield decline over time. Averaged over four crops and expressed on a whole-field basis, predicted crop yields for the P hedgerow intercropping system are slightly below this control crop. Hedgerow intercropping will clearly give increased crop growth in zone 4, where the positive effects of mulch are felt, without much shading. For the P trees, however, zone 3 will drop below the control level in the third crop, and may give a yield similar to that of zone 2.

The overall trend in crop yields is negative for P trees and less so for G trees, as the P system is gradually depleting its N stocks, in the absence of atmospheric N_2 fixation in P trees or maize. In the long term field experiments in Lampung crop yields for the control indeed declined rapidly, but no such yield decline was recorded for the treatments resembling P trees; this raises questions about additional sources of N in the field trials, not accounted for in the WaNuLCAS model (current fieldwork tries to resolve the possible contributions of subsurface flow of N in these experiments).

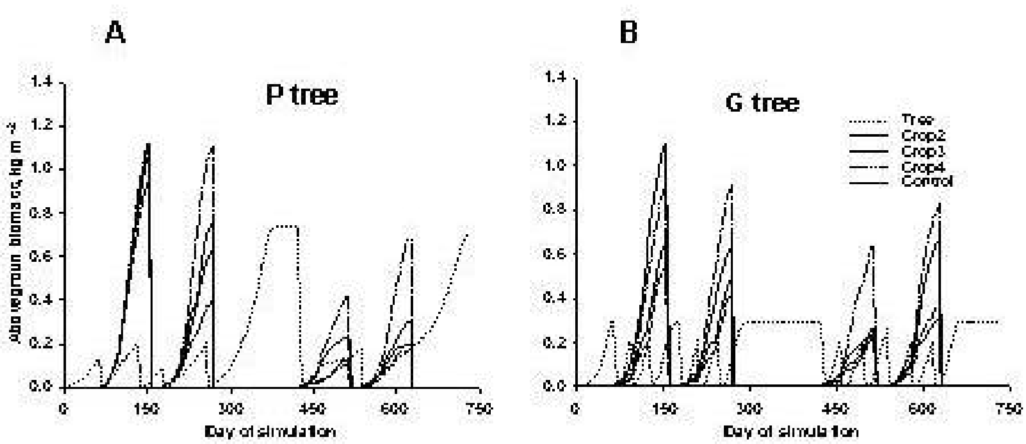


Figure 4.4 Model predictions with Wanulcas 1.2 of development of hedgerow tree canopy and crop biomass (on a whole field basis) over four cropping seasons in two years, for three crop zones (2, 3 and 4) within the alleys (the P and G trees approximate *Peltophorum* and *Gliricidia*, respectively, as used in experiments in Lampung (Indonesia); van Noordwijk *et al.*, 1998a); zones 1, 2 and 3 are 1 m wide each, and zone 4 is making up the rest of the field; soil type, rainfall pattern and potential maize production inputs were derived form the Lampung site

Table 4.2 Input parameter modifications to generate example 4.4 and output parameters to retain.Figure 4.2.

Parameter		Input / Output Section location
INPUT	New Value	
Same settings as above with different AF_ZoneTot	2, 4, 8, 16, 32	Agroforestry zone
Ca_PlantDOY	7, 122, 7, 122	Excel sheet Crop Management
Ca_PlantY	0, 0, 1, 1	Excel sheet Crop Management

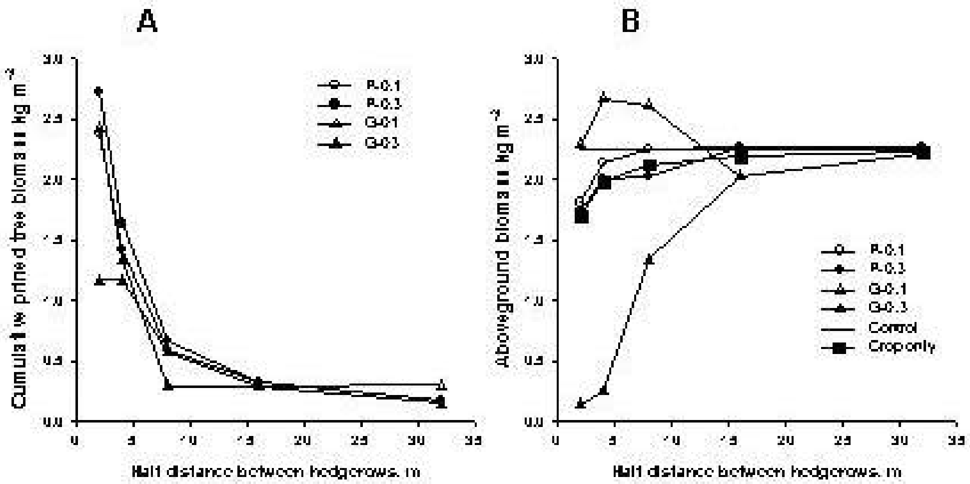


Figure 4.5 Predicted effect on cumulative pruned tree biomass (A) crop biomass at harvest (B) of four crops if the distance between two hedgerows is gradually increased; results are given for P and G trees (compare Fig. 4.2 and two values of the 'prune limit', i.e. the hedgerow canopy biomass at which hedgerows are pruned back (For details see Table 4.2); one control refers to a whole field planted with crops, the other accounts for the space nit cropped in hedgerow intercropping

The G parameterization (wider canopy shape, lower LAI within the canopy, shallower roots, N fixation) leads to crop yields which are substantially below the control yields for the first crop, but which are maintained with time. Although the total average yield for G trees will be similar to that for P trees, it is obtained in a different way. Initially yields are depressed due to the stronger shading effects. From the third crop onwards, however yields in zone 3 as well as 2 will be similar to or higher than those in the control. In the longer run hedgerow intercropping with G trees is predicted to lead to substantial gains over the pure crop control, but this applies to situations where the pure crop control would not have been planted with maize by any sensible farmer. The square shape in the tree canopy data occurs when the tree (leaf + fine branch) canopy reaches its maximum value (determined by canopy size and maximum LAI); further tree dry matter production is then allocated to stem growth and litterfall. Model results for crop yield are sensitive to the pruning regime implemented (the threshold of current canopy size), as well as the initial soil fertility. For well-specified pruning regimes on soils of low-intermediate N fertility, hedgerow intercropping can result in an increase of predicted crop yield. However, there are many parameter situations where negative effects by competition will dominate over positive effects of soil fertility increase. The window of opportunity for positive effects of hedgerow intercropping on crop yields at low soil N supply and adequate soil water supply described by the algebraic shade/mulch model with growing seasons as time step (Van Noordwijk, 1996a) can be confirmed by this model on a daily time step. The algebraic solution suggested an optimum distance between hedgerows with monotone rising and declining functions on either side, the WaNuLCAS model indicates that more complex responses can occur.

If the distance between hedgerows is gradually increased (Fig. 4.3), the various positive and negative effects on crop yield result in a rather complex overall response. The cumulative pruned biomass clearly decreases with increased hedgerow spacing, but differs remarkably little between the two values of the prune limit: the higher frequency of pruning at a low prune limit compensates for the smaller biomass per pruning event.

Narrow hedgerow spacings obviously reduce crop yields below the control value, especially for G trees with a high prune limit (infrequent pruning). For G-0.1 (frequently pruned, as in Fig. 4.2), an intermediate hedgerow spacing (8 to 16 m between hedgerows, leading to a half-distance of 4 - 8 m) can lead to a 10% yield benefit (and expected stronger benefits in later years). At wider spacings, however, predicted yields drop below the control value for G trees, as the loss of yield in zone 1, 2 (and 3) is not compensated by the benefits from the mulch in zone 4. A consequence of the way the prune limit is ex-pressed (as tree biomass per unit field area), is that at wider spacing the biomass per m of hedgerow in-creases, and hence the negative effects on adjacent zones. As second type of control' yield we included in Figure 4.3 the field-level yields if we simply account for the fact that there are no crops in zone 1.

The P trees with a high prune limit (P-0.3) give yields close to this second type of control at all hedgerow spacings, suggesting that under the conditions of the simulation positive and negative effects balance. The P trees at lower prune limit (P-0.1) give a slight advantage when compared to this control, but do not exceed the whole-field control.

Further exploration of pruning criteria (on a per tree rather than per area basis) will be desirable. In earlier runs with a higher nitrate fraction in the mineral N and hence a higher N leaching rate the P trees gave overall positive effects, as their relatively deep root system is apparently of more value under such circumstances.

In contrast to Fig. 4.2, the results of Fig. 4.3 can not be compared with any existing experiments we know of, as hedgerow spacing has seldom been systematically evaluated in hedgerow inter cropping experiments. The pattern predicted here is more complex at wider hedgerow spacing than the simple 'shade and mulch' model of Van Noordwijk (1996b), which did not consider spatially zone effects (which matter especially at wider spacing).

4.5 Hedgerow intercropping: safety-net function of tree roots

The WaNuLCAS model can be used to estimate the tree root length density in the subsoil required for efficient functioning of a safety net. A practical definition of the safetynet efficiency is the tree N uptake from the soil layers considered, as fraction of total output from this layer by leaching plus uptake. An additional output variable had to be created to capture this parameter.

WaNuLCAS calculations (Cadisch *et al.* 1997) (using verison 1.1) where tree root length density in the subsoil was varied over the 0 - 2 cm cm^{-3} range indicated that about 25% of the N leaching below the crop roots can not be recovered (for the soil, climate and tree parameters used) by hedgerow tree roots as it occurs at times that the tree have no current unsatisfied N demand. A nearly linear increase was predicted in safetynet efficiency (tree N uptake from the soil layers considered, as fraction of total output from this layer by leaching + uptake) between a tree root length density of 0 and 1 cm cm^{-3}. The model thus predicts that under conditions of continuous leaching a substantially higher tree root length density is needed than what would be adequate for near complete N uptake without a rainfall excess (Van Noordwijk, 1989; De Willigen and Van Noordwijk, 1987). Further data are currently collected from trials in Lampung (Rowe *et al.*, in press), which can test these model

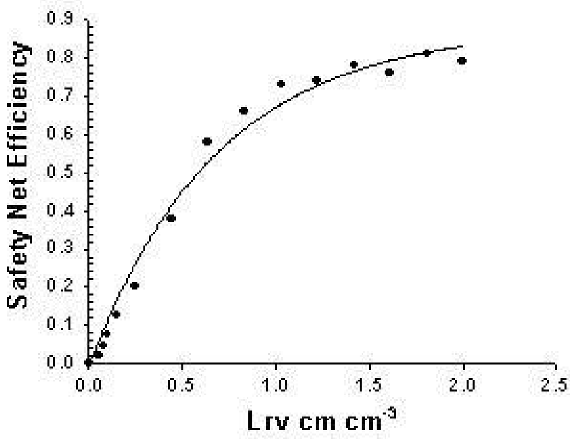


Figure 4.6 Use of the WaNuLCAS model to estimate the tree root length density in the subsoil required for efficient functioning of a 'safety net' (modified from) Cadisch *et al.* (1997); model runs were made with an N adsorption constant Ka of 0.2, reflecting a nitrate-dominated situation as can be expected at high soil pH values

4.6 Tree fallow - crop rotations

The WaNuLCAS model can also be parameterized for simulating crop yields on small farms where part of the plot is currently under a tree fallow (such as the *Sesbania* fallows currently tested in Southern Africa), and other parts are cropped. The crop-fallow mosaic will not be drastically different from a hedgerow-intercropping situation: the spacing between hedgerows is wider, hedgerows are replaced by broader zones of tree growth and the pruning regime is modified, but otherwise the processes of tree-soil-crop interactions are the same.

Parameters modification needed to simulate the system are shown in Table 4.3. The simulation requires two runs in which output from 1st run becomes the input of 2nd run. Notice also that output values from tree zone should become the input values in crop zone and vice versa. In general output from tree zone automatically becomes input for crop zones while weighted average of output from crop zones becomes input for tree zone. Here is an example of how to do that for initial N in 1st soil layer.

For tree zone:

N_Init1[Zn1] = (AF_Zone[Zn2]*N_Soil1[Zn2]+AF_Zone[Zn3]*N_Soil1[Zn3]+F_Zone[Zn4]*N_Soil1[Zn4])/(AF_Zone[Zn2]+ AF_Zone[Zn3]+ AF_Zone[Zn4])

For crop zone:

N_Init1[Zn2] = N_Init1[Zn3] = N_Init1[Zn4] = N_Soil1[Zn1]

During the first cycle (4 crops in zone 1 and 2), crop growth in zone 4 (Fig. 4.5) is similar to that in the crop-only control without fertilizer shown in Fig. 4.1. The second cycle, on land fallowed during phase 1 is similar to the first, suggesting that with a 1:1 ratio of fallowing and cropping yields can be maintained from one cycle to the other, for the conditions of the simulation. The soil organic matter pools are increased during a fallow period (in the model mainly by litterfall, which is supposed to be mixed through the upper soil layer by abundant faunal activity) and depleted during cropping. The model predicts that there will be substantial 'border effects' of the fallow on neighbouring crop land, not only caused by shading (zone 2) but also by root competition (zone 3).

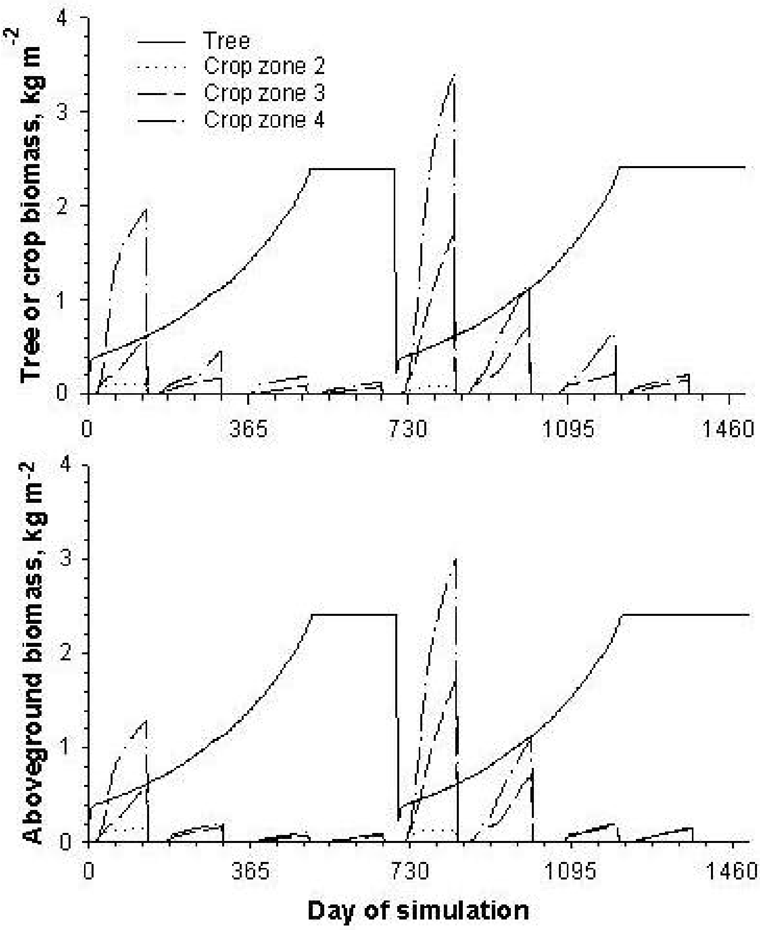


Figure 4.7 Predicted development of a tree fallow vegetation as well as the simultaneous yield of crops with increasing distance to this fallow plot, over two cycles of a two year fallow and 2 years of cropping (4 crops/ cycle); A. tree root length density decreases by a factor 0.6 from zone 1 to zone 2 and again from zone 2 to zone 3; no tree roots in zone 4; B. Tree root length density in zone 2 and 3 is equal to that in zone 1, but there are no tree roots in zone 4

Table 4.3 Input parameter modifications from default to generate example 4.4 and output parameters to retain.

Parameter for 1st run		Location on WaNuLCAS Input / Output Section
INPUT	**New Value**	
AF_Zone[Zn1]	10	Agroforestry Zone
AF_Zone[Zn2]	2	
AF_Zone[Zn3]	3	
AF_ZoneTot	20	Agroforestry Zone
Cq_PlantYear (graphical input) x axis (Cq_ComplCrop) =		Crop Calendar
0	0	
1	1	
2	1	
3	2	
Cq_PlantDoY (graphical input) x axis (Cq_ComplCrop) =		Crop Calendar
0	340	
1	90	
2	340	
3	90	
T_CanHMax	5	Tree Growth
T_CanWidthMax	12	Tree Growth
T_PrunPlant?	0	Pruning
T_PrunDoY (graphical input) x axis (T_PrunPast) =		Pruning
0	364	
T_PrunYear (graphical input) x axis (T_PrunPast) =		Pruning
0	1	
T_PrunLimit	100	Pruning
OUTPUT	Remarks	
Mn_ActSZone]	Use values at the end of run as initial values for the 2nd run	Table 1 page 2
Mn_SlwS[Zone]		
Mn_PassS[Zone]		
Mn_StrucS[Zone]		
Mn_MetabS[Zone]		
N_Soil*i*[Zone]		
W_Theta*i*[Zone]		

The WaNuLCAS model may offer the first opportunity to consider crop-fallow mosaics as a coherent system, in stead on only regarding the sequential effects on plots which are supposed to be spatially isolated. The models may stimulate a renewed research attention on border effects in crop-fallow experiments, as no published data exist on the topic. Substantial border effects of teak (*Tectona)* stands in Java (Indonesia) were described in the 1930's (publications of Coster, reviewed in Van Noordwijk *et al.*, 1996), and these were larger than what WaNuLCAS predicted for the parameters in Fig. 4.5. Unfortunately, no tree root length densities are known for these (or similar) teak stands. Border effects in crop-fallow mosaics make that the overall effect will depend on the scale (absolute plot size) and not only on the crop: fallow ratio.

4.7 Contour hedgerows on sloping land

Figure 4.6B gives initial results for a contour hedgerow system on sloping land, cumulated over four crops. Model comparisons were made to separate the terms of the general tree-soil-crop interaction equation (Chapter 1), but adding two effects of slope: 1. topsoil can be redistributed from the upper to the lower part of the alley, forming a terrace, but exposing crops in the upper alley to subsoil with a lower organic matter content, 2. Water will be re-distributed by run-off in some zones and run-on in others. If we follow the lines in the figure from left to right, we see that the effect of not growing crops on the space reserved for hedgerows is negative, but that the uneven water infiltration can make up for the yield loss in the humid series (it reduces N leaching from the crop zone). Considering a regularly pruned hedgerow on the contour instead of a bare strip has a moderate positive effect on crop yields, but terrace formation has a negative effect on yields. For the sub-humid series all effects are weak, and no treatment combination can make up for the space lost to make the contour strip. The results per crop zone (Figure 4.6C and D) contain some surprises, as they show a range of patterns between crops: for some crops the middle of the alleys gives the highest yield, for others the lower alley, or even the upper alley. Although all types of patterns can be observed in real-world experiments, it is surprising that the balance of positive and negative interactions can, apparently, change so easily in the complexity of the WaNuLCAS model. stride for prominence. Further model validation is necessary before any soil, climate, tree and crop specific model predictions should be seen as more than 'interesting hypotheses'

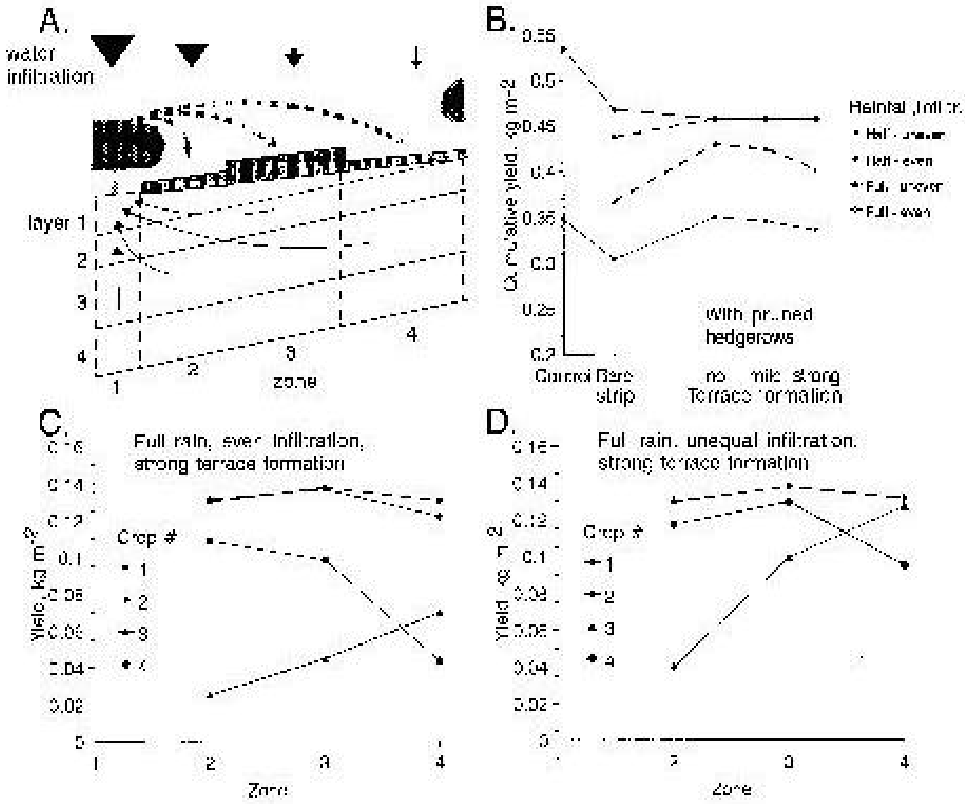


Figure 4.8 Calculations with the WaNuLCAS model (Van Noordwijk and Lusiana, 1999) of crop yield in a contour hedgerow system on sloping land; *A*. Model scheme for applications on sloping land; *B*. Cumulative yield over four crops (2 years) for a humid (3 000 mm/year) and sub-humid (1 500 mm/year) climate, with and without uneven infiltration of rainfall over the respective zones; *C*. and *D*. results per crop and zone

4.8 Tree-soil-crop interactions across a rainfall gradient

To further explore the sensitivity of the model a series of calculations was made for an agroforestry system with scattered trees and crops growing on all land except for a circle directly around each tree (Fig. 4.7).

For these runs the soil profile consisted of four layers (15, 15, 50 and 30 cm thick, respectively) and had a sandy texture (61% sand, 11% silt, 28% clay) and a bulk density of 1.3 Mg m^{-3} and thus had a rather low waterholding capacity according to the pedotransfer function. Calculations were made for five climate zones, based on random daily rain events with a set monthly average and daily rainfall probability of about 20%. The five climates consisted of:

- annual average 240 mm (1 month of 30 mm, followed by 3 months of 60 mm and 1 month of 30 mm; in practice the average was 285 mm for the runs presented here),
- annual average 450 mm (1 month of 75, followed by 3 months of 100 and 1 month of 75 mm; in practice the average was 525 mm)
- annual average 1000 mm (1 month of 125, followed by 5 months of 150 and 1 month of 75 mm; in practice the average was 937 mm)
- annual average 1500 mm (10 months of 150 mm; in practice the average was 1645 mm)
- annual average 2400 mm (12 months of 200 mm; in practice the average was 2285 mm).

As the same starting value was used for the random generator, all runs for different agroforestry systems in a given climate were made with the same daily rainfall pattern. The simulation run was 2 years, and two crops were grown per year for the 1500 and 2400-mm rainfall zone. Simulations for pure crops (covering the whole field) were compared with those of trees only (unrestricted tree growth) or agroforestry systems were trees occupied the inner circle and crops the remainder of the land. The trees were pruned at sowing time for each crop, and a second time during the crop if their biomass exceeded a set value of 0.2 kg m^{-2} (averaged over the whole field). For comparison a set of simulations was included where the tree was pruned in the same way as in the agroforestry system, but where no crop was grown. Four variants were considered for the agroforestry system, indicated by 'narrow', 'medium', 'broad' and 'very broad' tree canopies with a crown diameter of 1, 2, 3 or 4 quarts of the diameter of the whole system. Note that all zoning is relative to tree size and no absolute distances have to be specified. Tree root length density was 2, 1.5, 0.6 and 0.2 cm cm-3 for the four depth layers directly under the tree, respectively, and 0.6, 0.36, 0 times that value in the three other zones, respectively; thus tree roots were confined to a circle of 3/4 the total diameter. The tree was able to derive 40% of its daily N demand by atmospheric nitrogen fixation and tree N could be transferred to the crop via litterfall and tree prunings, based on a gradual N mineralization. The crop was supposed to have a 98 day duration and a rather shallow root system, with a harvest index under non-limiting conditions of 41%. No N fertilizer was used.

From the simulation results we focus here on grain production (actual harvest index was between 36 and 41%), stem wood production for the tree (treating crop residues, litterfall, pruning and current tree canopy as intermediate components of the system). The simulation involved a gradual shift from water to nitrogen as the major factor limiting crop production. At high rainfall the total N supply in the soil was effectively exhausted by the first crop in the pure crop control and the three following crop yields were low. Under these conditions the agroforestry system could increase crop yield (by up to 8%), by supplying at least some N for the later crops, thus compensating for the area without a crop and competition effects on crop growth. The medium tree canopy shape (2/4) gave the highest crop yield of all agroforestry systems in the three wettest climates. For the simulations at 450 and 240 mm rainfall, crop yields were reduced in agroforestry by 11 and 35% respectively, as competition for water dominated over positive effects on N supply; at 450 mm the four agroforestry systems gave equal grain yields, while at the 240 mm run, the narrow tree morphology was best. In contrast to grain yield, wood production was always higher in the pure tree system than in the agroforestry system. The narrow tree morphology produced more wood, as it invested less resources in a leaf + fine branch canopy.

Total yield for the agroforestry system can be calculated if the value of wood can be expressed relative to that of grain. In Fig. 4.7 a 1:4 ratio is used. In the driest simulations there is agroforestry system will reduce total yield, while the curve for the 450 mm zone is nearly flat (and a slightly higher or lower relative value of wood (or other tree products) could shift the balance). For the three wettest climates the positive effects of agroforestry on grain yield are accompanied by additional wood production and agroforestry is superior, unless the relative value of wood is at least 50% higher then we assumed here. The additional production of agroforestry is based on a more complete use of water: the fraction of rainfall draining from the profile is substantially (about 15-20% of rainfall) reduced by the tree - crop combination, while model results for soil evaporation losses are intermediate between pure crop and pure tree systems

The share of the crop in total transpiration was always around 50% and peaked in the 1000 mm rainfall situation. Crop water use efficiency was highest at the driest site, as N limitations reduced it in wetter zones. For the tree water use efficiency was not effected by climate as its N fixation was not limited by drought.

As a whole, model calculations may present a reasonable correspondence with real world options, although no experimental data sets exist on the same agroforestry system at the same soil but widely differing rainfall conditions. Any of the effects mentioned here would vary with parameters such as soil depth, soil texture, tree canopy characteristics and rooting pattern or crop root length density, but the basic pattern of response to climate zones would remain determined by overall resource availability. Model results agree with conclusions about the perspective of simultaneous agroforestry systems from experimental evidence (Rao *et al.*, 1997; Breman and Kessler, 1997). Mobbs *et al.* (1998) and Cannell *et al.* (1998) came to similar conclusions on the basis of the HYPAR model, which gives a more detailed treatment of aboveground processes and a similar, but less elaborate treatment belowground.

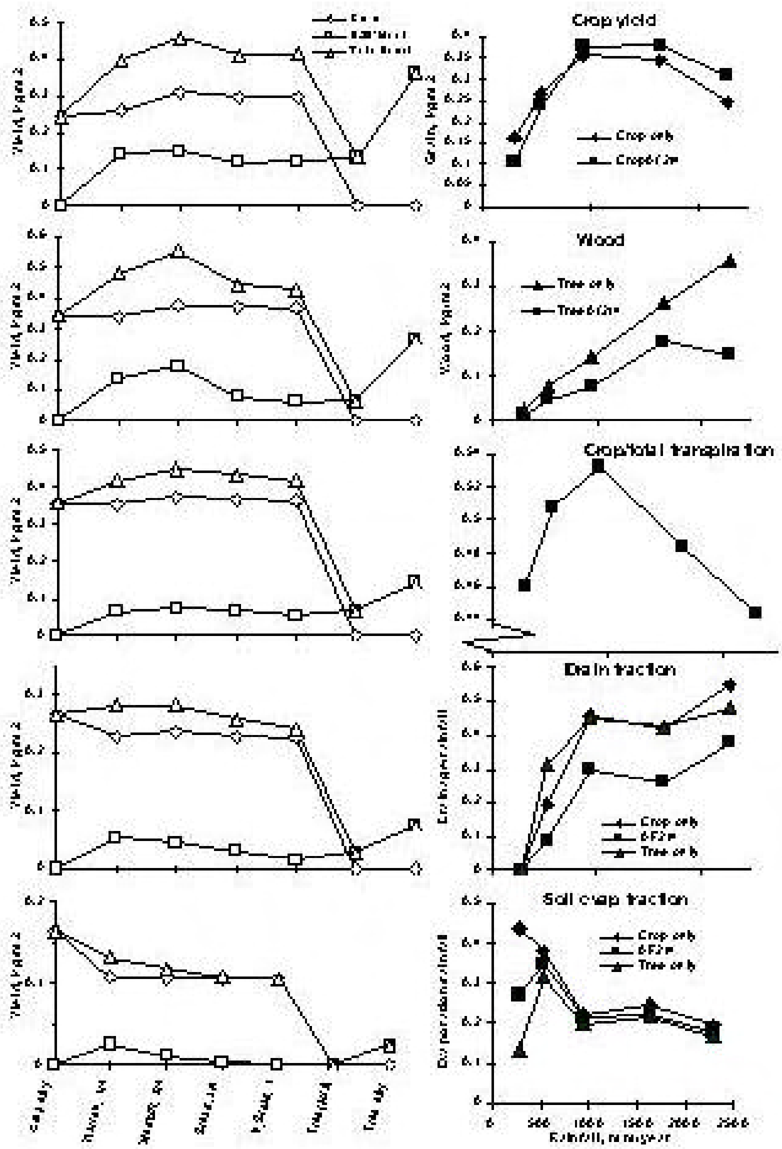


Figure 4.9 Calculations with the WaNuLCAS model of grain and wood production and water use for a range of annual rainfall conditions in an agroforestry system with isolated trees which are pruned when a crop is sown, resembling an early stage of a parkland system; production is accumulated over 2 years, involving 4 (at 2285 and 1645 mm/year) or 2 crops of 98 days duration, on a sandy soil with limited N mineralization from soil organic matter (for main parameter settings see text)

4.9 Model parameter sensitivity for P uptake

The predicted P uptake for both tree and crop (Fig. 4.8A and B) respond to changes in root length density (Lrv) and mycorrhizal parameters and initial soil P content as one might have expected, with mildly negative responses to increased effective root length density by the other partner (tree or crop). The model's sensitivity indicates that reasonable estimates of effective root length density will be essential for a 'process-based' model. When rhizosphere modification is included (Fig. 4.8C and D) , the results point to a clear effect of the synlocation parameter in deciding whether the net effect for the crop of trees with P mobilizing properties will be positive or negative.

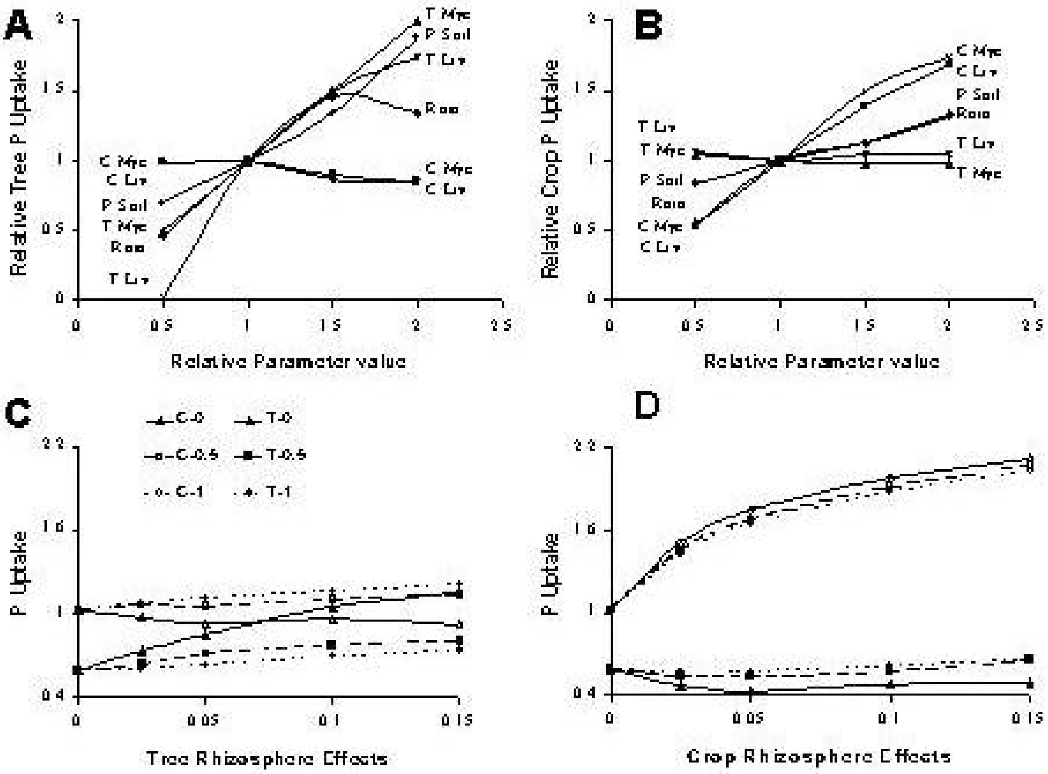


Figure 4.8 Preliminary calculations with the WaNuLCAS model after incorporating a P balance. **A** and **B** Sensitivity of predicted P uptake by tree (A (and crop (B) to changes in parameters for root length density T_Lrv and C_Lrv, respectively), mycorrhiza (C_Myc and T_Myc), soil P content (P_Soil) and rainfall. **C** and **D**. Effect on P uptake by tree (T) and crop (C) of rhizosphere modification by the tree (C) and crop (D), depending on the synlocation parameter (0 = only plant modifying rhizosphere benefits, 1 = benefits shared on basis of root length density)

Chapter 5
Discussion and desired future developments

5.1 Comparison of WaNuLCAS and SCUAF

The Soil Changes Under Agro-Forestry (SCUAF) model (Young and Muraya, 1990; Young, 1997; Young et al. 1998) aims at predicting the effects of land use under given climate conditions on soil loss and medium term productivity. The model is essentially based on a soil organic matter model coupled to a modified Universal Soil Loss Equation for predicting net sediment loss. Land uses in the agriculture – agroforestry – forestry continuum are treated first of all as a weighted sum of their agriculture and forestry proportions, with a user-defined option for introducing specific agroforestry effects on soil conservation beyond the proportional tree cover. The model thus does not **predict** agroforestry effects, but allows the user to study the long-term consequences of a range of **assumed** effects, as they relate to the spatial pattern of the trees. Competition between tree and crop is based on a user-specified degree of spatial mixing of their root systems, but as the model runs with a time step of 1 year, interactions for water are ignored and nutrient competition is supposed to be independent of soil water contents. The soil organic matter sub-model does not include effects on clay and silt in partly stabilizing soil organic matter (as most current models do) and thus predicts that 'labile' carbon can be reduced to virtually zero in a time frame of 15 years. The linkage of crop productivity to changes in soil depth and soil organic matter is based on user-defined functions, not on representation of underlying processes.

The use of the USLE gives the impression that erosion can be assessed independent of scale and expressed as kg ha^{-1} $year^{-1}$, without specifying where the sediment goes and whether or not it can be used for plant production at sedimentation sites. The SCUAF model shares this approach with the majority of erosion assessment tools, but future progress is expected to come from models which consider both erosion and sedimentation and their impacts, considering scale dependence and the landscape mosaic in which land use takes place.

The SCUAF model is sufficiently flexible that the model user can produce a wide range of results, reflecting initial assumptions and expectations. One may wonder, however, if this flexibility is not too high – especially if the model is used without access to empirical data and where model outputs are used for financial and economic evaluations with considerable implications for policy. Does the computer model give too much status to what are essentially unsubstantiated assumptions? One cannot blame a model for the way it is used…

The WaNuLCAS model differs in scope, time-step and approach. WaNuLCAS does not in its current form predict soil movement, but can be used to evaluate the impacts of heterogeneity in topsoil and soil organic matter content in a zoned agroforestry system. Impacts are based on daily interactions for below- and aboveground resources. It may be possible to derive the 'agroforestry effect' parameters which SCUAF needs as input, from outputs generated with WaNuLCAS.

5.2 Desired future developments in WaNuLCAS

The WaNuLCAS model is now in a testing stage, with the experiments described by Rowe *et al.* (1999) as the most critical test so far. Testing the water balance model will be possible especially for data sets where the water flow in vertical and horizontally oriented roots has been measured separately (Howard *et al.*, 1997; Lott *et al.*, 1996).

The model can be further developed in many directions and choices will gave to be made.

Options include:

- Further refining the N balance differentiating between NH_4^+ and NO_3^- with a dynamic nitrification function and uptake preference, adding nitrous oxide emissions,
- Further elaborating the options for tree canopy development based on fractal branching (Van Noordwijk and Purnomosidhi, 1995),
- *Idem* for roots,
- Improving the description of nutrient remobilization before leaf fall.
- Improving the dynamic description of erosion and sedimentation processes, leading to a gradual process of terrace formation,

- Improving the slash and burn module to include the production of particulate matter as source of haze,
- Improving the description of weed growth especially during a cropping episode.

A number of processes is not yet represented in the WaNuLCAS model and may have to be included in future to make the model more realistic:

- crop failure to germinate and crop death induced by severe drought,
- temperature effects on crop and tree performance,
- maintenance respiration for woody parts of the tree,

The treatment of canopy structure and light interception may be reasonable as a first step in the tropics with a predominantly vertical light orientation, but would have to be modified for temperate zone applications where orientation becomes more important. More detailed models exist which could provide inspiration for this step (Sinoquet *et al.*, 1997; Mobbs *et al.*, 1998).

The main improvement needed probably is to further link the model to existing databases of parameters and to provide outputs of the simulations in terms that are easily understood. For example, in the context of the Alternatives to Slash and Burn (ASB) program a systematic effort is made to evaluate land use systems, including agroforestry options, on their impacts on local, regional and global concerns. This assessment includes a number of criteria that WaNuLCAS can provide, once a technical specification of the system is given and the properties of soils, crops, trees and climate are specified: profitability, agronomic sustainability, watershed functions, carbon stocks and greenhouse gas fluxes are included in or can be derived from processes represented in the WaNuLCAS 2.0.

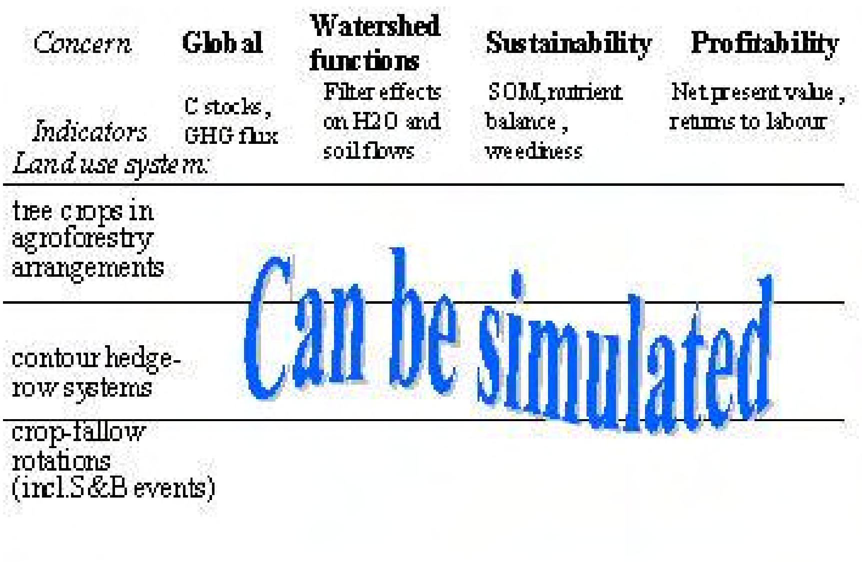


Figure 5.1 The WaNuLCAS model may be used to compare global, regional and local impacts of a land use system, to fill in the land use matrix used in the Alternatives to Slash and Burn project (Tomich *et al.*, 1998ab)

To increase the user-friendliness of the model, WaNuLCAS should be more easily linked to existing databases of tree, soil, climate and crop parameters.

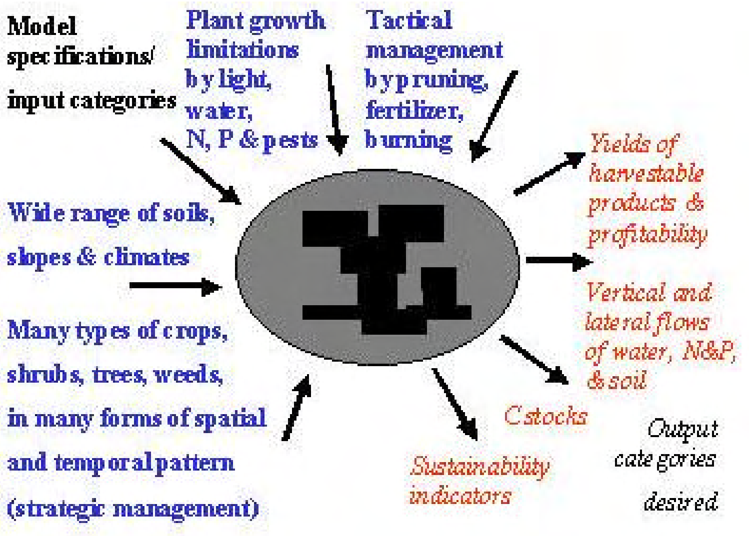


Figure 5.2 The model as input-output converter, taking in data on soils, climate, crops, trees and management and producing predicted impacts on local, regional and global concerns

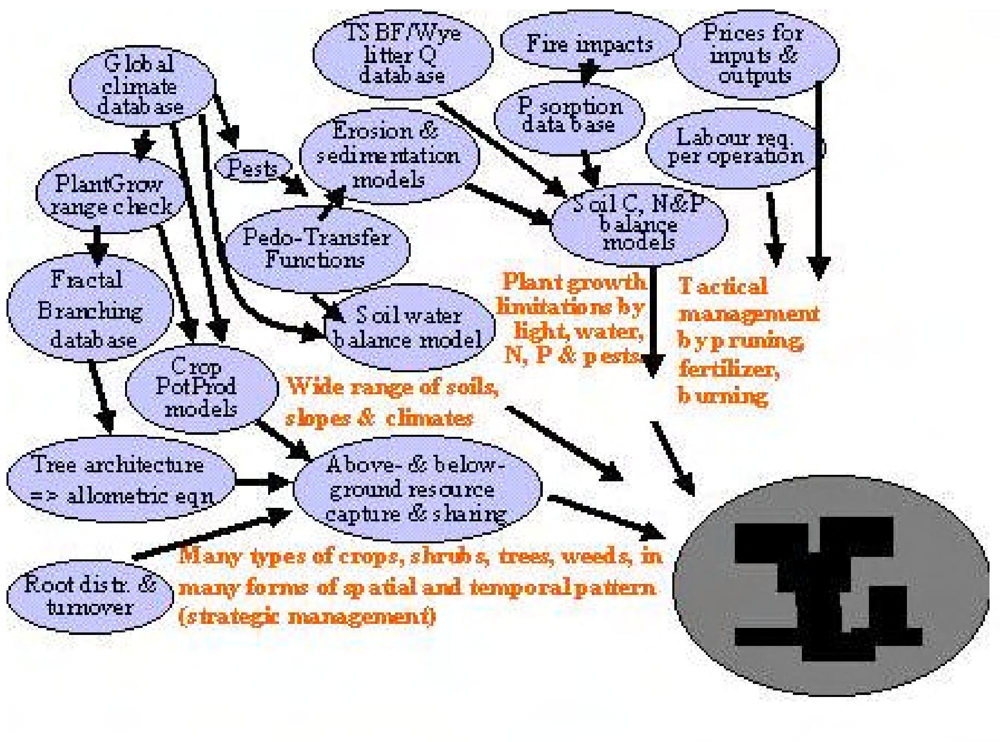


Figure 5.3 Elaboration of the input requirements for WaNuLCAS and the way it can be linked to existing databases or requires databases yet to be developed

5.3 Integrating WaNuLCAS into agroforestry training and education

During the development phase of WanuLCAS a number of training courses were organized, that provided valuable feedback on the current state of the model, as well as hopefully helped participants over the threshold of using the model for their own purposes. A typical course program has been:

Program of 5-day course on agroforestry modelling

requirement: classroom with at least 1 computer per 2 participants; manuals and software

Day 1 morning: opening ceremony (as required/desired by local standards), introductions of participants, introductory lecture (PPT file on all computers), scoping of expectations of agroforestry models, their use and program of this course.

Day 1 afternoon: use of STELLA to make a simple model of a crop-fallow cycle, involving a single pool ('soil fertility'), two flows (an outflow during cropping and an inflow during a fallow phase) and a couple of converters (parameters) - see appendix 1 of the WaNuLCAS manual.

Excercises with the CDFU (crop down, fallow up) model that uses the core equation just developed in a landscape (100 field) context, and allows participants to modify a number of key parameters and see a range of performance indicators.

Day 2 morning: explore the WANuLCAS.XLS excel workbook with different categories of parameters (weather, soil water, soil phosphorus, crop, tree) to see what type of pre-processing of parameters is needed for the model and what type of databases are required to use a model for a specific climate-tree-soil-crop situation.

Exploring the WaNuLCAS.STM stella model to make simulation runs for the default and modified parameters. Learning to use the manual for looking up definitions of parameter names, and to read the graphs, forming hypotheses about cause and effect of tree and crop growth and checking them out by considering other outputs.

Day 2 afternoon: following the examples in section 4 of the manual and try to reconstruct a number of case studies by modifying parameters as indicated in the tables.

Demonstration of the HYPAR model and its users interface.

Scoping for ideas of participants for new case-studies they would like to develop as a 'mini-project' in the coming days, grouping participants with related interests. The instructors have to use judgement in what is feasible among the proposals made.

Day 3 morning: developing an outline for the various mini-projects, by relating a real-world agroforestry system to a set of issues that need research attention, and formulating specific objectives for the modeling effort. Based on these objectives, choices about model structure and parametrization can be made. Reporting the progress in each miniproject to the whole group and allowing for re-grouping of participants if desired. Some groups may use the existing CDFU, WaNuLCAS or HYPAR model with a new parametrization, others may try to add some model structure, or start a completely new 'simple' model.

Day 3 afternoon + day 4 - work on model development as well as documentation of results, with inputs from instructors as requested by the group; compare the strengths and weakness of approaches based on 'modifying an existing model' with 'starting from scratch'.

Day 5 morning: final preparations of group reports using computer presentation methods, and plenary presentation and discussion of all mini-projects (inviting some interested parties not directly involved in the course); followed by general remarks and reiteration of points from the introductory lecture, including use and mis-use of models in the research - development - policy continuum.

Day 5 afternoon: evaluation of the course and round table discussion on the way forward, how to keep contact, work on more serious versions of the model applications tried here, etc., as determined by the interests of participants; closing ceremony as determined by local customs.

A ***seven-step*** approach to a new model application:

1) Start with **description and analysis of a 'real world' problem**

- what type of agroforestry system?
- which aspects are of interest to farmers, or outside stakeholders?
- what questions do we have about these aspects that cannot yet be answered satisfactorily?
- how are these questions (possibly) linked?
- are trade-offs between components of the system likely?
- which questions will form a good starting point?

2) Formulate **objective(s) for the modelling excercise** derived from the most relevant questions, translated to a quantifiable form; decide on ***'performance indicators'*** that will be used to chararcterize the results, the '***external determinants'*** (e.g. soil properties, weather, prices, properties of the tree and crop components) and the ***'management options'*** that you want to consider (e.g. planting density and spacing of the various components, calendar of crop and tree management, fertilizing, pruning etc.) - the model should be sensitive to the way the real world system responds to them.

3) What **model structure** will we need to represent the real world agroforestry system in view of the objectives, can we start with an existing model (e.g.; WaNuLCAS or CDFU), do we have all 'performance indicators' available as output? do we have 'management options' represented? If not can we add them?

If you decide to 'start from scratch', the Stella environment allows you to first put elements of your model on a screen and gradually work out relations between them It may help to start with defining 'converters' with the names of the 'performance indicators' you want somewhere on the right of the screen, converters with the main management options you want to include on the left and external deperminants on the top or bottom of the screen. In the centre you define stocks representing the major components of the system (e.g. one labeled *tree*, one *annual crop* and one for *soil water*) with inflows (e.g. growth, rainfall) and outflows (e.g. harvest, uptake). Then you work out a link between the changes in these stocks and the various types of converters. The last step is to specify quantitative forms for these relations, by using equations or graphical sketches. The model structure is in fact a ***hypothesis*** about the way the real world works.

4) Decide on **model parameters** - where can we derive data for the climate, soils, crops, trees, prices and management parameters we want to use in the simulation? Can we modify existing parameter files (e.g. for 'similar' crops) to derive the ones we need? A model plus parameters will act as an ***experiment*** - if the outcome of the model is unrealistic, it tells you there is something wrong with your hypothesis (model structure), with the input parameters you used, or with your perception of what is 'realistic'....

5) Link model structure and parameters and make **simulation runs**

6) Analyze the **results** and especially relate the 'performance indicators' to the relevant range of 'management options' as specified in the 'objectives'.

7) Perform a **reality check** on the results and **discuss** the way the results obtained ware related top the assumptions made; does the model have 'emergent' properties, not directly obvious from the way you defined the model components? Are model results likely to be of interest to stakeholders? Can they be presented attractively?

Appendix 1
Introduction to STELLA

STELLA is a flowchart-based modelling software. It enable users to construct model by drawing boxes, circles and arrows. **STELLA** is similar to ModelMaker.

During this session you will learn to build a model, step by step using **STELLA**. The purpose of this session is to familiarize yourself with **STELLA** and to learn how to use basic features of **STELLA** for simulation modelling.

Initiating **STELLA**

Start **STELLA** by clicking on its icon on the window screen. You will be automatically inside a new file.

STELLA is a multi-level hierarchical environment. It consist of 3 layers:

(1) the High Level Mapping Layer; which contain input output relationship
(2) Model Construction Layer; where you construct the model
(3) an Equation View; to view list of all model elements and relations

Move between layers

- Currently you are in the second layer. You can move between layers by clicking on arrow at the top left hand corner.
- You will find all the layers are still empty because you have not construct anything.

Let's try building a simple model based on Trenbath (1984).

Trenbath formulated a simple model of restoration and depletion of 'soil fertility' during fallow and cropping periods, respectively.

'Soil fertility' is defined as a complex of effective nutrient supply and biological factors (diseases, weeds) affecting crop yield. Crop yield is assumed to be directly proportional to 'soil fertility'.

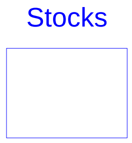
Assume during a cropping period soil fertility declines with a fraction D per crop, while during a fallow period soil fertility can be recreated with a fraction of R.

Constructing a model

- Make sure you are in the second layer. You will notice a globe (world) icon underneath the arrow at the top left hand corner. On the top you will see 14 icons, starting with 'box' icon at the furthest left and 'ghost' at the furthest right.
- Make a variable of soil fertility. To do this, click on the box icon then click again anywhere on the empty space. Change the name from 'Noname1' into 'Soil Fertility' or any variable name you like. There are no restriction on length. What you have just made is called **building blocks.**

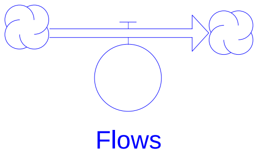
STELLA has 4 types of building box:

1. Stocks



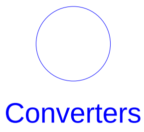
Stocks are accumulations. They collect whatever flows into and out of them

2. Flows



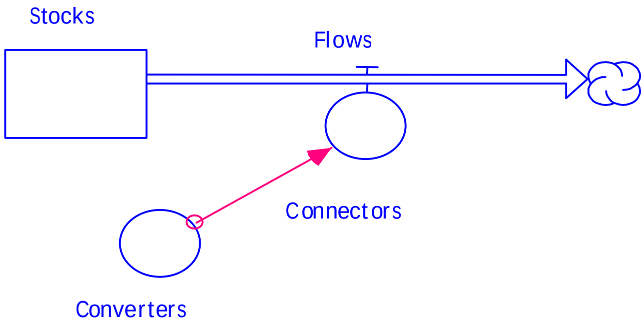
The job of flows is to fill and drain accumulation s. The unfilled arrow head on the flow pipe indicated the direction of the flow.

3. Converters



The converter serves a practical and handy role. It holds values for constants, defines external inputs to the model, calculates algebraic relationships and serves as the repository for graphical functions. In general it converts inputs into outputs.

4. Connectors



The job of the connector is to connect model elements.
This is an example of how building blocks are used.

Constructing a model (Continued.)

- Since 'Soil Fertility' will decrease during cropping year, you will have to make an outflow from 'Soil Fertility'. Name the flow as 'Depletion'.
- 'Depletion' depend on depleting factor (D), length of cropping year **and length of fallow year** (if it is a fallow year, depletion will not occur). Make 3 converters and name them as D, TimeCrop and TimeFallow. Connect all 3 converters to 'Depletion'
- Now you will need to define the relationship between those parameters into an equation in 'Depletion'. See what happen if you click twice on 'Depletion'.
- Click Cancel and see what happen if you click on the globe icon then clicking twice on 'Depletion'.
- You are now in equation box. Type out the following equation:
  IF(MOD(TIME, (TimeCrop+TimeFallow)) <TimeCrop) THEN
  (Soil_Fertility*D) ELSE(0)[1]
  Make sure there is a connection from 'Soil Fertility' to 'Depletion'
- You will see that all building blocks except 'Depletion' has question mark on them. They are asking for a value. Put the following value just for a try out. D=0.4, Soil fertility=10, TimeFallow=3, TimeCrop=3
- Now, do the same step for recreation factor, which is an inflow to 'Soil Fertility'. What do you think should be the equation in 'Recreation'? First try a constant value, for example put IF(MOD(TIME, (TimeCrop+TimeFallow)) > TimeCrop)THEN(0.2) ELSE(0)
- The Trenbath model used a 'saturation' function in which the recreation depends on the difference between current fertility and a maximum value (Finf), modified by a 'half-recovery time' Kfert, so we make converters for Finf (value e.g. 10) and Kfert (value e.g. 5): IF(MOD(TIME, (TimeCrop+TimeFallow)) >TimeCrop)THEN((Finf-Soil_Fertility)*Soil_Fertility/(Finf-Soil_Fertility+Kfert*Finf))
  ELSE(0)
- Now go to the third layer. You will now see the values and equations of your model.

[1] MOD(TIME,(TimeCrop+TimeFallow)) will give current time minus the already completed cycles. The early part of a new cycle is cropped, the latter part is fallow.

Two types of output can be generated from **STELLA**; graphs and tables.

Making an Output

- To make a graph click on graph icon (7th icon from left) and click again anywhere. A box named untitled graph will emerge.
- Click twice on the graph then select 'Soil Fertility' from Allowable Box. Click the arrow pointing to the right. Then click OK.
- You may do the same thing with table icon (8th icon from left)

Running the Program

- To run the program choose **Run** from Run Menu. You can also run the program by pressing **Ctrl-R** or clicking the running-man icon in the bottom left hand corner then click an arrow pointing to the right.
- To see the simulation result, click twice on the graph or table.
- You will notice that the simulation run until time 12 with Delta Time (DT)=0.25. You can change this by choosing **Time Spec** on Run Menu. Try putting DT=1 and length simulation to 50.
- Run the model again and see what happen.
- Try changing R and D value. At what value would they result in stable condition?

Sensitivity Analysis

STELLA has a sensitivity analysis option. Let's try to see how sensitive 'Soil fertility' to changes in 'Depletion'

- Choose **Sensi Spec** from Run Menu. Choose D from Allowable Box then click an arrow pointing to right.
- Click D on Selected Box, then fill the following value: Start=0.2, End=0.6. Click on **Set** then **OK.**
- Click twice on graph, then choose graph type as Comparative.
- Now Run the model and see the result.

Exercises

The model you have built is very simple. Now try adding other variables to add complexity into it. Below are several exercises you may like to try out.

- Add crop production into it. Assume crop production is linearly proportional to decreased in 'soil fertility'/depletion. Find the total crop production during simulation.
- Assume that in the sum of cropping time and fallow time is a constant over time (a constant cycle). Fallow time is a function of total cumulative production. If the cumulative production meet a certain target then continue with the same length of fallow time. If cumulative production below target you need to shortened the length of fallow time to make up for.
- Assume target production as a function of population density and food needed per capita

Appendix 2
User's guide to WaNulCAS

Introduction

This user's guide is designed to help users in working with **WaNuLCAS** model. Throughout this document, we assumed users have a basic experience on using software under Microsoft Windows.

The document is accompanied by:

1. Two (2) disks containing two (2) files:
   a) WaNuLCAS.zip
   b) WaNuLCAS.xls and WANHELP.xls
2. One document titled ''**WaNuLCAS 2.0**, Backgrounds of a model of water, nutrient and light capture in agroforestry systems'.

To be able to run WaNuLCAS reasonably well the recommended system requirements are:
Pentium processor or better
Microsoft Windows^{TM} 95
64 MB RAM
VGA display of at least 256 colors

There are two options for running WaNuLCAS:

1. Under Stella 5.0 Commercial Run Time (CRT), which is a 'stripped' version of Stella Research. You can:
   a. run the model
   b. change most of the parameter values within the ranges set (directly or by copying from EXCEL files), and
   c. save/save as to maintain modified parameters
   d. save graphs as pictures for printer
2. Under Stella Research 5.11. In addition to the above you can also:
   a. modify parameters ('constant') not included in the input lists
   b. modify the parameter ranges
   c. save output tables as text files for further data handling with other software
   d. create new graphs or tables
   e. print a listing of all program equations
   f. modify the layout of the model
   g. modify equations, add or delete pools and flows, i.e. modify 'the model itself'.

If you do any modification, please keep track of changes made for any future report on your 'modified WaNuLCAS'.

This document deals with the second option that is running WaNuLCAS in Stella Regular/Research version. A free downloable version of Stella is available at **http://www.hps-inc.com/**. All option available except saving a file.

Installing WaNuLCAS

Decompressed WaNuLCAS model and excel file from the disk. You may copy the model into any directory but the excel file has to be copied to **c:\stella5c**. This is to make sure the link between the stella file and excel file is working.

Starting WaNuLCAS

Initiate EXCEL. Open **Wanulcas.xls**. It will give warning that the file contains a macro.

Choose **enabled macro**. This is to make sure the macro built to ease inputting parameters in the model is working properly.

Then run **Stella**. It will automatically open a blank working model. Close it then open **Wanulcas.stm** from appropriate directory. You are now inside the **Main Menu** of WaNuLCAS and ready to work! In your screen you will see something like Figure App2.1.

Please be patient in waiting for the model to load. Inside WaNuLCAS you will see several buttons, each has specific function written on it.

To familiarize yourself with WaNuLCAS we suggest you to try the following exercise:

- First, view the model then return to main menu
- Second, run the model using default parameters, then look into the simulation result
- Third, check nitrogen, phosphorus, carbon and water input-output summary of model
- Fourth, modify input parameters and try new run
- Fifth, import output resulting from new run

In the following sections you will find description on how to perform each of the suggested exercise.

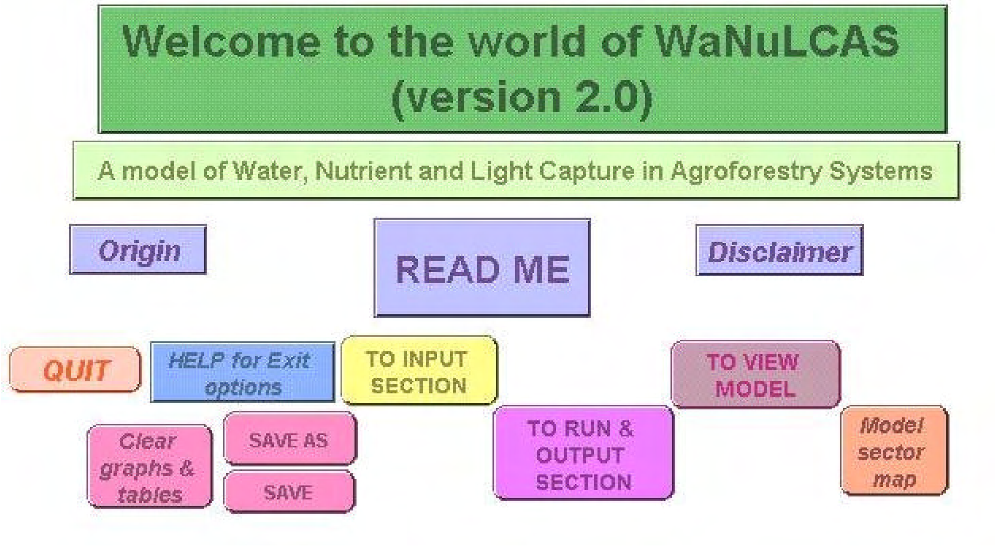


Figure App2.1. View of WaNuLCAS Main Menu

To View Model

This option will give you a bird's eye view of model structure: sectors, pools, flows and influences (see figure below). Using Stella 5.0 Research you can modify the model at this level.

To return to **Main Menu** you may click on the available button or click on an arrow pointing upwards in the top left corner.

Figure App2.2. A bird's eye view of WaNuLCAS

To Run and See Simulations Results

To run or to see simulation result from **Main Menu** click on **TO RUN AND OUTPUT SECTION** button.

Running WaNuLCAS

On the output screen you will find 5 buttons which control simulation run as listed below.

Buttons	Purpose
Run	To start simulation
Pause	To pause during simulation run
Stop	To stop simulation
Resume	To resume simulation after pausing
Time Spec	To specify length of simulation time

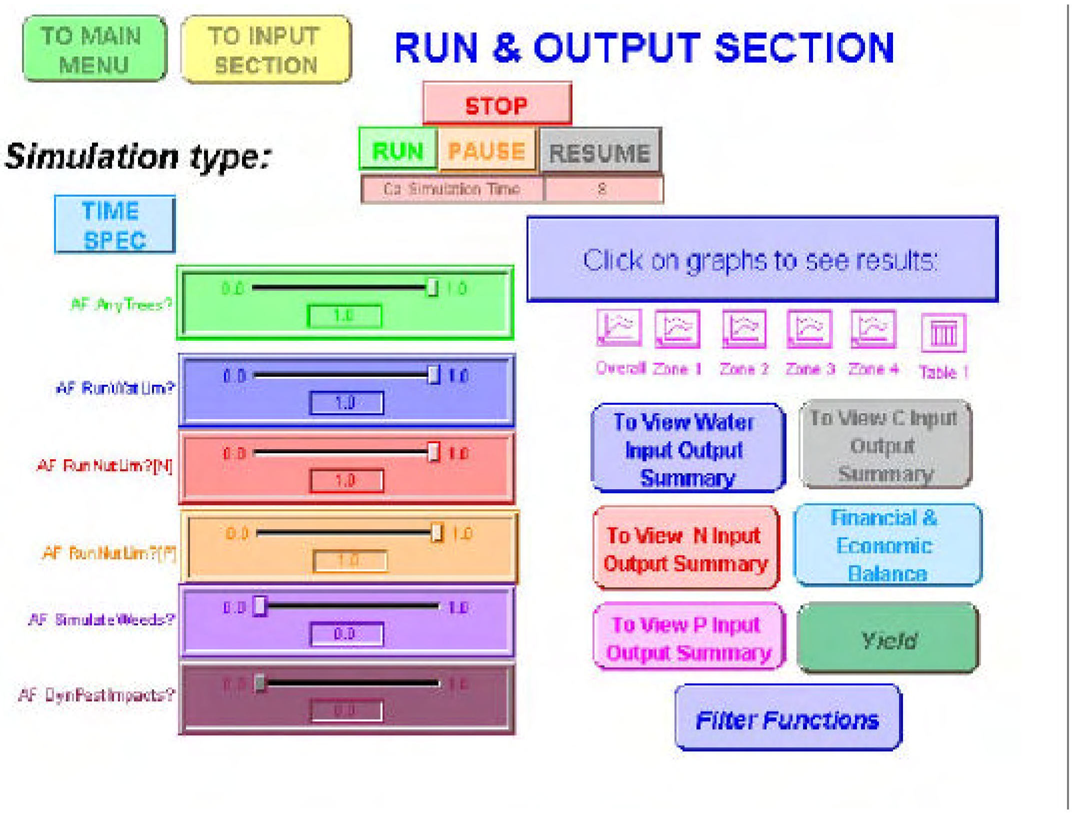


Figure App2.3. View of Output Section

Below the running control buttons, you will see a box displaying time lapsed since start of simulation (see Figure App2.3).

There are 6 sliders to simplify running different type of simulations. See Appendix 7 on acronyms to know more of the function of these sliders. The *Time Specs* screen will appear (Figure App2.4) allowing you to change beginning and ending period of simulation, also DT which is incremental time of simulation. We strongly advise you to keep DT value at 1.

There are 6 sliders under Click Me button. These sliders are options of a general different simulation you can run. Click on Click Me button to find out more on the function of each slider.

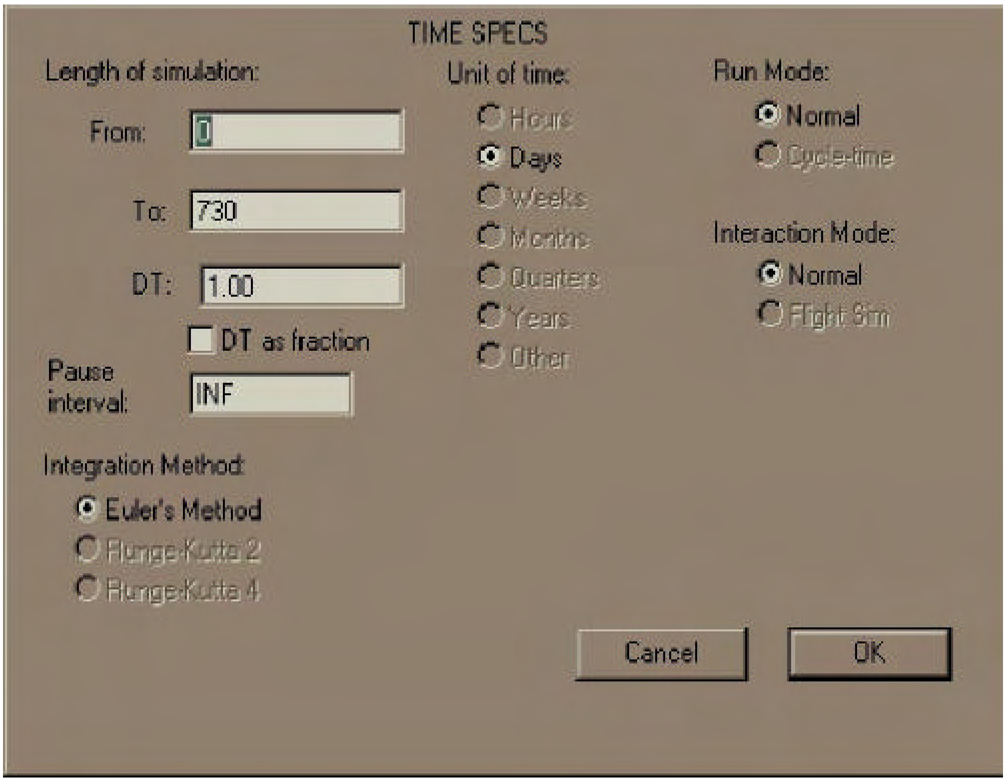


Figure App2.4. View of *Time Specification* screen

Output Result

There are two types of output result, (1) Tables and (2) Graphs.

To view a graph/table, click twice on the graph icon. What you will see is actually a stack of graphs/tables. To view the rest of graphs, click on the folded page at the bottom left corner.

When you look at graphs, notice that the scale on Y axis between parameters on the same graph can be different. Match the index number of parameters with index number of scales in Y axis.

Listed below is summary of available output on display. More detailed descriptions on output parameters are listed in Appendix 4 of this document.

A. GRAPHS

Overall : Summaries of overall zones and specific output related to Tree

Output	Content
Page 1	Plant biomass
Page 2	Distribution of rainfall
Page 3	Distribution of cumulative amount of water drained out
Page 4-5	Distribution of cumulative amount of nutrient leached out
Page 6	Cumulative plant water uptake
Page 7	Total plant N & P uptake per day
Page 8-9	Amount of nutrient presence in plant aboveground biomass
Page 10	Water available, demanded and taken up by tree per day
Page 11-12	Nutrient available, demanded and taken up by tree per day
Page 13-15	Factors limiting treegrowth
Page 16	C and Nutrient in SOM + litter pool

Zone 1, **Zone 2**, **Zone 3**, and **Zone 4** : Each of these graphs contain similar output parameter related to zone 1, 2, 3 and 4

Output	Content
Page 1	Factors limiting crop growth
Page 2	Distribution of water stock
Page 3-4	Distribution of nutrient in soil
Page 5	Distribution of crop water uptake
Page 6	Distribution of tree water uptake
Page 7,9	Distribution of crop nutrient uptake
Page 8,10	Distribution of tree nutrient uptake
Page 11-12	Nutrient available, demanded and taken up by crop per day

B. TABLES

There is only one table containing 2 pages of water balance, plant biomass, water, N and SOM in soil.

Adding additional output parameters

To add more parameters to your tables or graphs do the following:

- Click twice on your graph/table. After a graph/table appear, click twice again on it. Now, you will see a box emerge with 2 small boxes in the upper section. The left box contains parameters that can be loaded into graph/table. The right box contains parameters already in the graph/table. A graph can contain up to 5 parameters while a table can contain more than 40 parameters.
- To load a parameter into the graph/table, highlight the parameter in **allowable** box then click an adjacent arrow pointing to the right.
- If you want to load a parameter to a new clean page, prior to the above you need to click an arrow pointing upward at the bottom left corner pointing (adjacent to **Page**). Keep on clicking until you see **NEW** as page number.

Locking graphs or tables to speed your simulation

You can lock pages in your graphs and tables that you do not need. Locked graphs or tables will not be updated in the next simulation run. This would save a lot of time needed to run the model. To lock graph or table click on the lock icon. It is in the bottom left corner of your graph or on the top right corner of your table.

Printing your output

You can print your output by clicking on printer icon. It is in the bottom left corner of your graph or on the top right corner of your table. It will ask you to specify which page of your graph or table you want to print.

Importing Output Results

You can save your table as a text file and your graph as a pct file. You can also use copy (Ctrl-C) and paste (Ctrl-V) your output table. For graphs you can use screen dump (Shift-Print) then paste to your favourite Microsoft software.

To View Input-Output Summary

To view Input-Output Summary, click on button **TO RUN & OUTPUT SECTION** in the **Main Menu**. There are 7 input-output summary you can see, Water, Nitrogen, Phosphorus, Carbon, Financial & economic, Yield and Filter functions. Choose the relevant one.

This screen gives you summary of input and output in the current system simulated. A list of parameters acronym found in this section is shown in **Appendix 4** under **Balance**.

Modifying Input Parameters

Click on button '**TO INPUT SECTION'** from **Main Menu**. It will lead you to list of input parameters.

Click again on button associated with specific parameters. Refer to **Appendix 5** in Documentation Manual for more detailed information on input parameters.

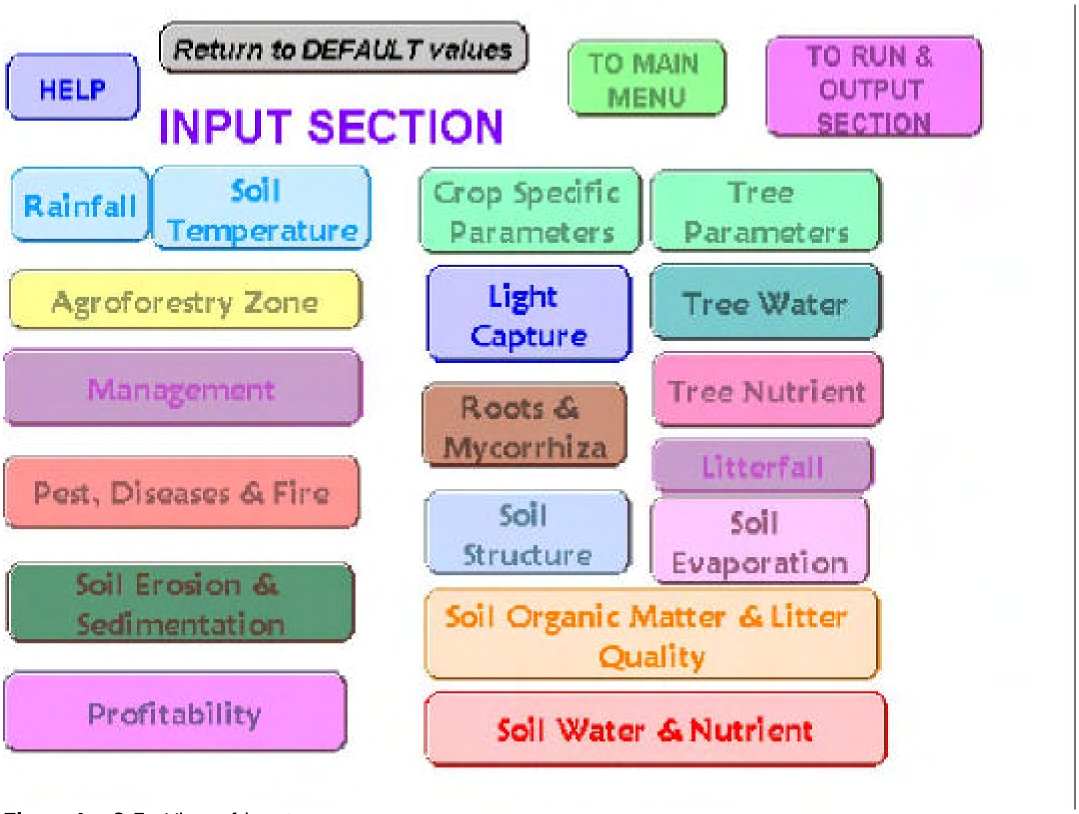


Figure App2.5. View of input menu

Basically data for WaNuLCAS model are placed in two locations, (1) the upper layer of the model and (2) WaNuLCAS.xls. When you click on input parameter button, it will either take to the actual input parameter location or inform you to enter it through Wanulcas.xls.

From upper layer of model there are basically three types of input device used, (1) list, (2) sliders and (3) graphical input

Changing Input Values

To modify input value just write over the current value. It will change if the new input value is within allowable range. If not, the maximum or minimum in the range will replace the value specified.

To check allowable value, please refer to Appendix 5 in documentation manual. If you experience problems, please let us know.

Please refer to Stella Technical Manual to change input values on specific input device.

Description on Wanulcas.xls

This Excel file is contains data used as input parameters and routines to help users in generating these input parameters. To be able to open the file you need at least Excel ver. 5.0 (MSOffice 97). The Excel must have Visual Basic Application as add-in working. The descriptions of each sheet are listed below.

All the sheets are protected by default in such a way that you will still be able to change input parameters. You can unprotect the sheets using password wanulcas (all lower case).

All input parameters in Wanulcas.xls are linked to WaNuLCAS model. For these parameters you should change it directly from the Excel sheet. For more detail description, please see Appendix 3.

Sheet	Content
READ ME	General information
Pedotransfer	Program to generate soil hydraulic properties. Output generated from this program forms data input for WaNuLCAS. These can automatically be copied to the sheet 'SOIL HYDRAULIC' where it is linked to WANuLCAS model.
Hydraulic Properties	Soil Hydraulic input parameters for each soil layer and zone. Linked to WaNuLCAS STELLA model
Phosphorus	Program to generate Ka (adsorption constant) of P, based on double Langmuir equation and related P_Bray to total mobile soil P content
Weather	Daily rainfall, daily soil temperature and daily potential evaporation
Crop Parameters/Library	Crop specific parameters
Tree Parameters/Library	Tree specific parameters
Crop Management	Planting schedule, fertilization schedule
Tree Management	Tree planting & timber harvesting schedule and pruning management.
Profitability	Input prices and labour requirement for the agroforestry system simulated and output produced.

Linking data

STELLA Research has a DDE facility, which enable users to link model to outside file.

Most of the contents of Wanulcas.xls are linked to WaNuLCAS model as input pa-rameters. Linking enable you to change input value in WaNuLCAS by changing associated values in Wanulcas.xls. The linked values are marked by blue font.

When you open WaNuLCAS model in STELLA Research version, STELLA will ask if you want to establish link. Answer Yes if you want to have the model linked with Wanulcas.xls, but be sure that you already have EXCEL running in the background and Wanulcas.xls have already been copied in directory STELA5C.

STELLA only allows the changes to occur when both Excel and STELLA files are open simultaneously. Changes made in Excel prior to establishing the link will not change parameter values in STELLA. To overcome this problem we have built an updating macro in Excel. Run this macro by pressing Ctrl-u after you have the link between STELLA and Excel file establish to make sure all the input parameters value in STELLA model corresponds to the value in Excel.

With this macro, you will be able to have different excel files representing different parameterization. Rename the file to Wanulcas.xls when you want to use it. Click the updating macro. All the parameter values in Stella will be updated.

To Make Changes in the Model

There are 2 levels of model changes you can do; (1) change a constant parameter into a dynamic variable and (2) adding additional influencing parameter /factor to existing equations.

Changing a constant into dynamic variable

You can do this by making a constant parameter depends on existing-state variable.For example: change biomass-to-height conversion factor (Cq_HBiomConv[Cr]) into crop stage (Cq_Stage) dependent.

Adding influencing factor to existing equations

You can do this by adding additional parameter to existing equations.for example: add effect of slope as a parameter influencing potential evaporation (Evap_Pot).

Appendix 3
Description on Excel files accompanying WaNuLCAS model

The WaNuLCAS model is accompanied by 2 excel files, Wanulcas.xls and Additional.xls. Wanulcas.xls contains input parameters and routines to generate these input parameters. The input parameters are linked to WaNuLCAS model. Additional.xls contains more routines and databases related to WaNuLCAS input parameters that might be of interest to some users. See table in Appendix 2, page 138 for short descriptions of Wanulcas.xls content. Below are more detailed descriptions of both files.

Wanulcas.xls

The basic purpose of this Excel file is to ease users in modifying input parameters needed to run WaNuLCAs model. Input parameters in this file are linked to the model (in the WaNuLCAS.STM file).

There are two ways to change input parameters in excel, making sure changes also occur inside the model:

1. Change input values in excel ONLY if you run the model and excel simultaneously with links established, or
2. Change input values in excel before hand then save the file. When you run the model and establish links with excel later, make sure you press Ctrl-U or Ctrl-Y. This is an updating macro built within this file, that re-activates the links and sends the current parameter values of the excel file to their counterparts in stella. The macro activated by Ctrl-U will update crop and tree parameters, the Ctrl-Y macro the soil and climate parameters.

The second option also allows you to store a number of parameter sets for specific locations under separate names (e.g. WanSite1.xls) and use them for simulations by renaming them to Wanulcas.xls and running the update macro's.

If in doubt whether parameters are actually sent across, you can open a table in Stella and ask to show (a sample of) the parameter values in the model and compare them with the input you expected to be used.

Below are comprehensive explanation of each sheet and the relevant WaNuLCAS input parameters are tabulated. Refer to Appendix 7 for definition of acronyms.

READ ME sheet.

This is the main menu of Wanulcas.xls. It contains general information and button commands to browse other sheets.

Pedotransfer sheet

The 'Pedotransfer' sheet contains calculation tools to help generating tables of soil hydraulic parameters. The routine is based from Wösten et al. (1998).

You will need to enter 5 input parameters for basic soil properties in the 'Input' section of this sheet. The pedotransfer function then estimates the parameters of a Van Genuchten equation and tabulates the relations between soil water content, hydraulic conductivity and pressure head.

The saturated hydraulic conductivity K_{sat} generated in this equation is used as a default value, representing a soil with little structure and macroporosity. The model will use the KsatInit value that you specify yourself – if it differs from the default value it is possible to simulate a gradual collapse of soil structure (with a rate governed by S_KStructDecay, set at 0.2); macroporosity can be re-created by 'Worm' activity (see Section 3.3.6).

In WaNuLCAS two definitions of 'field capacity' are used to determine the maximum soil water content one day after a rainfall event:

- Fieldcap1 = the soil water content (found in cell O11) at which downward drainage will become less then a small value Kcrit (set in cell B36 of the input section, e.g.. 0.1 cm d^{-1}), and
- Fieldcap2 = the soil water content that is in hydrostatic equilibrium with a water table at a distance defined from the bottom of layer 4 (default distance is 0). This second value is calculated inside the Stella model.

For the actual calculations the highest of these two values for any cell is used.

The results generated by the pedotransfer routine are found in the 'Output' section of this sheet. These generated values are input parameters for WaNuLCAS model.

WaNuLCAS input parameters	Location in Excel
W_PhiTheta	cells N13 – N64
W_Ptheta	cells O13 – O64
W_PhiP (this is linked to 4 tables in the stella: W_PhiPH, W_PhiPMH, W_PhiPML, W_PhiP)	cells R13 – R64
W_ThetaPMax, W_ThetaP	cells U13 – U64
KsatDflt (default value, endpoint of loss of soil structure)	N11
Ksat (value used to initializa the model)	M11
Field Capacity1 (conductivity-limited)	O11

These input parameters need to be copied to the sheet 'Soil Hydraulic' properties. To copy the parameters for soil layer i and zone j, fill in i and j in cell N8 and N9 then click on the **COPY** button.

You can set up the model with the same properties for all zones and layers by repeating this for i = 1...4 and j = 1...4, modify the properties by layer or use different properties for any of the 16 cells.

Soil Hydraulic sheet

This sheet contains soil hydraulic input parameters as generated and copied from Pedotransfer sheet. The cells here are linked to the WaNuLCAS model. There are no user inputs required here, as all input is generated by the pedotransfer sheet. You can, however, check that the COPY command has lead to the expected results or not.

Phosphorus sheet

The 'Phosphorus' sheet contains a procedure to calculate Ka_P, the apparent P adsorption constant as a function of the P concentration and P availability indices such as the P_Bray value. To run this, click on button **Psorption isotherm & Soil Database**. In this section you need to fill in the soil type for each layer of your soil in cells M8...M11. We provide default values for 9 soil types, as listed in U12....U20 If you have your own data, you can fill in parameters of a single or two-term Langmuir isotherm to describe your soil type. The parameters currently used for each soil layer are found in cells N8...R11. You also have to specify the bulk density of each layer (it is possible to use a value here that differs from the one used in the pedotransfer sheet...).

The parameters of the Langmuitr sorption isotherm are used to derive values of Ka_P for each layer, tabulated in the '**P Sorption Output'** section of the worksheet These values are linked to the WaNuLCAS.stm model.

This sheet also includes a section to initialize P in each cell (zone * layer), on the basis of indices of P availability such as the P_Bray value. To do this, you first have to specify two properties of the P availability index: the volume ratio of soil to solution used during the extraction, and the relative sorption affinity in the extraction medium (at the temperature and other conditions used). For two methods we provide these parameters P-water (compare De Willigen and Van Noordwijk, 1987) and P-Bray (with a tentative, poorly tested estimate of the relative sorption affinity of 2% of the original value).

Once the method has been thus defined, click on '**Initial P Soil**' and fill in the initial P soil indices for each cell (AD8...AG11). The values will be converted to amount of soil P in the units expected in WaNuLCAS.stm in cells (AD14...AG17). These converted values are linked to the Stella model.

WaNuLCAS input parameters	Location
Initial P in soil, N_Init*i*[P,Zone]; *i* = 1, .., 4	cells AD14 – AG17
N_KaPDef[Layer]	cells C34 – C83, E34 – E83, G34 – G83, I34 – I83

WEATHER sheet

This sheet stores daily data for 3 weather components in WaNuLCAS: Rainfall, Soil Temperature and Potential Evaporation. Default length of data and links are 1 year (365 days). These data are linked.

WaNuLCAS input parameters	Location
Rain_Data	cells C5 – C369
Temp_DailyData	cells D5 – D369
Temp_DailyPotEvap	cells E5 – E369

Slash&Burn sheet

This sheet holds input parameters related to impacts of slash and burn on soil as a function of increased temperature at the soil surface.

WaNuLCAS input parameters	Location
S&B_SurfLitBurnFrac	cells B12 – B26
S&B_NecroBurnFrac	cells C12 – C26
S&B_DeadWoodBurnFrac	cells D12 – D26
S&B_AerosolFrac	cells E12 – E26
S&B_NvolatFrac	cells F12 – F26
S&B_PvolatFrac	cells G12 – G26
S&B_SOMBurnFrac	cells J12 – J19
S&B_FirMortSeedBank	cells K12 – K19
S&B_FirIndPMobiliz	cells L12 – L19
S&B_FirImpPSorption	cells O12 – O26

CROP MANAGEMENT sheet

This sheet holds a schedule for planting crops (by zone and type) and applying N or P fertilizers. The current simulation year is defined as **YEAR 0**. See WANHELP.xls for an example on how to fill this sheet on the basis of a daily calendar.

In this sheet you will be able to define the type of crop you plan to use in the simulation. In cell B2-F2 fill the letter code of crop type associated with the code in the database. It is written as options on the left hand side or see sheet **CROP LIBRARY**. The type of crop you choose here determine the parameter values copied to sheet **CROP PARAMETERS** and **PROFITABILITY**, where the values are linked to model.

You have a maximum of 5 different crop type to grow in one simulation. The letter code you fill in here will be converted to crop type value of 1 to 5, which you will use as input parameter in **column D**, **I**, **N and S**.

WaNuLCAS input parameters	Location
Ca_PlantYear[Zone]	cells B11 – B31, G11 – G31, L11 – L31, Q11 – Q31
Ca_PlantDoY[Zone]	cells C11 – C31, H11 – H31, M11 – M31, R11 – R31
Ca_AType[Zone]	cells D11 – D31, I11 – I31, N11 – N31, S11 – S31
Ca_FertAppYear[NutSoil]	cells V11 – V51, AA11 – AA51
Ca_FertAppDoY[NutSoil]	cells W11 – W51, AB11 – AB51
Ca_FertAppRate[NutSoil]	cells X11 – X51, AC11 – AC51

CROP LIBRARY sheet

This sheet holds a database for crop specific parameters and crop related input-output for the system simulated. Overall there are 58 input parameters including 5 growth parameters as a function of crop stage. Some parameters are only required for specific settings in the simulation, e.g. there are three mutually exclusive ways of determining root length density in each cell in each time step, as governed by C_RootType.

Currently there are 10 possible type of crops in the database. For 5 of them we have provided default values, that is for crop **Cassava**, **Maize**, **Upland Rice**, **Groundnut** and **Cowpea**. If you have your own data you can fill your data values under crop type **Yours1**, ..., **Yours5**. For the whole list of input parameters stored, please refer directly to the excel sheet.

To choose the type of crop you use in simulation fill in relevant cell in sheet **CROP MANAGEMENT**.

TREE MANAGEMENT sheet

This sheet holds a schedule for tree planting, pruning and timber harvesting. As in **CROP MANAGEMENT** the current simulation year is defined as **YEAR 0**. See WANHELP.xls for an example on how to fill this.

This where you define the type of tree you plan to use in the simulation. In cell E4-G4 fill the letter code of tree type associated with the code in the database. It is written as options on the left hand side or see sheet **TREE LIBRARY**. The type of crop you choose here determine the parameter values copied to sheet **TREE PARAMETERS** and **PROFITABILITY**, where the values are linked to model.

It is possible to grow 3 different tree type simulteneously.

WaNuLCAS input parameters	Location
T_PlantY[Tree]	cells C11 – C31, E11 – E31, G11 – G31
T_PlantDoY[Tree]	cells D11 – D31, F11 – F31, H11 – H31
T_PrunY	cells K11 – K51
T_PrunY	cells L11 – L51
T_PrunFracD[Tree]	cells M11 – M51, O11 – O51, Q11 – Q51
T_PrunHarvFracD[Tree]	cells N11 – N51, P11 – P51, R11 – R51
T_WoodHarvY[Tree]	cells C37 – C57, E37 – E57, G37 – G57
T_WoodHarvDoY[Tree]	cells D37 – D57, F37 – F57, H37 – H57

TREE PARAMETERS sheet

This sheet holds tree specific parameters. There are 95 input parameters. As in crop specific parameters, some inputs are only required if you run certain type of simulations.

All you need to fill in this sheet is the letter code of tree type (cell E8 - G9) associated with the code in the database. You have a maximum of 3 different tree type grow simultaneously in one simulation. The tree type you fill in is link to **PROFITABILITY** sheet

In the database we have so far provided only 2 default values for the trees Gliricidia sepium and Peltophorum dasyrrachis. If you have your own data you can fill in this value into the database (see cell L6).

For the whole list of input parameters stored, please refer directly to the excel sheet.

PROFITABILITY sheet

The sheet contains input needed in the simulated systems and output produced. There are basically 3 categories of input, for the whole field, trees and crops. Input for the whole field you will need to fill in this sheet, while for plant input it is filled in database **TREE/CROP LIBRARY**

See directly in the excel sheet the whole list of input parameters.

WanHelp.xls

Deriving Crop Growth sheet to convert data on crop growth (under local climate & soil conditions) ito the form required by WaNuLCAS.xls

Crop Try Out sheet to use the parameters specified in a crop file for a simulation of potential crop productiopn (in the absence of light, water or nutrient limitations) and compare the outcome with the data used in the 'deriving crop growth' sheet

Agrofores TREEs sheet to derive part of the tree files from easily observable tree characteristics

FBAWan sheet to derive the remaining parts of the tree files from a 'functional branch analysis' scheme used to generate a self-similar branching pattern and its resultant allometric equations

Plant Calendar a sheet that allows you to enter events such as crop planting or fertilizer application on a daily calendar, and convert in to the form required in the Crop Management and Tree Management sheets

Julian days to convert calendar days per month into the 'day-of-year' (DOY) or 'Julian days' format used in the stella model.

Appendix 4
List of Output Acronyms and Definition

Acronym	Definition	Units	Location
BC_CO2Burn	Cumulative amount of carbon released into air from burning event	g m^{-2}	Carbon Balance
BC_CPhotosynth	Amount of carbon produced by crop through photosynthesis	g m^{-2}	Carbon Balance
BC_CRespforFix	Amount of carbon released by crop due to respiration needed for N fixation	g m^{-2}	Carbon Balance
BC_Crop&Weed	Current amount of carbon in crop biomass	g m^{-2}	Carbon Balance
BC_CropInitTot	Total amount of carbon initialized as crop biomass	g m^{-2}	Carbon Balance
BC_HarvestedC	Amount of carbon in harvested crop / yield (average over total field length)	g m^{-2}	Carbon Balance
BC_HarvestedT	Amount of carbon in harvested component of tree	g m^{-2}	Carbon Balance
BC_Necromass	Amount of carbon as necromass	g m^{-2}	Carbon Balance
BC_NetBal	Balance value for carbon. It is used to check model calculation and should be (virtually) 0	g m^{-2}	Carbon Balance
BC_SOM	Current amount of carbon in soil organic matter and surface litter pools	g m^{-2}	Carbon Balance, Graph Overall (16)
BC_SOMInit	Initial amount of carbon in soil organic matter and surface litter pools	g m^{-2}	Carbon Balance
BC_TimeAvgStock	Total amount of carbon in the whole system averaged over the simulation period	g m^{-2}	Carbon Balance
BC_TotalRespired	Total carbon respired	g m^{-2}	Carbon Balance
BC_Tphotosynth	Amount of carbon produced by tree through photosynthesis	g m^{-2}	Carbon Balance
BC_Tree	Current amount of carbon in tree biomass	g m^{-2}	Carbon Balance
BC_TreeInitTot	Total amount of carbon initialized as tree biomass	g m^{-2}	Carbon Balance
BC_TrespforFix	Amount of carbon released by crop due to respiration needed for N fixation	g m^{-2}	Carbon Balance
BN_CBiom[SlNut]	Current amount of nutrient (N or P) in crop biomass (average over total field length)	g m^{-2}	Graph Overall (8-9)
BN_CBiomInit [SlNut]	Initial amount of nutrient in crop biomass		N Balance, P Balance
BN_CHarvCum [SlNut]	Amount of nutrient in harvested crop / yield (average over whole field)	g m^{-2}	N Balance, P Balance
BN_CNFixAmount Cum	Total amount of N fixed by crop	g m^{-2}	N Balance
BN_Crop[SlNut]	Current amount of nutrient in tree biomass	g m^{-2}	N Balance, P Balance
BN_CUptTot[SlNut]	Total amount of nutrient taken up by crop (average over total field length)	g m^{-2}	Graph Overall, (7)
BN_FertCum[SlNut]	Cumulative amount of fertilizer input (average over total field length)	g m^{-2}	N Balance, P Balance
BN_Immob[SlNut]	Current amount of nutrient in immobile pool	g m^{-2}	N Balance, P Balance
BN_ImmPoolInit [SlNut]	Initial amount nutrient in immobile pool	g m^{-2}	N Balance, P Balance
BN_LatInCum [SlNut]	Nutrient input due to lateral flow	g m^{-2}	N Balance, P Balance

Acronym	Definition	Units	Location
BN_LatOutCum [SlNut]	Amount nutrient flows out due to lateral flow	g m^{-2}	N Balance, P Balance
BN_LeachingTot [SlNut]	Total amount of nutrient leached out from bottom layers (average over total field length)	g m^{-2}	N Balance, P Balance
BN_NetBal[SlNut]	Balance value for nutrient. It is used to check model calculation and should be (virtually) 0	g m^{-2}	N Balance, P Balance
BN_NutVolatCum [SlNut]	Total amount of carbon volatilized from burnt necromass	g m^{-2}	N Balance, P Balance
BN_SOM[SlNut]	Current amount of nutrient in soil organic matter pool	g m^{-2}	N Balance, P Balance, Graph Overall (16)
BN_SOMInit[SlNut]	Initial amount of nutrient in soil organic matter pool	g m^{-2}	N Balance, P Balance
BN_StockInit[SlNut]	Initial amount of nutrient (average over all zones and layers)	g m^{-2}	N Balance, P Balance
BN_StockTot[SlNut]	Total amount of nutrient in soil (average over all zones and layers)	g m^{-2}	N Balance, P Balance
BN_THarvCumAll [SlNut]	Amount of nutrient in biomass harvested from tree (average over total field length)	g m^{-2}	N Balance, P Balance
BN_TNFixAmountCum	Total amount of N fixed by crop	g m^{-2}	N Balance
BN_TreeInit[SlNut]	Initial amount of nutrient in tree biomass	g m^{-2}	N Balance, P Balance
BW_DrainCumV	Total amount of water draining (average over all zones and layers)	l m^{-2}	Water Balance
BW_EvapCum	Total amount of water evaporates from soil surface (average over all zones and layers)	l m^{-2}	Water Balance
BW_LatInCum	Amount of lateral inflow (subsurface) of water	l m^{-2}	Water Balance
BW_LatOutCum	Amount of lateral outflow (subsurface) of water	l m^{-2}	Water Balance, Graph Overall (3)
BW_NetBal	Overall balance of input and output of water in the model. A value of 0 means that the model calculation is in balance.	l m^{-2}	Water Balance
BW_RunOffCum	Amount of (surface) run off water	l m^{-2}	Water Balance
BW_RunOnCum	Amount of (surface) run on water	l m^{-2}	Water Balance
BW_StockInit	Initial total amount of water in all layers and zones of soil	l m^{-2}	Water Balance
BW_StockTot	Current total amount of water in soil profile	l m^{-2}	Water Balance
BW_UptCCum	Cumulative amount of water uptake by crop	l m^{-2}	Water Balance, Graph Overall (6)
BW_UptTCum[Tree]	Cumulative water uptake by each tree	l m^{-2}	Water Balance Graph Overall (6)
C_AgronYields[Crop]	Agronomic yield for each type of crop	kg m^{-2}	Yield
C_Biom[Zone,DW]	Current crop biomass in each zone	kg m^{-2}	Graph Overall (1), Graph Zone*i* (1)
C_NDemand[Zone]	Amount of nutrient demanded by crop in each zone	kg m^{-2}	Graph Zone*i* (11-12)
C_NPosGro [Zone,SlNut]	The effect of nutrient stress on crop growth (0=no growth, 1=no stress)	g m^{-2}	Graph Zone*i* (1)
C_NUptPot[Zone]	Amount of nutrient available for crop uptake in each zone	g m^{-2}	Graph Zone*i* (11-12)
C_NUptTot[Zone]	Amount of nutrient uptake by crop in each zone	g m^{-2} day^{-1}	Graph Zone*i* (11-12)

Acronym	Definition	Units	Location
Cent_Bal[SlNut]	Overall balance of input and output in mineralization module (adapted from CENTURY model). A value of 0 means that model calculations are in balance	g m^{-2}	N Balance, P Balance
CW_PosGro[Zone]	The effect of water stress on crop growth in each zone (0=no growth, 1=no stress)	l m^{-2}	Graph Zone*i* (1)
Light_CRelCap[Zone]	Relative light capture by crop (on scale 0-1)	g m^{-2}	Graph Zone*i* (1)
N_CUpt*i*[Zone,SlNut]	Amount of nutrient uptake by crop from *i*-th soil layer of each zone per day	g m^{-2} day^{-1}	Graph Zone*i* (7, 9)
N_FFEdgeH[SlNut]	A value describing filter function horizontally at the edge of plot	dimensionless	Filter Function
N_FFEdgeV[SlNut]	A value describing filter function vertically at the edge of plot	dimensionless	Filter Function
N_FFLoc3*i*[SlNut]	A value describing filter function in the 3rd layer of soil	dimensionless	Filter Function
N_FFTot[SlNut]	A value describing how the whole system fuction as a filter. Filter function defined as nutrient taken up by plant divided by total nutrient taken up and loss	dimensionless	Filter Function
N_LeachCumV [Zone,SlNut]	Total amount of nutrient leached out from bottom layer of each zone	g m^{-2}	Graph Overall (4-5)
N_Leach*i*[Zone,SlNut]	Amount of nutrient leached out from *I*-th layer of each zone	g m^{-2}	Graph Zone*i* (6-7)
N_Stock*i*[Zone,SlNut]	Amount of nutrient stock in each zone of layer *i*	g m^{-2}	Graph Zone*i*(3,4)
N_TUpt*i*[Zone,SlNut]	Amount of nutrient taken up by tree from i-th soil layer of each zone per day	g m^{-2} day^{-1}	Graph Zone*i* (8, 10)
P_CCostTot[Price]	Total cost needed to grow crop	currency unit ha^{-1}	Economic & Financial Balance
P_CReturnTot[Price]	Amount of money contributed from crop production	currency unit ha^{-1}	Economic and Financial Balance, Yield
P_GeneralCost[Price]	Total cost needed to maintain the system	currency unit ha^{-1}	Economic & Financial Balance
P_NPV[Price]	Net present value of the system	currency unit ha^{-1}	Economic and Financial Balance
P_TCostType[Price]	Total cost needed to grow trees	currency unit ha^{-1}	Economic & Financial Balance
P_TReturnTot[Price]	Amount of money contributed from tree production	currency unit ha^{-1}	Economic and Financial Balance, Yield
Rain	Amount of rain per day	l m^{-2} day^{-1}	Graph Overall (2)
Rain_Cum	Cumulative amount of rainfall	l m^{-2}	Water Balance, Table 1
Rain_In[Zone]	Actual amount of rain going into each zone	l m^{-2} day^{-1}	Graph Overall (2), Table 1
Rain_IntercEvapCum	Amount of water evaporated from intercepted water	l m^{-2}	Water Balance
T_BiomAllTrees	Total amount of aboveground biomass for all trees	kg m^{-2}	Graph Overall (1)
T_CumLatexHarv[Tree]	Total latex harvested	kg m^{-2}	Yield
T_FruitHarvCum[Tree]	Total fruit harvested	kg m^{-2}	Yield
T_HarvPrunCum[Tree]	Total pruned tree biomass harvested	kg m^{-2}	Yield
T_Light[Tree]	Fraction of light received by tree	dimensionless	Graph Overall (13-15)

Acronym	Definition	Units	Location
T_NBiom[SlNut,Tree]	Current amount of nutrient in tree aboveground biomass	g m^{-2}	N Balance, Graph Overall (8-9)
T_NDemandAll[SlNut]	Amount of nutrient demanded by tree per day	g m^{-2} day^{-1}	Graph Overall (11-12)
T_NDfaTot[SlNut]	Cumulative amount of nutrient fixed from atmosphere by tree	g m^{-2}	N Balance
T_NPosgro[SlNut]	The effect of nutrient stress on tree growth (0=no growth, 1=no stress)	g m^{-2}	Graph 1 (13-15)
T_NUptPotAll[SlNut]	Total amount of nutrient in all soil layers available for tree per day	g m^{-2} day^{-1}	Graph Overall (11-12)
T_NUptTotAll[SlNut]	Total amount of nutrient taken up by tree (average over total field length)	g m^{-2} day^{-1}	Graph Overall (7,11-12)
T_WoodHarvCum [Tree]	Total timber / wood harvested	kg m^{-2}	Yield
TW_DemandActAll	Amount of water demanded by all tree per day	l m^{-2} day^{-1}	Graph Overall (10)
TW_Posgro[Tree]	The effect of water stress on tree growth (0=no growth, 1=no stress)	l m^{-2}	Graph Overall (13-15)
TW_UptPotAll	Total amount of water in all soil layers available for tree per day	l m^{-2} day^{-1}	Graph Overall (10)
TW_UptTotAll	Current amount of water uptake by tree from all soil layers per day	l m^{-2} day^{-1}	Graph Overall (10)
W_CUpt*i*[Zone]	Amount of water taken up by crop from *i*-th soil layer of each zone per day	l m^{-2} day^{-1}	Graph Zone*i* (5)
W_DrainCumV[Zone]	Cumulative amount of water drained out from bottom layer	l m^{-2}	Graph Overall (3)
W_Stock*i*[Zone]	Amount of water each zone in *i*-th soil layer	l m^{-2}	Graph Zone*i* (2)
W_TUpt*i*[Zone]	Amount of water taken up by all tree from *i*-th soil layer of each zone per day	l $m^{-2=}$ day^{-1}	Graph Zone*i* (6)

Appendix 5
Deriving uptake equation (P. de Willigen)

According to De Willigen and Van Noordwijk (1987 - Table 9.1, equ. 12.9) uptake rate is given by:

$$\frac{r^2 \Theta b}{2fh} = \frac{(r^2-1)\bar{c}}{2G(r)} \qquad \textbf{[A1]}$$

Now (*l.c.* page 125):

$$G(r) = \frac{1}{2}\left\{\frac{1-3r^2}{4} + \frac{r^4 \ln r}{r^2-1}\right\} \qquad \textbf{[A2]}$$

As normally $r \ll 1$

$$G(r) \approx r^2 \left(-\frac{3}{8} + \frac{1}{2}\ln r\right) \qquad \textbf{[A3]}$$

The parameters *r* 1, *f* 2 and *h* 3 are given by:

$$r = \frac{R_1}{R_0} \quad 1$$

$$f = \frac{D \;\; S_i}{U\,R_0} = \frac{Dqb\,C_i}{U\,R_0} \quad 2 \qquad \textbf{[A4]}$$

$$h = \frac{H}{R_0} \quad 3$$

and the dimensionless concentration by:

$$\bar{c} = \frac{C}{C_i} \qquad \textbf{[A5]}$$

where *D* is the diffusion coefficient ($m^2.d^{-1}$), *H* is the thickness of the soil layer (m), *U* is the uptake rate ($g.m^{-2}.d^{-1}$), R_0 the radius of the root (m) and R_1 the radius of the soil cylinder surrounding the root. The latter is given by:

$$R_1 = \frac{1}{\sqrt{p\,L_{rv}}} \qquad \textbf{[A6]}$$

The parameter 4 denotes the buffer power of the soil. Substitution of (A2)-(A6) into (A1) leads to:

$$U = \frac{D\bar{C}H}{R_1^2\left(-\frac{3}{8} + \frac{1}{2}\ln r\right)} \qquad \textbf{[A7]}$$

The diffusion coefficient is a function of the water content Θ 5, according to:

$$D = (a_1\Theta + a_0)\;\Theta\;\; D_0 \qquad \textbf{[A8]}$$

where D_0 is the diffusion coefficient of the nutrient in question in water, whereas the concentration can be calculated from the amount in the layer N_{stock} (g.m^{-2}):

$$C = \frac{N_{stock}}{K_a + \Theta} \qquad \textbf{[A9]}$$

K_a being the adsorption constant. Substitution of (A2)-(A9) into (A1) ultimately yields (A10) which is the basis for equation (10) in WaNuLCAS.

$$U = \frac{p\, D_0\, (a_1\Theta + a_0)\, \Theta\, H\, N_{stock}}{(K_a + \Theta)\left[-\frac{3}{8} + \frac{1}{2}\ln\left\{\frac{1}{R_0\sqrt{p\, L_{rv}}}\right\}\right]} \qquad \textbf{[A10]}$$

Appendix 6
Trouble-shooting and Tips

As for any complex system, the number of ways in which the model can go wrong is nearly infinite, while there is only one (or a few) ways it can go right., So the odds certainly are against us. If things go wrong, however, there are a number of ways to identify the source of the errors as a step towards mending it.

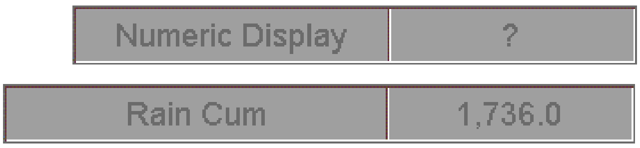
Difficulties in loading the files:

- **Links can not be established**: check whether you have indeed opened the right XLS file and have not changed the position of any of the linked parameters by adding or deleting rows or columns or moving cell contents around,
- **Low Memory ('cannot continue DDE conversation')**; it may help to remove all memory demanding programs, including net-work links and microsoft office toolbars from the memory; sometimes it helps to re-boot the computer and start afresh; this type of error message may occur when you update the links by running the Ctrl+Y or Ctrl+U macro in the excel; if the problem persists you'll have to get more RAM on your computer (32 MB is a bare minimum); you can also make runs in the Stella model without opening the excel + links, or close the excel file after updating parameter values, to increase the memory allocation for the Stella model.
- R**unning speed** can be increased by locking graphs/tables that you're not currently interested in.

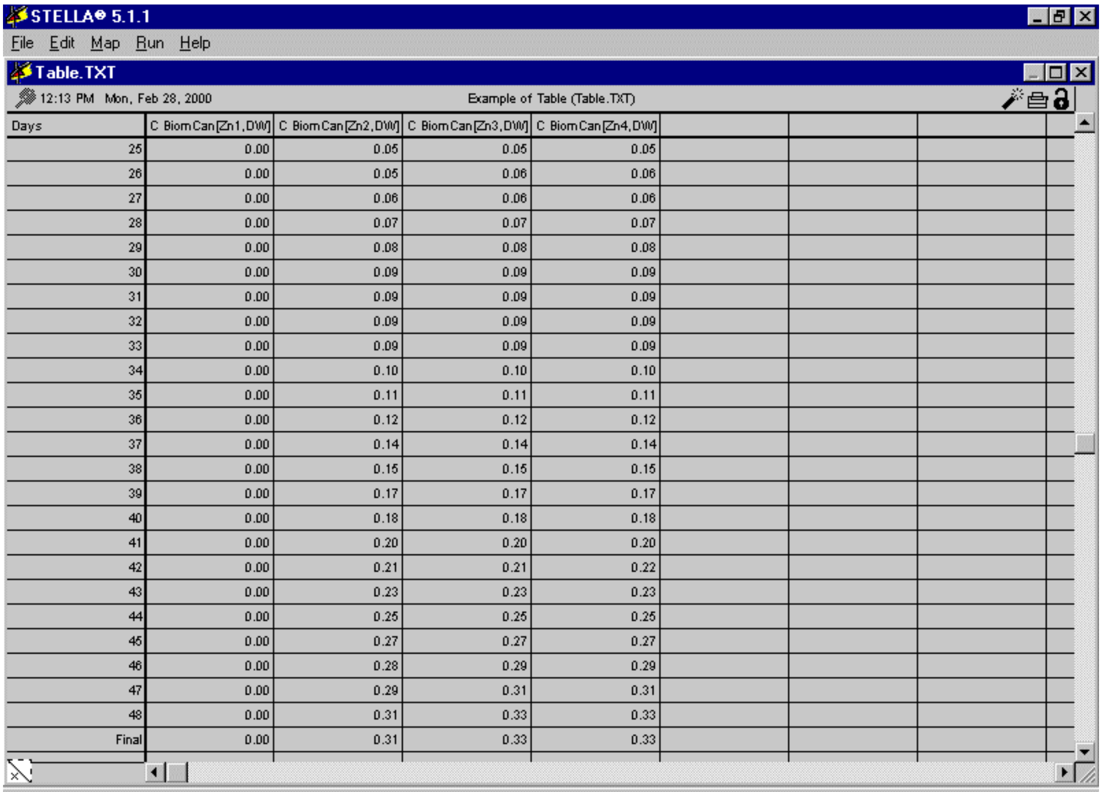
Error message at start or during RUN

It is possible that when you press RUN you get an error message, in stead of output. The message will indicate a parameter name and the error usually consists of division by zero. We have tried to protect all equations from such an event, but if necessary you can add an 'If *** <> 0 then '...existing equation...' else 0' statement to the equation involved, with the *** replaced by any divisor in the equation.

The current value of all parameters and variables at the time of the crash can be viewed by inserting a numeric display output. Below is an example.



as a step towards identifying what goes wrong. If the RUN actually starts, a Table can be used to view more then one parameter at a time, and check its changes with time.


STELLA® 5.1.1
File Edit Map Run Help
Table.TXT
12:13 PM Mon, Feb 28, 2000 Example of Table (Table.TXT)

Days	C BiomCan[Zn1,DW]	C BiomCan[Zn2,DW]	C BiomCan[Zn3,DW]	C BiomCan[Zn4,DW]
25	0.00	0.05	0.05	0.05
26	0.00	0.05	0.06	0.06
27	0.00	0.06	0.06	0.06
28	0.00	0.07	0.07	0.07
29	0.00	0.08	0.08	0.08
30	0.00	0.09	0.09	0.09
31	0.00	0.09	0.09	0.09
32	0.00	0.09	0.09	0.09
33	0.00	0.09	0.09	0.09
34	0.00	0.10	0.10	0.10
35	0.00	0.11	0.11	0.11
36	0.00	0.12	0.12	0.12
37	0.00	0.14	0.14	0.14
38	0.00	0.15	0.15	0.15
39	0.00	0.17	0.17	0.17
40	0.00	0.18	0.18	0.18
41	0.00	0.20	0.20	0.20
42	0.00	0.21	0.21	0.22
43	0.00	0.23	0.23	0.23
44	0.00	0.25	0.25	0.25
45	0.00	0.27	0.27	0.27
46	0.00	0.28	0.29	0.29
47	0.00	0.29	0.31	0.31
48	0.00	0.31	0.33	0.33
Final	0.00	0.31	0.33	0.33

Trees or crops do not grow at all

A second class of errors is that trees or crops do not grow as expected, or other events do not happen as you thought you asked for in the calendar. In such case you can add a new table to the output screen and check where the error originates by tabulating output values related to the event. For trees and crops it is helpful to tabulate the growth stage as well as components of the biomass, to check whether the error is in the plants not getting started at all, or not making biomass. It may be necessary to tabulate input values and compare with the values you intended.

Sometimes the x-axis for tabulated input parameters, such as the strings of crop or tree parameter, gets changed and all parameter values are shifted by one or more positions, leading to nonsensical results; if this happens open the graph and re-adjust the number of points.

You can try the 'return to default' button on the 'input' screen to restore (un-intentional) modifications of parameter settings that may be responsible for unex-pected run results; if you want to modify the 'default' values to which you return with this button, you have to modify the values in the dialogue boxes on the 'second level' (the modelling layer).

Appendix 7
Summary of acronyms of input parameters and their definition

No	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
1	AF_AnyTrees?	Parameter governing an option to simulate system with trees. Value 0 means system without trees, value 1 means system with trees is possible	dimensionless	0 or 1 (1)	OUTPUT SECTION
2	AF_Circ?	Switch to decide on circular versus linear symmetry. 1 = circular system, 0 =linear system	dimensionless	0 or 1 (0)	Agroforestry Zone
3	AF_DeepSubSoil	Equivalent depth of the subsoil below layer 4, that is used to calculate the effective water outflow from the soil column, via S_KsatVDeepSub	m	0 - 10 (3)	Agroforestry Zone
4	AF_DepthGWTable	Depth of groundwater table below the bottom of layer 4, expressed in m. For the time being the value is used as a constant in defining 'field capacirty'.	m	0 – 10 (0)	Agroforestry Zone
5	AF_DepthLay*i*[Zone]	Soil depth increment in (= layer thickness of) *i*-th soil layer, *i* = 1, 2, 3, 4. For sloping land systems the value for the layer 1 is used as average topsoil depth at the start of the run; actual depth of layer 1 will be calculated from the two AF_Slope parameters	m	0 - 1 (.05, .15, .5, .3 for i = 1,..,4)	Agroforestry Zone
6	AF_DynPestImp?	Parameter governing an option to simulate system with pest impact dynamically . Value 0 means no dynamic pest impacts, value 1 means dynamic pest impacts is possible.	dimensionless	0 – 1 (0)	Agroforestry Zone
7	AF_RunNLim [SoilNut]?	Parameter governing an option to simulate system with nutrient limitation. Value 0 means no nutrient limitation, value 1 means nutrient is possible.	dimensionless	0 – 1 (1)	Agroforestry Zone
8	AF_RunOnFrac	Fraction of surface runoff from the area uphill that enters the simulation area as run-on.	dimensionless	0 – 1 (0)	Agroforestry Zone
9	AF_RunWLim?	Parameter governing an option to simulate system with water limitation. Value 0 means no water limitation, value 1 means water limitation is possible.	dimensionless	0 – 1 (1)	Agroforestry Zone
10	AF_SimulateWeeds?	Parameter governing an option to simulate weed growth. Value 0 means no weed growth, value 1 means weed will start growing whenever crop is absent.	%	0 or 1 (0)	OUTPUT SECTION
11	AF_SlopeInit	Slope (expressed as percent elevation increment per horizontal distance) of the soil surface at the start of the simulation; this value can differ from the slope of the soil profile AF_SlopeSoilHoriz, but should not differ too much.	%	0 – 100 (0)	Agroforestry Zone
12	AF_SlopeSoilHoriz	Slope (expressed as percent elevation increment per horizontal distance) of the soil horizons below the surface, especially that of the topsoil, used to calculate actual topsoil depth per zone.	%	0 – 100 (0)	Agroforestry Zone

No	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
13	AF_TreeCanMirr?	Switch to decide on a 'mirror' image of the tree canopy shading zone 4 as and when it shades zone 2; when it is set at 'true' (= 1) zone 2 and 4 should have equal width	dimensionless	0 or 1 (0)	Agroforestry Zone
14	AF_TreePosit [Tree]	Position of each tree type. It can be in zone 1 (1) or zone 4 (4); if one wants it to be in both, two otherwise equal tree types can be defined.	dimensionless	1 or 4 (1)	Agroforestry Zone
15	AF_Zone[Zone]	Width of each zone. Width of zone 4 is calculated back from AF_ZoneTot minus the sum of zone 1+2+3	m	0 – 100 (.5, 1,1)	Agroforestry Zone
16	AF_ZoneTot	Total width of agroforestry system simulated	m	0 – 100 (3.5)	Agroforestry Zone
17	AF_ZoneWidthUphill	Length of slope uphill from the simulated area potentially generating subsurface flows of water and nutrients, as well as surface run-on; the length of slope is expressed in AF_ZoneTot units.	dimensionless	0 – 25 (0)	Agroforestry Zone
18	C_AgronYMoistFrac	Standard moisture content for expressing marketable yields of each crop	dimensionless	0 – 1 (0.15)	(Crop Parameters)
19	C_DailyWeedSeedFrac	Fraction of the weed seed bank that looses viability and is transferred to the litter pool for decomposition	fraction day^{-1}	0 – 1 (0)	Management/Weed Growth
20	C_ResidRemFrac	Fraction of crop residue removed from field (not returned as mulch). The same value applies for all zones and all crops used in the simulation	fraction	0 – 1 (0)	Mangement/Mulchin g
21	C_WeedGermFrac	Fraction of weed seeds in the seedbank that germinates when a new opportunity arises, e.g. at the end of a cropping season	fraction	0 –1 (0)	Management/Weed Growth
22	C_WeedSeedBankInit	Initial dry weight of weed seeds in seedbank	kg m^{-2}	0 –1 (0)	Management/Weed Growth
23	C_WeedSeedExtInflux	Daily influx of weed seeds from outside of the plot	kg m^{-2} day^{-1}	0 – 0.1 (0)	Management/Weed Growth
24	Ca_CType[Zone]	A graphical input parameter governing the type of crop planted in sequence, with the possibility of having different crops (and/or planting times) in different zones. Associated with type of crop in database. See WaNuLCAS.xls	dimensionless	1 – 10 (2)	(Crop Management)
25	Ca_DoYStart	Day of year at which simulation starts	Julian days	1 – 365 (310)	Management
26	Ca_ExtOrgAppDOY	Day of external organic input application.	Julian days	1 – 365	(Crop Management)
27	Ca_ExtOrgAppRate	Amount of external organic input applied	g m^{-2}	0 – 10	(Crop Management)
28	Ca_ExtOrgAppY	Year of external organic input application. Two type of external organic input is possible	dimensionles	any integer value	(Crop Management)
29	Ca_FertAppDoY[SlNut]	Time of fertilizer application. A graphical input parameter.	Julian days	1 – 365	(Crop Management)
30	Ca_FertAppRate[SlNut]	Amount of N or P fertilizer applied. A graphical input parameter.	g m^{-2}	0 – 10	(Crop Management)
31	Ca_FertAppYear[SlNut]	Year of fertilizer application. A graphical input parameter.	dimensionless	any integer value (table)	(Crop Management)
32	Ca_FertWeight[Zone]	Input value to decide amount of inorganic fertilizer going into each zone relative to other zones (eg. to obtain equal fertilizer amount per unit area in each zone, use	dimensionless	0 – 10 (0, 1, 1, 1)	Management/ Fertilizer application

No	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
		1:1:1:1)			
33	Ca_PlantDoY[Zone]	Day of crop planting for each subsequent crop. A graphical input parameter.	Julian days	1 – 365	(Crop Management)
34	Ca_PlantYear[Zone]	Year of planting for each subsequent crop. A graphical input parameter	dimensionless	any integer value	(Crop Management)
35	Cq_ClosedCan[Cr]	Amount of crop canopy biomass at which canopy is closed and nutrient demand per unit new biomass shifts from Cq_ConcYoung to Cq_ConcOld.	kg m^{-2}	0 – 0.5 (0.2)	(Crop Parameters/ Nutrient Uptake)
36	Cq_ConcOld[Cr,SlNut]	Nutrient concentration in crop tissue formed after biomass has reached the Cq_ClosedCan value.	dimensionless	0 – 0.1 (N=0.01, P=0.001	(Crop Parameters/ Nutrient Uptake)
37	Cq_ConcRt[Cr]	N concentration in crop roots	dimensionless	0 – 0.1 (0.001)	(Crop Parameters/ Roots)
38	Cq_ConcYoung [Cr,SlNut]	Nutrient concentration in young crop biomass (before biomass has reached the Cq_ClosedCan value).	dimensionless	0– 0.1 (N=0.015 P=0.005)	(Crop Parameters/ Nutrient Uptake)
39	Cq_CovEff[Cr]	Crop Cover Efficiency factor, used in calculating erosion (Erosion type 1)	dimensionless	0 – 0.5 (0)	(Crop Parameters/ Soil Erosion)
40	Cq_DOYFlwBeg[Cr]	The earliest day in a year when crop start to flowers	Julian days	1 – 365 (1)	(Crop Parameters)
41	Cq_DOYFlwEnd[Cr]	The latest day in a year when crop start to flowers	Julian days	1 – 365 (365)	(Crop Parameters)
42	Cq_GroMax[Cr]	Maximum daily dry matter production rate at full light capture, for each crop species under local conditions	kg m^{-2} day^{-1}	0.001 – 0.1 (0.02)	(Crop Parameters/ Crop Growth)
43	Cq_HarvAlloc[Cr]	Allocation of biomass to harvested parts (grain, tuber) as a function of crop growth stage.	dimensionless	table	(Crop Parameters)
44	Cq_HBiomConv[Cr]	Factor for conversion of crop biomass increment (up to crop stage 1) to crop height increment	dimensionless	0.1 – 10 (4)	(Crop Parameters/ Crop Growth)
45	Cq_kLight[Cr]	Light extinction coefficient for the crop canopy = efficiency of crop foliage in absorbing light.	dimensionless	0 – 1 (0.65)	(Crop Parameters/ Light Capture)
46	Cq_LignResid	Lignin concentration of crop residue (eg. 20%=0.2).	dimensionless	0 – 1 (0.2)	(Crop Parameters/ Litter Quality)
47	Cq_LignRootRes	Lignin concentration of crop root residues	dimensionless	0 – 1 (0.1)	(Crop Parameters/ Litter quality)
48	Cq_Lp[Cr]	Hydraulic conductivity of crop roots, reflecting the physiological entry resistance to water per unit root length and unit gradient.	cm day^{-1}	0 – 0.00001 (0.00001)	(Crop Parameters/ Water Uptake)
49	Cq_LWR[Cr]	Crop leaf weight ratio = gram of green leaf area per gram of shoot, for each crop species as a function of crop growth stage.	g m^{-2}	table	(Crop Parameters)
50	Cq_MaxRemob[Cr]	Maximum proportion of stem and leaves remobilized per day to the CarbHydrReserves pool, from which it can, for example, be used for growth of the storage component (grain, tuber)	day^{-1}	0 – 0.1 (0.05)	(Crop parameters/ Crop Growth)
51	Cq_MycMaxInf[Cr]	Fraction of crop roots infected by mychorrhiza for a soil layer where the Rt_MTInfFrac parameter is 1	dimensionless	0 – 1 (0.25)	(Crop Parameters/ Mychorrhiza Fraction)
52	Cq_NFixDayFrac[Cr]	Fraction of current N deficit derived from atmospheric N_2 fixation per day for each crop type, if Cq_NFixVariable = 0 (('false').	day^{-1}	0 – 1 (0.4)	(Crop Parameters/ N Fixation)

No	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
53	Cq_NFixDWMaxFrac [Cr]	Maximum fraction of the C_GroRes[Dw] pool that can be respired for N_2 fixation if Cq_NFixVariable = 0 (('false')	day^{-1}	0 – 0.5 (0.1)	(Crop Parameters/ N Fixation)
54	Cq_NFixDWUnitCost [Cr]	Dry weight cost for respiration per unit N_2 fixation, if Cq_NFixVariable = 0 (('false')	kg [dw] g^{-1} [N]	0 – 1 (0.01)	(Crop Parameters/ N Fixation)
55	Cq_NFixResp[Cr]	Responsiveness of N_2 fixation to N stress (N in biomass divided by N target), if Cq_NFixVariable = 0 (('false')	dimensionless	0 – 5 (1)	(Crop Parameters/ N Fixation)
56	Cq_NFixVariable?[Cr]	Switch (0 = false, 1 = true) to choose between variable (N-stress dependent) versus constant N_2 fixation as fraction of N deficit	dimensionless	0 or 1 (0)	(Crop Parameters/ N Fixation)
57	Cq_PotSuctAlphMax [Cr]	Plant potential where transpiration is (1-Alpha)*potential transpiration,Alpha is a small value (e.g. 0.01). Value could be different depend on crop type.	cm	-6000 – -4000 (-5000)	(Crop Parameters/ Water Uptake)
58	Cq_PotSuctAlphMin[Cr]	Plant potential where transpiration is Alpha*potential transpiration, Alpha is a small value (e.g. 0.01). Value could be different depend on crop type.	cm	-16000 – -14000 (-15000)	(Crop Parameters/ Water Uptake)
59	Cq_RainWStorCap[Cr]	Rainfall water stored as thin film at leaf surface	mm	0 – 2 (0.1)	(Crop Parameters/ Rain Interception)
60	Cq_RelLightMaxGr [Crop]	Relative light intensity at which shading starts to affect tree growth	dimensionless	0 – 1 (1)	(Crop Parameters/ Light Capture)
61	Cq_RelLUE[Cr]	Relative light use efficiency (fraction of Cq_GroMax achieved per unit light capture) for each type of crop grown as a function of crop growth stage.	dimensionless	table	(Crop Parameters)
62	Cq_RtAlloc[Cr]	Fraction of crop growth reserves allocated to root biomass in the absence of water or nutrient stress as a function of crop stage (only for Rt_ACType=2).	day^{-1}	0 - 0.6	(Crop Parameters)
63	Cq_RtAllocResp[Cr]	Crop root allocation responsiveness to water or nutrient (the factor currently in minimum supply) stress; 0 = constant root allocation, 1 = linear response to water and nitrogen stress, >1 more-than-proportional response (only for Rt_ACType = 2)	dimensionless	0 – 2 (0)	(Crop Parameters/ Roots)
64	Cq_RtDiam[Cr]	Crop root diameter. It is used in calculating water and nutrient uptake.	cm	0.05 – 1 (0.02)	(Crop Parameters/ Roots)
65	Cq_Seed[Cr]	Seed weight (initial C_CarbHydrReserves to be used for growth).	kg m^{-2}	0.001 – 0.1 (0.004)	(Crop Parameters/ Crop Growth)
66	Cq_SingleCycle?	A parameter deciding what happens after fruits are ripe: 1 = annual that dies back, 0 = perennial that returns to crop stage =1.	dimensionless	0 or 1 (1)	(Crop Parameters/ Annual or Perennial?)
67	Cq_SLA[Cr]	Crop specific leaf area = green surface area (one-sided) per unit leaf dry weight, for each crop species as a function of crop growth stage. For Cq_Atype =1, .., 5, default values are provided. Cq_AType = 6, .,10 user defined, as before.	m^2 g^{-1}	-	(Crop Parameters)
68	Cq_TimeGen[Cr]	Length of generative stage for each crop. For Cq_Atype =1, .., 5, default values are provided, but can be modified to adopt the default crop parameters to local conditions.	days	0 – 1000 (30)	(Crop Parameters/ Crop Stage)
69	Cq_TimeVeg[Cr]	Length of vegetative stage for each crop. For Cq_Atype =1, .., 5, default values are provided, but can be modified to adopt the default crop parameters to local conditions.	days	0 – 1000 (60)	(Crop Parameters/ Crop Stage)

No	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
70	Cq_TranspRatio[Cr]	Amount of water needed per unit dry matter production of each crop species. For Cq_Atype =1, .., 5, default values are provided. For Cq_AType=6, .., 10 user defined	l kg^{-1}	200 – 600 (300)	(Crop Parameters/ Crop Growth)
71	Cq_WeedType	Weed type. This is user defined. Weed biomass growth follows the rules of crop growth. It takes the same type of parameters as crop. All the related input parameters are in Excel sheet	dimensionless	6 – 10 (10)	Management/Weed Growth
72	E_BulkDens	Bulk density used in converting soil mass movement to changes in volume of topsoil per zone	g cm^{-3}	0.5 – 1.6 (1.4)	Soil Erosion
73	E_CovEffT[Tree]	Tree cover efficiency factor (per unit tree LAI)	dimensionless	0 – 1 (0.5)	(Tree Parameters/ Erosion Protection)
74	E_Entrailment CoeffBarePlot	Entrailment coefficient for sediment movement (Rose equation) in the absence of vegetative soil cover	kg^{-1} (soil) mm^{-1} m^2	0 – 1 (02)	Soil Erosion
75	E_ErosiType	Parameter to decide on model of erosion used. 1 = using USLE, 0 = using Rose	dimensionless	0/1 (1)	Soil Erosion
76	E_FilterEff	Filter efficiency in retaining soil sedimentation in plot	dimensionless	0 – 1 (0.7)	Soil Erosion
77	E_PloughDoY	Date of ploughing	Julian days	1 – 365 (364)	Soil Erosion
78	E_PloughY	Year of ploughing	dimensionless	0 – 100 (100)	Soil Erosion
79	E_RainFac	A multiplier determining impact of rainfall on soil erosion	dimensionless	0 – 10 (1)	Soil Erosion
80	E_SoilMoveperPlough	Amount of soil moved per ploughing event	kg	0 – 500 (0)	Soil Erosion
81	E_SoilType	Type of soil. 1 = medium, 2 = sandy, 3 = clay	dimensionless	1, 2, 3 (1)	Soil Erosion
82	Evap_Pot	Amount of water evaporating from top soil in absence of plant cover	mm day^{-1}	0 – 10 (3)	Soil Evaporation
83	Light_kT[Tree]	Tree canopy (leaves component) extinction light coefficient = the efficiency of tree foliage in absorbing light	dimensionless	0 – 1 (0.7)	(Tree Parameters/ Light Capture)
84	Mc_Carbon	Proportion of total carbon in plant litter and residue	dimensionless	0 – 0.5 (0.42)	Soil Organic Matter
85	Mc_ExtOrgLig [ExtOrInp]	Lignin concentration of external input.	dimensionless	0 – 1 (0.2)	Litter Quality/Quality of ext. organic input
86	Mc_InitMetab[Zone]	Initial amount of C in metabolic Litter pool of each zone	g m^{-2}	0 - 2 (0)	Soil Organic Matter
87	Mc2_ClaySilt	Proportion of clay and silt in the soil (weighted average over the layers containing soil organic matter), influencing the rates of decomposition	dimensionless	0 – 1 (0.516)	Soil Organic Matter
88	Mc2_InitMetab[Zone]	Initial amount of C in metabolic SOM pool of each zone	g m^{-2}	0 - 2 (0)	Soil Organic Matter
89	Mc2_SOMDistribution [SoilLayer]	Relative distribution of carbon between different soil layers	fraction	0 – 1 (1, 0.2, 0.1, 0.05)	Soil Organic Matter
90	Mn_CNActTarget	C:N ratio of active pools	dimensionless	5 – 10 (8)	Soil Organic Matter
91	Mn_CNPass	C:N ratio of passive pools	dimensionless	8 – 15 (11)	Soil Organic Matter
92	Mn_CNSlwTarget	C:N ratio of slow pools	dimensionless	8 – 15 (11)	Soil Organic Matter
93	Mn_CNStruc	C:N ratio of structural pools	dimensionless	100 – 200 (150)	Soil Organic Matter
94	Mn_ExtOrgN [ExtOrInp,SlNut]	N concentration of external input	dimensionless	0 – 0.1 (N=0.05, 0.1; P=0.005, 0.001)	Litter Quality/Quality of ext. soil organic

No	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
95	Mn_InitAct[Zone]	Initial amount of N in active Litter pool of each zone	mg cm^{-3}	0 – 1 (0.01)	Soil Organic Matter
96	Mn_InitMetab[Zone]	Initial amount of N in metabolic Litter pool of each zone	mg cm^{-3}	0 – 1 (0)	Soil Organic Matter
97	Mn_InitPass[Zone]	Initial amount of N in passive Litter pool of each zone	mg cm^{-3}	0 – 1 (0)	Soil Organic Matter
98	Mn_InitSlw[Zone]	Initial amount of N in slow Litter pool of each zone	mg cm^{-3}	0 – 1 (0.01)	Soil Organic Matter
99	Mn_InitStruc[Zone	Initial amount of N in structural Litter pool of each zone	mg cm^{-3}	0 – 1 (0)	Soil Organic Matter
100	Mn_NutRatAct[P]	Ratio of N to P (N:P) in active organic matter pools	dimensionless	1 – 10 (0)	Soil Organic Matter
101	Mn_NutRatMetab[P]	Ratio of N to P (N:P) in metabolic organic matter pools	dimensionless	1 – 10 (0)	Soil Organic Matter
102	Mn_NutRatMetab[P]	Ratio of N to P (N:P) in passive organic matter pools	dimensionless	1 – 10 (0)	Soil Organic Matter
103	Mn_NutRatSlw[P]	Ratio of N to P (N:P) in slow organic matter pools	dimensionless	1 – 10 (0)	Soil Organic Matter
104	Mn_NutRatStruc[P]	Ratio of N to P (N:P) in structural organic matter pools	dimensionless	1 – 10 (0)	Soil Organic Matter
105	Mn2_InitAct[Zone]	Initial amount of N in active SOM pool of each zone	mg cm^{-3}	0 – 1 (0.2)	Soil Organic Matter
106	Mn2_InitAct[Zone]	Initial amount of N in active SOM pool of each zone	mg cm^{-3}	0 – 1 (0.2)	Soil Organic Matter
107	Mn2_InitMetab[Zone]	Initial amount of N in metabolic SOM pool of each zone	mg cm^{-3}	0 – 1 (0)	Soil Organic Matter
108	Mn2_InitPass[Zone]	Initial amount of N in passive SOM pool of each zone	mg cm^{-3}	0 – 1 (3.9)	Soil Organic Matter
109	Mn2_InitSlw[Zone]	Initial amount of N in slow SOM pool of each zone	mg cm^{-3}	0 – 1 (1)	Soil Organic Matter
110	Mn2_InitStruc[Zone	Initial amount of N in structural SOM pool of each zone	mg cm^{-3}	0 – 1 (0)	Soil Organic Matter
111	N_BypassMacro*i*[Zone]	Prefential flows of nutrients in the leachate relative to average concentration * water flow; values < 1 indicates retardation of nutrients due to bypass flow of water in macropores	dimensionless	0 – 2 (1)	Soil Nutrient / Bypass macro
112	N_DiffCoef[SlNut]	Nitrogen diffusion coefficient	cm^2 day^{-1}	0 - 1 (1)	Soil Nutrient / Diffusivity coefficient
113	N_FracNO3i[Zone]	Fraction of NO_3 of total N in i-th soil layer	dimensionless	0 - 1 (0.4)	Soil Nutrient / Nitrate Fraction
114	N_ImInit[Zone,SlNut]	Initial amount of nutrient in immobile pool of each zone	mg cm^{-3}	0 – 0.1 (N = 0.05, P = 0.01)	Soil Nutrient / Initial Immobile Nutrient
115	N_Init*i*[Zone,SlNut]	Initial amount of nutrient in soil layer *i* of each zone	mg cm^{-3}	0 – 0.5 (N = 0.05, P = 0.01)	For N in Soil Nutrient / Initial Soil Nutrient For P in (Phosphorus)
116	N_KaNH4*i*[Zone]	Apparent (instantaneous) adsorption constant or ratio of amount NH_4 adsorbed and amount in solution for *i*-th layer	mg cm^{-3}	0 – 1 (5)	Soil Nutrient / N Adsorption constant
117	N_KaNO3*i*[Zone]	Apparent (instanteneous) adsorption constant or ratio of amount NO_3 adsorbed and amount in solution for *i*-th layer	mg cm^{-3}	0 – 1 (0.3)	Soil Nutrient / N Adsorption constant
118	N_KaPDef*i*[Zone]	Apparent (instantaneous) adsorption constant for inorganic P, or ratio of amount of inorganic P adsorbed ant the amount in soil solution; the adsorption constant depends on the P concentration oin soil solution and is read in a tabular form (as graphical input parameter).	mg cm^{-3}	table	(Phosphorus)

No	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
119	N_Lat4InflowRelConc	Nutrient concentrations in the incoming sub-surface flows into zone 4, relative to the current average nutrient concentration in that layer across all zones in the simulated area	dimensionless	0 – 10 (1)	Agroforestry Zone
120	N_NutMobC[SlNut]	Relative rate of transfer, per unit root length density (cm cm-3), from the 'immobile' pool of nutrients to the 'mobile' or sorbed pool, due to Crop root activity	m^2 day^{-1}	0 – 0.02 (0)	(Crop Parameters/ Root impacts on nutrient mobility)
121	N_NutMob*i*	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}	0 – 0.02 (0)	Soil Nutrient/Nutrient Mobilization
122	N_NutMobT[SlNut]	Relative rate of transfer, per unit root length density (cm cm-3), from the 'immobile' pool of nutrients to the 'mobile' or sorbed pool, due to tree root activity	m^2 day^{-1}	0 – 0.02 (0)	(Tree Parameters/ Root impacts on nutrient mobility)
123	N_RhizEffKaPC[Zone]	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	m^2 day^{-1}	0 – 0.2 (0)	(Crop Parameters/ Root impacts on P mobility)
124	N_RhizEffKaPT[Zone]	Proportional reduction of the apparent adsorption constant for P due to root activity of the crop, expressed as fraction of N_KaPdef per unit tree root length density	m^2 day^{-1}	0 – 0.2 (0)	(Tree Parameters/ Root impacts on P mobility)
125	N_RtSynloc*i*	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; 1 = sharing of rhizosphere modifications by all roots present, based on their share in total root length, 0 = complete monopoly by roots modifying the rhizosphere	dimensionless	0 – 1 (0)	Roots/Roots Synlocation
126	P_BurnLab	Amount of labour involved in burning the field per unit simulated filed	person days	see EXCEL sheet Profitability	(Profitability)
127	P_CFert [PricePrice,SlNut]	Cost of fertilizer at social and private prices, respectively.	currency unit kg^{-1}		(Profitability)
128	P_CHarvLab[Crop]	Amount of labour involved in harvesting crop products per unit dry weight	person days ha^{-1} kg^{-1}		(Profitability)
129	P_CPestContLab[Crop]	Amount of labour involved in pest control per cropping season	person days ha^{-1} per cropping season		(Profitability)
130	P_CPestContPrice [Price]	Amount of direct costs (outside labourt) involved in pest control per cropping season	currency unit per ha^{-1} per cropping season	See EXCEL sheet Profitabilty	(Profitability)
131	P_CPlantLab[Crop]	Amount of labour involved in planting per cropping season	person days ha^{-1} per cropping season		(Profitability)
132	P_CSeedPrice[Price]	Cost of crop seed per kg at social and private prices, respectively.	currency unit kg^{-1}		(Profitability)
133	P_CWeedLab[Crop]	Amount of labour involved in weeding per cropping season	person days ha^{-1} per cropping season		(Profitability)
134	P_CYieldPrice [Crop, Price]	Price of crop yield per unit dry weight at social and private prices, respectively.	currency unit kg^{-1}		(Profitability)
135	P_DiscountRate	Discount rate (% per year) that applies to both social and private prices	% $year^{-1}$		(Profitability)
136	P_FenceMatCost [PriceType]	Price of off-farm material used for building or maintaining a fence around the field	currency unit		(Profitability)

No	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
137	P_ExtOrgPrice [ExtOrgInp,PriceType]	Price of external organic input	currency unit kg-1		(Profitability)
138	P_TFruitHarvLab	Amount of labour involved in harvesting fruits per unit dry weight	person days kg^{-1}	See Excel sheet Profitability	(Profitability)
139	P_TFruitPrice[Price]	Price of tree fruit yield per unit dry weight at social and private prices, respectively.	currency unit kg^{-1}		(Profitability)
140	P_TLatexHarvLab	Amount of labour involved in harvesting latex per unit dry weight			(Profitability)
141	P_TLatexPrice[Price]	Price of tree latex yield per unit dry weight at social and private prices, respectively.	currency unit kg^{-1}		(Profitability)
142	P_TPlantLab	Amount of labour involved in planting trees per unit dry weight	person days kg^{-1}		(Profitability)
143	P_TPrunLab[Tree]	Amount of labour involved in pruning trees per unit dry weight	person days kg^{-1}		(Profitability)
144	P_TPrunPrice[Price]	Price of tree prunings harvested from the field per unit dry weight at social and private prices, respectively.	currency unit kg^{-1}		(Profitability)
145	P_TSeedPrice[Price]	Costs of tree planting material per unit initial tree biomass at social and private prices, respectively.	currency unit kg^{-1}		(Profitability)
146	P_TWoodHarvLab	Amount of labour involved in harvesting wood products per unit dry weight	person days kg^{-1}		(Profitability)
147	P_TWoodPrice[Price]	Price of tree wood product yield per unit dry weight at social and private prices, respectively.	currency unit kg^{-1}		(Profitability)
148	P_UnitLabCost[Price]	Cost per unit labour at social and private prices, respectively	currency unit		(Profitability)
149	PD_CEatenBy[Animals]	Fraction of crop component lost if eaten by animals. Default animals are pigs, monkey, locust, nematode, goat, buffalo and birds	dimensionless	0 – 1 (0)	(Crop Parameters/ Pest Impacts)
150	PD_CFrugivore? [Animals]	A switch determining the presence of attack by each default animal. 0 = animals is not a crop frugivore,1 = animal is frugivore	dimensionless	0 or 1 (0)	Pest and Disease
151	PD_CFrugivoryConst [Croptype]	Constant daily fraction of crop fruit biomass removed due to the action of frugivores	dimensionless	0 – 1 (0)	Pest and Diseases
152	PD_CHerbivore? [Animals]	A switch determining the presence of attack by each default animal. 0 = animals is not a crop herbivore,1 = animal is herbivore	dimensionless	0 or 1 (0)	Pest and Disease
153	PD_CHerbivoryConst [CropType]	Constant daily fraction of crop leaf biomass removed due to the action of herbivores	dimensionless	0 – 1 (0)	Pest and Diseases
154	PD_CRhizovore? [Animals]	A switch determining the presence of attack by each default animal. 0 = animals is not a crop rhizovore,1 = animal is rhizovore	dimensionless	0 or 1 (0)	Pest and Disease
155	PD_CRhizovoryConst [CropType]	Constant daily fraction of crop root biomass removed due to the action of rhizovores	dimensionless	0 – 1 (0)	Pest and Diseases
156	PD_FenceBuildLab	Amount of labour needed to build fence for each fencing event. A graphical input.	man days	table	Pest and Disease
157	PD_FenceDecayFrac	Daily fractional decay of fence quality	day^{-1}	0 – 1(0.02)	Pest and Diseases
158	PD_FenceDOY	Schedule for day of fencing for each fencing event. A graphical input.	Julian days	table	Pest and Disease
159	PD_FenceFullQua	Maximum quality of fence	dimensionless	1 – 4 (2)	Pest and Diseases
160	PD_FenceMaint?	Switch determining fence maintenance. 1 = fence maintenance will be done automatically, 0 = no fence maintenance	dimensionless	0 or 1 (0)	Pest and Disease

No	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
161	PD_FenceMUnit	Unit improvement of fence quality once it falls below the theshold set in PD_FenceQThresh	dimensionless	0 – 2(0.25	Pest and Disease
162	PD_FenceQThresh	Theshold of (relative) fence quality below which labour will be used to repair the fence	dimensionless	0 – 2 (1)	Pests and Disease
163	PD_FenceY	Schedule for year of fencing for each fencing event A graphical input.	dimensionless	table	Pest and Disease
164	PD_Frugivore?[animals]	Flag (0 = false, 1 = true) to indicate whether or not an animal group eats fruits	-	0/1	Pest and Diseases
165	PD_HalfFenceTime	Time constant of deacy of fence quality: time interval after which qualkity is reduced by 50%	Days	0 – 365 (50)	Pest and Disease
166	PD_HalfFenceTime	Number of labour days needed to construct a fence of half the PD_FenceFullQuality	day	1 – 100 (20)	Pest and Diseases
167	PD_Herbivore?[animals]	Flag (0 = false, 1 = true) to indicate whether or not an animal group eats leaves	-	0/1	Pest and Diseases
168	PD_JumptheFence?[animals]	The degree to which animals are deterred by a fence from entering the plot	-	0 – 1 (0)	Pest and Diseases
169	PD_Lignivore?[animals]	Flag (0 = false, 1 = true) to indicate whether or not an animal group eats woody stems	-	0/1	Pest and Diseases
170	PD_PestDynamic?	Flag (0=false, 1 = true) to indicate whether or not dynamic pests and disease impacts on trees and crops will be taken into account (on top of the constant fractions)	-	0 – 1 (0)	Pest and Diseases
171	PD_PopDensOutside [animals]	Population density outside the plot, influencing the presence	-	0/1	Pest and Diseases
172	PD_Rhizovore?[animals]	Flag (0 = false, 1 = true) to indicate whether or not an animal group eats roots	-	0/1	Pest and Diseases
173	PD_TEatenBy?[Animals]	A switch determining tree attacks by specific animals. Default animals are pigs, mokey, locust, nematode, goat, buffalo and birds. 0 = no attack, 1 = attacked		0 – 1 (0)	(Tree parameters/ Pest Impacts)
174	PD_TFrugivore? [Animals]	A switch determining the presence of attack by each default animal. 0 = animals is not a tree frugivore,1 = animal is frugivore	dimensionless	0 or 1 (0)	Pest and Disease
175	PD_TFrugivoryConst [Treetype]	Constant daily fraction of tree fruit biomass removed due to the action of frugivores	-	0 – 1 (0)	Pest and Diseases
176	PD_THerbivore? [Animals]	A switch determining the presence of attack by each default animal. 0 = animals is not a tree herbivore,1 = animal is herbivore	dimensionless	0 or 1 (0)	Pest and Disease
177	PD_THerbivoryConst [Treetype]	Constant daily fraction of tree leaf biomass removed due to the action of herbivores	-	0 – 1 (0)	Pest and Diseases
178	PD_TLignivoryConst [Treetype]	Constant daily fraction of tree woody stem biomass removed due to the action of lignivores	-	0 – 1 (0)	Pest and Diseases
179	PD_TLignovore? [Animals]	A switch determining the presence of attack by each default animal. 0 = animals is not a tree lignovore,1 = animal is lignovore	dimensionless	0 or 1 (0)	Pest and Disease
180	PD_TPreference [treetype, animals]	Matrix of multipliers to derive the impact of all animals (if they are present in the plot) on the various tree types	-	0-1	Pest and Diseases
181	PD_TRhizovore? [Animals]	A switch determining the presence of attack by each default animal. 0 = animals is not a tree rhizovore,1 = animal is rhizovore	dimensionless	0 or 1 (0)	Pest and Disease
182	PD_TRhizovoryConst [Treetype]	Constant daily fraction of tree root biomass removed due to the action of rhizovores	-	0 – 1 (0)	Pest and Diseases

No	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
.183	Rain_AType	A number 1, 2 or 3 to decide rainfall rate (1= rainfall rate follows precipitation data from external file, rainfall rate follows tabulated data , 2 = rainfall rate follows random generator, 3= rainfall rate follows tabulated monthly total data)	dimensionless	1, 2 or 3 (1)	Rainfall
184	Rain_BoundHeaLi	Boundary value between heavy and light rain (only for Rain_AType=1)	mm	20 – 30 (25)	Rainfall
185	Rain_CoeffVar	Coefficient variation of rainfall in mm . It used in rainfall generated randomly (Rain_Atype=2) and rainfall based on tabulated monthly rainfall (Rain_Atype=3)	dimensionless	0 – 1	Rainfall
186	Rain_Cycle?	Parameter governing ways to read rainfall data. Corresponds to Rain_AType=1 (0 = use multiple yearrainfall data, 1 = use 1 year data in cycle/continously)	dimensionless	0 or 1 (1)	Rainfall
187	Rain_Data	Actual daily rainfall data. Entered as graphical function or read from WaNuLCAS.XLS (Stella non-CRT users only). Corresponds to Rain_AType=1.	mm	table	(WEATHER)
188	Rain_DayP	Probability of raining each day as a function of Jullian day scaled monthly. Corresponds to Rain_AType=2 and 3.	dimensionless	0 – 1 (0.32)	(WEATHER)
189	Rain_GenSeed	Seed Random Generator. For Rain_AType=2 and 3.	dimensionless	1 – 32767 (300)	Rainfall
190	Rain_Heavy	Average precipitation rate of on a heavy rain day; for Rain_AType=2.	mm day^{-1}	0 – 100 (42)	Rainfall
191	Rain_HeavyP	Probability of heavy rain; for Rain_AType=2.	dimensionless	0 – 1 (0.5)	Rainfall
192	Rain_Light	Average precipitation rate of a light rain day day; for Rain_AType=2.	mm day^{-1}	0 – 40 (9)	Rainfall
193	Rain_MonthTot	Tabulated data of monthly rainfall; for Rain_AType=3. Entered as graphical function or read from WaNuLCAS.XLS (Stella non-CRT users only).	mm $month^{-1}$	table	(WEATHER)
194	Rain_Weight[Zone]	Input weight value to decide amount of rain falling on each zone relative to other zones (eg. equal rainfall in each zone on area basis means 1:1:1:1)	dimensionless	0 – 10 (1)	Rainfall
195	Rain_YearStart	Initial year based on rainfall data at which simulation starts	dimensionless	any integer (0)	Rainfall
196	Rt_ACType	Parameter governing type of root density data for crop. 0=Lrv data available, 1=Lrv calculated using exponential function model where length root area is constant, 2= Lrv calculated using exponential function model where length root area is derived from root biomass	dimensionless	0, 1, or 2 (0)	Roots/Crop Root
197	Rt_ATType	Parameter governing type of root density data for tree. 0=Lrv data available, 1=Lrv is constant calculated using ellipticall function model, 2= Lrv is calculated using elliptical function but dynamically changes according to water or N stress	dimensionless	0, 1 or 2 (0)	Roots/Tree Root
198	Rt_CDecDepth[Cr]	Parameter governing decrease of crop root with depth; corresponds to Rt_ACType=1 and Cq_AType.	m^{-1}	0 - 10 (7)	(Crop Parameters/ Roots)
199	Rt_CDistResp[Cr]	Responsiveness of crop root distribution to the depth at which uptake of the currently limiting resource (water, N or P) is most successful. Value 0 = no response to stress, 0 – 1 = mild response, 1 = proportional change to inverse of relative depth of	dimensionless	0 – 3 (0)	(Crop Parameters/ Roots)

No	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
		uptake, > 1 = strong response. Only for Rt_ACType = 2.			
200	Rt_CHalfLife[Cr]	Crop root half-life (only for Rt_ACType=2)	days	30 – 100 (50)	(Crop Parameters/ Roots)
201	Rt_CLraConst[Cr]	Total root length per unit area. It is used to calculate crop root density in exponential decrease model (Rt_ACType=1). Also corresponds to Cq_AType.	$cm\ cm^{-2}$	0 – 150 (100)	(Crop Parameters/ Roots)
202	Rt_CLrvm*i*[Cr]	Maximum crop root length density in *i*-th soil layer; corresponds to Rt_ACType=0 and Cq_A Type.	$cm\ cm^{-3}$	0 – 15 (0.5)	(Crop Parameters/ Roots)
203	Rt_CSRL[Cr]	Specific root length (length per unit dry weight) of crop roots	$m\ g^{-1}$	50 – 100(100)	(Crop Parameters/ Roots)
204	Rt_MCHypDiam	Diameter of crop mycorrhizal hyphae	cm	0.001 – 0.05 (0.01)	Roots & Mycorrhiza
205	Rt_MCHypL	Length of crop mycorrhizal hyphae per unit infected root length	dimensionless	10 – 100 (100)	Root s &Mycorrhiza
206	Rt_MCInfFrac*i*	Fraction of crop roots that is mycorrhizal (infected) in i-th soil layer	dimensionless	0 – 1 (0)	Roots & Mycorrhiza
207	Rt_MTHypDiam	Diameter of tree mycorrhizal hyphae	cm	0.001 – 0.05 (0.01)	Roots & Mycorrhiza
208	Rt_MTHypL	Length of tree mycorrhizal hyphae per unit infected root length	dimensionless	10 – 100 (100)	Roots & Mychorriza
209	Rt_MTInfFrac*i*[Zone]	Fraction of tree roots that is mycorrhizaal (infected)	dimensionless	0 – 1 (0)	Root & Mychorriza
210	Rt_TAlloc[Tree]	Fraction of tree growth reserves allocated to roots in the absence of water or nutrient stress (only for Rt_ATType=2)	dimensionless	0 – 1 (0.1)	(Tree Parameters/ Roots)
211	Rt_TAllocResp[Tree]	Responsiveness of tree root allocation to stress factors; 0 = constant root allocation, 1 = linear response to water and nitrogen stress, >1 more-than-proportional response (only for Rt_ACType = 2),	dimensionless	0 – 2 (0)	(Tree Parameters/ Roots)
212	Rt_TDecDepthC[Tree]	Parameter governing decrease of tree root with depth ; for Rt_ATType=1	m^{-1}	0 – 10 (3)	(Tree Parameters/ Roots)
213	Rt_TDiam[Tree]	Tree root diameter. It is used in calculating water and nutrient uptake. For all root type.	cm	0.05 – 3 (0.1)	(Tree Parameters/ Roots)
214	Rt_TDistResp[Tree]	Responsiveness of crop root distribution to the depth at which uptake of the currently limiting resource (water, N or P) is most successful. Value 0 = no response to stress, 0 – 1 = mild response, 1 = proportional change to inverse of relative depth of uptake, > 1 = strong response. Only for Rt_ACType = 2.	dimensionless	0 – 5 (0)	(Tree Parameters/ Roots)
215	Rt_TDistShapeC[Tree]	Tree root distribution shape for Rt_ATType=1 and 2; for a value of 1 root length density decreases as much with horizontal as with vertical distance to the tree stem	dimensionless	0 – 2 (0.05)	(Tree Parameters/ Roots)
216	Rt_THalfLife[Tree]	Tree root half life (only for Rt_ATType=2)	days	30 – 150 (60)	(Tree Parameters/ Roots)
217	Rt_TLraX0[Tree]	Total root length per unit area at X(distance to tree)=0 (tree stem). for Rt_ATType=1	$cm\ cm^{-2}$	0 – 150 (1)	R(Tree Parameters/ Roots)

No	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
218	Rt_TLrvData*i* [Zone,Tree]	Tree root density in soil layer .*i* in each zone; for Rt_ATType=0	cm cm^{-2}	0 – 15	(Tree Parameters/ Roots)
219	Rt_TProxGini	Distribution coefficient of proximal root diameters (CumFreq = $(Diam/Diam_{max})^{TProxGini}$ of a tree, used in calculation of the specific root length of a tree root system	dimensionless	0.001 – 10 (0.3)	(Tree Parameters/ Roots)
220	S&B_2ndFireafterPileup	Number of days between piule up and secondary burn event	days	1 – 100 (5)	Management/Slash and Burn
221	S&B_CritMoist	Limit value for internal + adhering (intercepted from rainfall) moisture content of slashed necromass; below this value necromass is categorized as dry. and fire can take place	l kg^{-1}	0 – 1(0.05)	Management/Slash and Burn
222	S&B_DeadWoodFuelFact	Temperature of the fire per unit dry weight of fuel in dead wood	°C kg^{-1}	0 – 100 (10)	Management/Slash and Burn
223	S&B_FirImpPSorption	Fire impacts on P sorption, as a function of soil surface temperature increase	dimensionless	table	(Slash&Burn)
224	S&B_FirIndPMobiliz	Fire impact on mobilization fraction of P from the inorganic P immobile pool, as a function of soil surface temperature increase	dimensionless	table	(Slash&Burn)
225	S&B_FirMortSeedBank	Fractional mortality in the weed seed bank as a function of soil surface temperature increment	dimensionless	table	(Slash&Burn)
226	S&B_FuelLoadFactor	Temperature of the fire per unit dry weight of fuel in slashed necromass and structural surface litter	°C kg^{-1}	0 – 100 (10)	Management/Slash and Burn
227	S&B_MaxDryingPer	The latest time after slashing when fire can occur; if the fuel does not get dry enough before this time, no fire will be occur	days	1 – 200 (50)	Management/Slash and Burn
228	S&B_MinDryingPer	The earliest time after slashing that fire can occur	days	0 – 100 (20)	Management/Slash and Burn
229	S&B_NecroBurnFrac	Fraction of surface necromass burnt as a function of fire temperature at the soil surface.	dimensionless	table	(Slash&Burn)
230	S&B_NutVolatFracN	Volatilization fraction of N in the burnt necromass, as a function of soil surface temperature increment	dimensionless	table	(Slash&Burn)
231	S&B_NutVolatFracP	Volatilization fraction of P in the burnt necromass, as function of soil surface temperature increment	dimensionless	table	(Slash & Burn)
232	S&B_pHRecFrac	Daily recovery fraction of soil pH in the topsoil from its post-fire towards its pre-fire value	fraction	0.001–0.1 (0.01)	Management/Slash and Burn
234	S&B_PSorpRecFrac	Daily recovery fraction of the P_sorption in the topsoil from its post-fire towards its pre-fire value	fraction	0.001–0.1 (0.01)	Management/Slash and Burn
235	S&B_ScorchWRemFra	Fraction of scorched wood removed after slash and burn event	fraction	0 – 1 (0.3)	Management/Slash and Burn
236	S&B_SlashDOY	A graphical input tabulating day of year at which slashing is performed	Jullian day	table	Management/Slash and Burn
237	S&B_SlashYear	A graphical input tabulating year at which slashing is performed	integer value	table	Management/Slash and Burn
238	S&B_SOMBurnFrac	Fraction of all SOM pools in the topsoil (Layer 1) respired (C) or mineralized (N & P) as a function of soil surface temperature increment	dimensionless	table	(Slash&Burn)
239	S&B_SurfLitBurnFrac	Fraction of all surface litter respired (C) or mineralized (N & P) as a function of soil surface temperature increment	dimensionless	table	(Slash&Burn)

No	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
240	S&B_TimetoPileUp	Number of days between primary burn and pile up (redictribnution across the zones) for a secondary burn	days	1 – 100 (15)	Management/Slash and Burn
241	S&B_TimetoWoodRem	Number of days between primary burn and removal of scorched wood	days	1 – 50 (10)	Management/Slash and Burn
242	S&B_TTempTol[Tree]	Maximum fire temperature that a tree can tolerate. Temperature above the value will induce tree mortality	^{0}C	40 – 90 (75)	(Tree parameters/ Slash&Burn)
243	S&B_WatRetRecFrac	Daily recovery fraction of soil water retention in the topsoil from its post-fire towards its pre-fire value	fraction	0.001 – 0.1 (0.005)	Management/Slash and Burn
244	S&B_WetnessTempImp	Fractional reduction in fire temperature per unit of moisture content of the fuel	fraction	0 – 1 (0.5)	Management/Slash and Burn
245	S_KSatDefV*i*[Zone]	Saturated hydraulic conductivity of the soil in the absence of macropore structure, as derived from texture-based pedotransfer functions. Read from WANULCAS.XLS	cm day^{-1}	1 – 500 (100, 67, 45, 30)	(Soil Hydraulic)
246	S_KsatHperV$_i^{[}$	Ratio of saturated hydraulic conductivity in horizontal and vertical direction for layer *i*	dimensionless	0 – 5 (1)	Soil Structure
247	S_KSatInitV*i*[Zone]	Saturated hydraulic conductivity of the soil at the macropore structure existing at the start of the simulation. Read from WANULCAS.XLS	cm day^{-1}	1 – 500 (100, 67, 45, 30)	(Soil Hydraulic)
248	S_KSatVDeepSub	Saturated hydraulic conductivity of the soil below layer 4, determining the rate of vertical drainage from the soil column	cm day^{-1}	1 – 100 (10)	Soil Structure
249	S_KStrucDecay	Relative rate of decay of the macropore structure, returning the saturated hydraulic conductivity towards S_KSatDefV	day^{-1}	0 – 0.1 (0.03)	Soil Structure
250	S_RelWorm*i*	Relative impact of 'worms' (soil fauna) on increase of saturated hydraulic conductivity in each layer	dimensionless	0 – 1 (1, 0.5, 0.3, 0.1)	Soil Structure
251	S_RelWormSurf	Relative impact of 'worms' (soil fauna) increase of infiltration rate of the soil surface	dimensionless	0 – 1 (1)	Soil Structure
252	S_SoilStructDyn?	Switch determining dynamics of soil structure (0 = false, 1 = true) based on decay and re-creation of macropores by soil fauna above the texture-based default values	day^{-1}	0/1 (0)	Soil Structure
253	S_SurfInfiltrDef[Zone]	Infiltration rate of the soil surface in the absence of soil biological activity	cm day^{1}	10 – 1000 (100)	Soil Structure
254	S_SurfInfiltrInit[Zone]	Infiltration rate of the soil surface at the start of the simulation	cm day^{1}	10 – 1000 (100)	Soil Structure
255	S_WormsLikeMetab [Zone]	Activity (in arbitrary units) of soil fauna ('worms") per unit of organic inputs in the metabolic pool	m^2 kg^{-1}	0.05 – 0.1 (0.01)	Soil Structure
256	S_WormsLikeStruc [Zone]	Activity (in arbitrary units) of soil fauna ('worms") per unit of organic inputs in the structural pool	m^2 kg^{-1}	0.001 – 0.1 (0.005)	Soil Structure
257	T_ApplyFBARules?	Switch (1 = yes, 0 = no) to determine whether the allocation of biomass from the canopy to the wood (branches + stem) pools is governed by the fractal branching paremeters (allometric equations)	dimensionless	0/1 (0)	Tree parameters
258	T_CanHMax[Tree]	Maximum height of tree canopy	m	0 – 15 (2.5)	(Tree parameters/ Canopy)
259	T_CanShape[Tree]	Factor determining in which part of the tree leaves are concentrated. A value of 1 gives an even spread of tree leaves over the alley, a higher value (eg 2) concentrates tree leaves above the hedgerow	dimensionless	0 – 2 (1)	(Tree parameters/ Canopy)

No	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
260	T_CanWidthMax[Tree]	Maximum tree canopy width (excluding width of canopy in the first zone)	m	0 – 10 (2.5)	(Tree parameters/ Canopy)
261	T_ConcFruit [Nutrient,Tree]	Nutrient concentration in fruit component	dimensionless	0 – 0.1 (N=0.01, P=0.001)	(Tree parameters'N-P concentration)
262	T_ConcGroRes [Nutrient,Tree]	Nutrient concentration in carbohydrate reserves	dimensionless	0 – 0.1 (N=0.02, P=0.002)	(Tree parameters/N-P concentration)
263	T_ConcLf [Nutrient, Tree]	N concentration in leaf component of tree	dimensionless	0 – 0.1 (N=0.025, P=0.0025)	(Tree Parameters/N-P concentration)
264	T_ConcRt [Nutrient, Tree]	Nutrient concentration in tree roots (only for Rt_ATType=2)	dimensionless	0 – 0.1 (N=0.25, P=0.025)	(Tree Parameters/N-P concentration)
265	T_ConcTwig [Nutrient, Tree]	Nutrient concentration in twig component of tree	dimensionless	0 – 0.1 (N=0.01, P=0.001)	(Tree Parameters/N-P concentration)
266	T_ConcWood [Nutrient, Tree]	Nutrient concentration in wood component of tree	dimensionless	0 – 0.1 (N=0.04, P=0.004)	(Tree Parameters/N-P concentration)
267	T_Diam1Biom[Tree]	Biomass of a tree of diameter 1 cm; Intercept (a) of allometric equation (Branch biomass = a StemDiameter^b)	kg	0.01 – 1 (0)	(Tree parameters/ Allometric branching)
268	T_Diam1Branch[Tree]	Intercept (a) of allometric equation (Tree branch biomass = a Diameter^b)	kg	0.01 – 1 (0.3)	(Tree parameters/ Allometric branching)
269	T_Diam1CumLit[Tree]	Cumulative litterfall expected for a stem diameter of 1 cm	kg	0.01 – 1 (0.3)	(Tree parameters/ Allometric branching)
270	T_Diam1LfTwig[Tree]	Intercept (a) of allometric equation (Leaf &Twigbiomass = a StemDiameter^b)	kg cm^b	0.01 – 1 (0)	(Tree parameters/ Allometric branching)
271	T_Diam1RtLeng[Tree]	Length of (branch) roots of a tree root with a proximal (at stem base) diameter of 1 cm; Intercept (a) of allometric equation (RootLength = a StemDiameter^b)	cm cm^{-b}	0.01 – 1 (10)	(Tree parameters/ Roots)
272	T_Diam1RtWght [Tree]	Biomass of a (branched) tree root with a proximal (at stem base) diameter of 1 cm; Intercept (a) of allometric equation (Root weight = a StemDiameter^b)	kg cm$^{-b\,z}$	0.01 – 1 (0.5)	(Tree parameters/ Roots)
273	T_DiamSlopeBiom [Tree]	Power coefficient (b) of allometric equation (Branch biomass = a StemDiameter^b)	cm^{-1}	0 – 3(0)	(Tree parameters/ Allometric branching)
274	T_DiamSlopeBranch [Tree]	Power coefficient (b) of allometric equation (Tree branch biomass = a Diameter^b)	cm^{-1}	0 – 3 (0)	(Tree parameters/ Allometric branching)
275	T_DiamSlopeCumLit [Tree]	Power coefficient (b) of the alloemtric equation describing the increase of cumulative litterfall with stem diameter	cm^{-1}	0 – 3 (0)	(Tree parameters/ Allometric branching)
276	T_DiamSlopeLfTwig [Tree]	Power coefficient (b) of allometric equation (Leaf&Twig biomass = a StemDiameter^b)	dimensionless	1 – 3 (2.0)	(Tree Parameters/ Allometric branching)
277	T_DiamSlopeRtLeng [Tree]	Power coefficient (b) of allometric equation (RootLength = a StemDiameter^b)	dimensionless	1 – 3 (1.5)	(Tree parameters/ Roots)
278	T_DiamSlopeRtWght [Tree]	Power coefficient (b) of allometric equation (RootWeight = a StemDiameter^b)	dimensionless	1 – 3 (2.3)	(Tree parameters/ Roots)
279	T_DOYFlwBeg[Tree]	The earliest day in a year when tree start to flowers	Julian days	1 - 365 (200)	(Tree parameters/ Growth stage)
280	T_DOYFlwEnd[Tree]	The latest day in a year when tree start to flowers	Julian days	1 - 365 (250)	(Tree parameters/ Growth stage)

No	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
281	T_FruitAllocFrac[Tree]	Allocation of biomass to fruit each day	kg m^{-2} day^{-1}	0 – 1 (0)	Management/Fruit Harvesting
282	T_FruitHarvFrac[Tree]	Harvest index for fruit. Constant value for every fruiting season	dimensionless	0 – 1 (0)	Management/Fruit Harvesting
283	T_GroMax[Tree]	Maximum growth rate of hedgerows at full canopy closure	kg m^{-2} day^{-1}	0 – 0.1 (0.02)	(Tree parameters/ Growth)
284	T_GroResFrac[Tree]	Fraction of tree carbohydrate reserves converted to biomass during regrowth stage after pruning	day^{-1}	0 – 0.5 (0.05)	(Tree parameters/ Growth)
285	T_InitCanBiom[Tree]	Initial amount of biomass in tree canopy (leaf and small stems)	kg m^{-2}	0 – 1 (0)	Tree parameters
286	T_InitGroRes[Tree]	Initial amount of tree carbohydrates as reserves of tree potential growth	kg m^{-2}	0 – 1 (0.01)	Tree parameters
287	T_InitWoodBiom[Tree]	Initial amount of biomass in tree stem	kg m^{-2}	0 – 1 (0)	Tree Parameters
288	T_InitWoodH[Tree]	Initial value of tree bare stem height (tree height excluded canopy)	m	0 – 15 (0)	Tree Parameters
289	T_KillDOY	Schedule date, day of year to kill tree	Jullian day	1 – 365 (1)	Management/Killing Tree
290	T_KillY	Schedule date, year to kill tree	dimensionless	any integer value	Management/Killing Tree
291	T_LAIMax[Tree]	Maximum value of LAI in the tree canopy	dimensionless	0 – 5 (5)	(Tree parameters/ Canopy)
292	T_LAIMinMaxRatio [Tree]	Parameter describing canopy thickness/dense. Value 1 is maximum thickness	dimensionless	0 – 1 (0.6)	(Tree Parameters/ Canopy)
293	T_LifallDroughtFrac [Tree]	Fraction of tree biomass becomes litterfall due to drought	day^{-1}	0 – 1 (0.2)	(Tree Parameters/ Litterfall)
294	T_LifallRed [Nutrient, Tree]	Reducing factor for nutrient concentration of tree litterfall which depend on type of tree	dimensionless	0 – 2 (1)	(Tree Parameters/ Litterfall)
295	T_LifallThreshWStress [Tree]	Threshold value for tree litterfall due to drought	dimensionless	0 – 1 (0.95)	(Tree Parameters/ Litterfall)
296	T_LifallWeight[Zone]	Input weight value governing amount of tree litterfall going into each zone relative to other zones (eg. 1:1:1:1 means equal mulch given in each zones on area basis)	dimensionless	0 – 10 (1, 0, 0, 0)	Litterfall
297	T_LightRelMaxGr[Tree]	Relative light intensity at which shading starts to affect tree growth	dimensionless	0 - 1 (1)	(Tree Parameters/ Light Capture)
298	T_LignLifall[Tree]	Lignin concentration of tree litterfall (eg. 20%=0.2)	dimensionless	0 – 1 (0.4)	(Tree Parameters/ Litter Quality)
299	T_LignPrun[Tree]	Lignin concentration of pruned tree biomass (eg. 20%=0.2)	dimensionless	0 – 1 (0.4)	(Tree Parameters/ Litter Quality)
300	T_LignRt	Lignin concentration of tree root	dimensionless	0 – 1 (0.2)	(Tree Parameters/ Litter Quality)
301	T_LWR[Tree]	Leaf Weight Ratio = leaf dry weight per unit shoot dry weight	dimensionless	0 – 5 (0.7)	(Tree Parameters/ Growth)
302	T_MycMaxInf	Fraction of tree roots infected by mychorrhiza for a soil layer where the Rt_MTInfFrac parameter is 1	dimensionless	0 – 1	(Tree Parameters/ Mychorrhiza
303	T_NFixDayFrac[Tree]	Fraction of current N deficit derived from atmospheric N_2 fixation per day for each tree if T_NFixVariable = 1 (('true')	day^{-1}	0 - 1 (0.4)	(Tree Parameters/N Fixation)
304	T_NFixDWMaxFrac [Tree]	Maximum fraction of the T_GroRes[Dw] pool that can be respired for N_2 fixation if T_NFixVariable = 0 (('false')	day^{-1}	0 - 0.5 (0.1)	(Tree Parameters/N Fixation)
305	T_NFixDWUnitCost [Tree]	Dry weight cost for respiration per unit N_2 fixation, if T_NFixVariable = 0 (('false')	kg [dw] g^{-1} [N]	0 - 1 (0.01)	(Tree Parameters/N Fixation)
306	T_NFixResp[Tree]	Responsiveness of N_2 fixation to N stress (N in biomass divided by N target), if	dimensionless	0 - 5 (1)	(Tree Parameters/N fixation)

No	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
		T_NFixVariable = 0 (('false')			
307	T_NFixVariable?[Tree]	Switch (0 = false, 1 = true) to choose between variable (N-stress dependent) versus constant N_2 fixation as fraction of N deficit	dimensionless	0 or 1 (0)	(Tree Parameters/N fixation)
308	T_PlantDOY	Schedule for date of planting time. Entered from WANULCAS.XLS	Julian days	table	(Tree Management)
309	T_PlantY	Schedule for year of planting time. Entered from WANULCAS.XLS	dimensionlee	table	(Tree Management)
310	T_PrunDoY	Schedule for date of pruning. Entered from WANULCAS.XLS	Julian days	1 – 365	(Tree Management)
311	T_PrunFrac?	Switch determining whether the fraction of tree canopies being pruned depends on tree type (0 = false, 1 = true)	dimensionless	0 or 1 (1)	Management/Pruning
312	T_PrunFracC[Tree]	Fraction of tree canopy gets pruned, for T_PrunFrac? = 0	dimensionless	0 - 1 (1)	Management/Pruning
313	T_PrunFracD[Tree]	Fraction of tree canopy that gets pruned, for T_PrunFrac? = 1	dimensionless	table	(Tree Management)
314	T_PrunHarvFrac?	Parameter governing type of harvested pruning fraction. 0 = constant harvested pruning fraction through out the simulation, 1 = dynamic harvested	dimensionless	0 or 1 (0)	Management/Pruning
315	T_PrunHarvFracC[Tree]	Fraction of tree pruned biomass harvested. (constant value)	dimensionless	0 or 1 (0)	Management/Pruning
316	T_PrunHarvFracD[Tree]	Fraction of tree pruned biomass harvested. Value changes overtime	dimensionless	0 or 1 (0)	(Tree Management)
317	T_PrunHarvRemain	Fraction of tree stem (wood) remain after pruning	dimensionless	0 – 1 (0.1)	Management/Pruning
318	T_PrunLimit	Critical total LAI of all trees shadowing the crop zone, triggering a pruning event	dimensionless	0 – 5 (0.5)	Management/Pruning
319	T_PrunPlant?[Tree]	Parameter governing pruning decision. 1 = tree is automatically pruned before crop planting , 0 = tree does not automatically pruned	dimensionless	0 or 1 (1)	Management/Pruning
320	T_PrunRecov[Tree]	Time needed for tree to recover after pruning	days	0 – 30 (14)	Management/Pruning
321	T_PrunStageLimit[Tree]	The latest crop stage at which automatic pruning is still performed. Corresponds to T_PrunPlant? = 1	dimensionless	1 – 2 (1.8)	Management/Pruning
322	T_PrunWeight [Zone, Tree]	Input weight value governing amount of tree pruning going into each zone relative to other zones (eg. equal pruned biomass given in each zones on area basis means 1:1:1:1)	dimensionless	0 – 10 (0, 1, 1, 1)	Management/Pruning
323	T_PrunY[Tree]	Schedule for year of pruning. Entered from WANULCAS.XLS	dimensionless	table	(Tree Management)
324	T_RainWStorCap[Tree]	Rainfall intercepted by tree stored as thin film at leaf surface	dimensionless	(1)	(Tree Parameters/ Rain Interception)
325	T_SLA[Tree]	Tree specific leaf area = tree leaf surface area per unit leaf dry weight	$m^2\ kg^{-1}$	0 – 30 (7)	(Tree Parameters/ Growth)
326	T_SlashLab	Amount of labour involved in slashing the field per unit simulated filed as a function of biomass slashed	person days	table	Management/Slash and Burn
327	T_SlashLabour	Amount of labour needed to slash plot	man days	table	Management/Slash and Burn
328	T_SlashSellWoodFrac [Tree]	Indicates the fraction of wood that is removed from the plot at the time of slashing the vegetation	dimensionless	0 – 1 (0)	Management/Slash and Burn
329	T_StageAftPrun[Tree]	Tree growth stage after pruning	dimensionless	0 – 2 (1)	(Tree Parameters/ Growth stage)

No	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
330	T_StageInit[Tree]	Initial stage of tree when it was planted. If tree already growing at the start of simulation, it is the stage at the start of simulation time	dimensionless	0 – 2 (0.5	(Tree Parameters/ Growth stage)
331	T_TimeGenCycle[Tree]	Length of generative cycles of tree	integer	0 – 1000 (120)	(Tree Parameters/ Growth stage)
332	T_TimeVeg[Tree]	Length of vegetative cycles of tree	integer	0 – 1000 (120)	(Tree Parameters/ Growth stage)
333	T_TranspRatio[Tree]	Amount of water needed per unit dry matter production of tree	l kg^{-1}	0 – 500 (300)	(Tree Parameters/ Growth stage)
334	T_TreesperHa	Tree plant density	dimensionless	any integer	Tree Parameters
335	T_WoodHarvDOY [Tree]	Schedule for date of pruning. Entered from WANULCAS.XLS	Julian days	table	(Tree Management)
336	T_WoodHarvY[Tree]	Schedule for year of timber harvesting. Entered from WANULCAS.XLS	dimensionless	table	(Tree Management)
337	Temp_AType	A number governing type of soil temperature data used in the simulation(0= constant value of soil temperature , 1 =read from monthly average data,2=read from daily data which is read from external file)	dimensionless	0, 1 or 2 (0)	Soil Temperature
338	Temp_Cons	Soil temperature throughout the simulation; corresponds to Temp_AType=0	^{0}C	15 – 40 (28)	Soil Temperature
339	Temp_DailyData	Actual daily data of soil temperature; corresponds to Temp_AType=2. Read from WaNuLCAS.XLS	^{0}C	-	(WEATHER)
340	Temp_DailyPotEvap	Daily potential evaporation. Entered from WANULCAS.XLS	day^{-1}	-	(WEATHER)
341	Temp_MonthAvg	Monthly average of soil temperature; corresponds toTemp_AType=1. Entered as graphical function	^{0}C	-	Soil Temperature
342	Temp_PotEvapConst?	Parameter governing type of soil evaporation potential data. 1 = constant throughout simulation, 0 = daily data	dimensionless	0 or 1 (1)	Soil Temperature
343	TW_PotSuctAlphMax [Tree]	Plant potential where transpiration is (1-Alpha)*potential transpiration, where Alpha is a small value (e.g. 0.01)	cm	-7000 – -3 000 (-5000)	(Tree Parameters/ Water Uptake)
344	TW_PotSuctAlphMin [Tree]	Plant potential where transpiration is Alpha*potential transpiration, where Alpha is a small value (e.g. 0.01)	cm	-30000 – -10000 (-15000)	(Tree Parameters/ Water Uptake)
345	W_FieldCapkCrit*i* [Zone]	Field capacity determined by a threshold rate of subsequent drainage (Kcrit) that is set in the pedotransfer worksheet; the actual field capacity used is the maximum of this value and the field capacity derived from the height above a groundwater table		table	(Soil Hydraulic)
346	W_Hyd?	Parameter governing water hydraulic lift application in model. 1= apply hydraulic lift in overall water balance, 0=otherwise	dimensionless	0 – 1	Soil Water
347	W_PhiP$_x$*i*[Zone]	Graphs showing relationship between pressure head in *i*-th soil layer of each zone and matrix flux potential (the index x refers to the plants with the highest (H), lowest (L), medium-high (MH) or medium low (ML) rank of root water potential), but the graphs will be identical.	cm^2 day^{-1}	table	(Soil Hydraulic)
348	W_PhiTheta*i*[Zone]	Matrix flux potential at a given theta/soil water content in layer *I* of each zone.	cm^2 day^{-1}	table	(Soil Hydraulic)
349	W_PTheta*i*[Zone]	Graphs showing relationship between volumetric soil water content and pressure head in *i*-th soil layer of each zone.	cm	table	(Soil Hydraulic)

No	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
350	W_ThetaInacc*i*[Zone]	Amount of volumetric soil water in *i*-th soil layer of each zone not available for plant. It is value of volumetric soil water at pF= 4.2 or P = -16000.	l m^{-2} day^{-1}	table	Soil Water
351	W_ThetaInit*i*[Zone]	Initial volumetric soil water content in *i* -th soil layer of each zone	ml cm^{-3}	0 – 0.1 (0.0339)	Soil Water
352	W_ThetaP*i*[Zone]	Graphs showing relationship between pressure head in *i*-th soil layer of each zone and volumetric soil water content.	cm	table	(Soil Hydraulic)
353	W_ThetaPMax[Zone]	Volumetric soil water content at a given maximum soil potential at top layer.	cm	table	(Soil Hydraulic)

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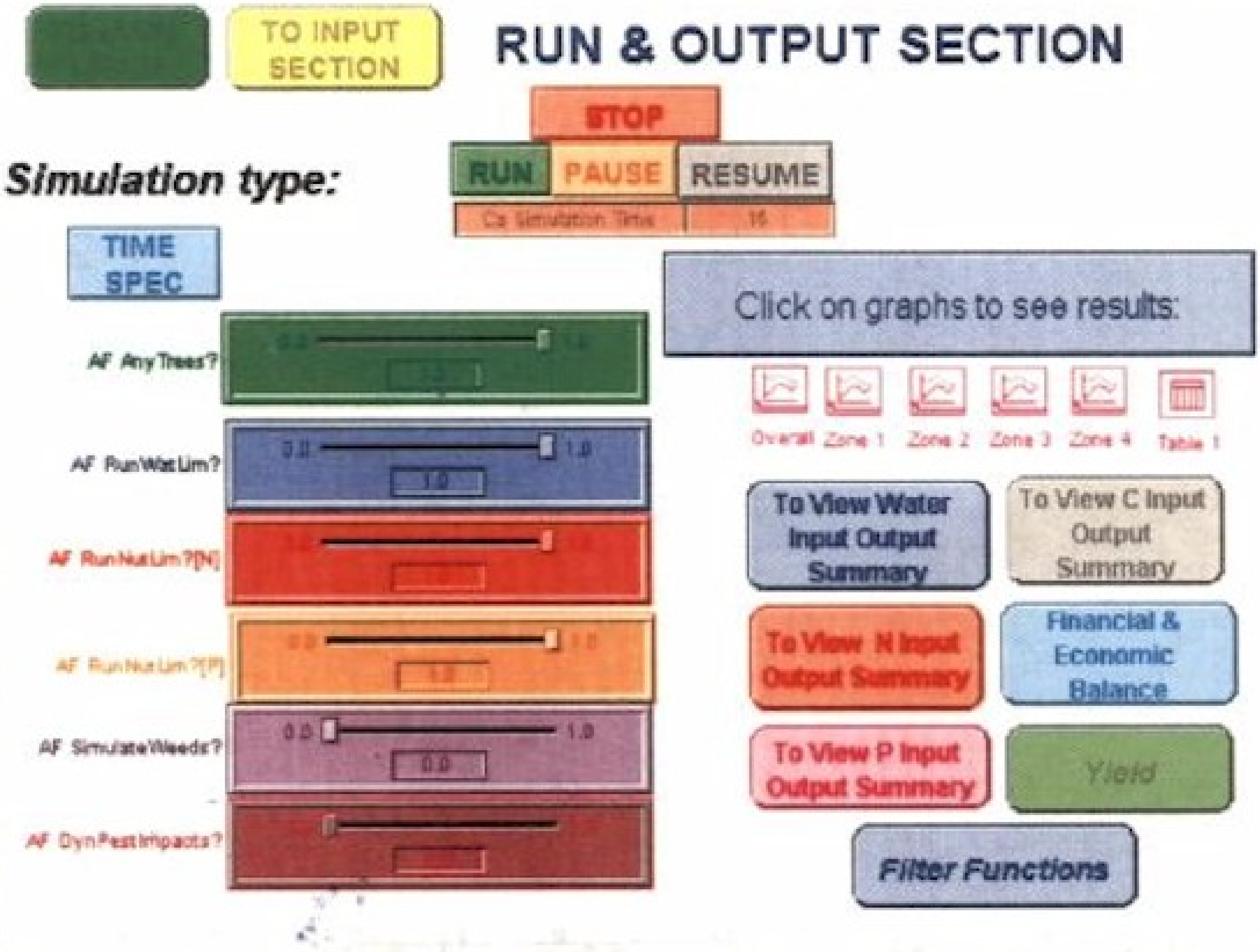

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