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:

$$LrvC(i,j)=Lra(i)DecWDepthC\ e^{(-DecWDepthC0.5(Depth(i,j))+(Depth(i,j-1)))} \qquad \textbf{[29]}$$

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 4.0

Rt_ACType	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_CdistResp. For Rt_CDistResp: 0 => no response, 0-1 => mild response 1 => 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, 0-1 => fairly late response to stress, 1 => 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.

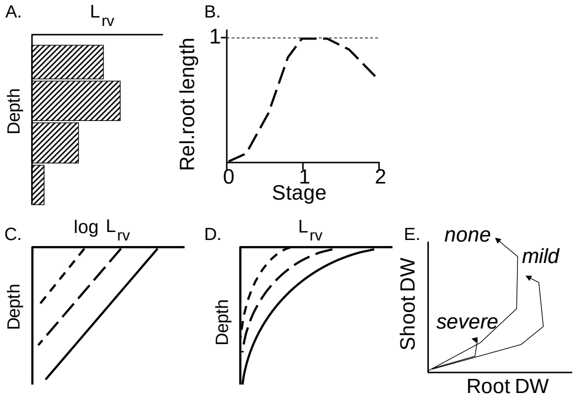


Figure 3.18. Distribution and development of crop root length density; A. Arbitrarily set values of maximum L_{rv} per depth interval (Rt_ACType = 0); B. multiplier to derive daily actual L_{rv} from maximum values per layer (Rt_ACType = 0 and 1); C Exponential decrease of L_{rv} with depth (on log scale), 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).

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.

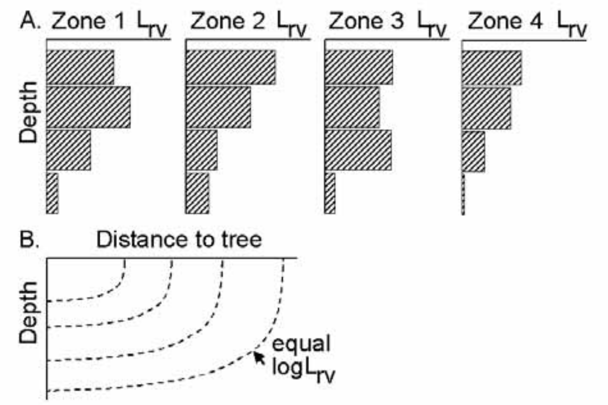


Figure 3.19. Root length density distribution for tree; A. (Rt_ATType = 0) user input of root length density for each cell ij; B. (Rt_ATType = 1) tree roots distributed according to an elliptical function.

3.5.2. Tree root length density

Four 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:

$$Lrv(i,j) = LraX0 * RtTDecDepth * e^{-RtTDecDepth\sqrt{Depth_j^2 + (RtDistShapeHorDist_i)^2}} \quad [30]$$

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.

$$Lrv = e^{0.25(\ln(Lrv_{00}) + \ln(Lrv_{01}) + \ln(Lrv_{10}) + \ln(Lrv_{11}))} \quad [31]$$

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

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.

Rt¬ATType = 3 simulates fine and coarse roots. This option describes the dynamics of fine tree root density in soil voxels (various layers and zones of the soil) and the consequences for coarse roots development to keep up with the transport demand. The dynamics of fine roots is modelled using voxel automata rules. The allocation of fine rootsto a voxel is based on current root length and its previous-day uptake efficiency. A stand alone **STELLA** model is available to learn more about this tree root dynamics option.

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:

$$T\_Root = Rt\_TWghtDiam1\, Rt\_T\,ProxDiam^{Rt\_TWghtDiamSlope} \qquad [32]$$

$$Rt\quad TLength = Rt\quad TLengDiam1\, Rt\quad T\,ProxDiam^{Rt\_TLengDiamSlope} \qquad [33]$$

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:

$$CumFreq = \left(T\,ProxDiam / T\,ProxDiam_{max}\right)^{T\,ProxGini} \qquad [34]$$

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, a_1 for T_DiamRtWght1, b_1 for T_DiamSlopeRtWght, a_2 for T_DiamRtLeng1, b_2 for T_DiamSlopeRtLeng and n for T_ProxGini):

$$Freq(D) = dCumfreq / dD = T\,ProxGini D_{\max}^{(-T\,ProxGini)} D^{(T\,ProxGini-1)} \qquad [35]$$

We can derive the total dry weight T_Root (Wt) from 42 and 44 as:

$$T\_Root = \int_0^{D_{max}} Freq\,W\;dD = a_1 n\, D_{max}^{-n} \int_0^{D_{max}} D^{b1+n-1} dD = a_1 n D_{max}^{b1} / (b_1 + n) \qquad [36]$$

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

$$SumD_r^2 = nD_{max}^2 / (2+n) \qquad [37]$$

and the equivalent single proximal root diameter as the square root of $SumD_r^2$.
Equations (36) and (37) can be used to derive the maximum proximal root diameter D_{max}:

$$D_{\max} = \left(W_t\left(b_1+n\right)/\left(a_1 n\right)\right)^{1/b1} = \left(sumD_r^2\left(2+n\right)/n\right)^{0.5} \qquad [38]$$

Relations between W$_t$ and SumD$_r^2$ can now be obtained as:

$$W_t = \left(\frac{(a_1 n)}{(b_1+n)}\right)\left(\frac{sumD_r^2(2+n)}{n}\right)^{b1/2} \qquad [39]$$

and

$$SumD_r^2 = n/\left(2+n\right)\left\{W_t\left(b_1+n\right)/\left(a_1 n\right)\right\}^{2/b1} \qquad [40]$$

Similarly, from (42) and (44) we obtain Rt_TLenght (L$_t$) as:

$$L_t = \left(a_2 n\right)/\left(b_2+n\right)\left\{SumD_r^2\left(n+2\right)/n\right\}^{b2/2} \qquad [41]$$

and from [50] and [51]:

$$L_t = \left(a_2 n\right)/\left(b_2+n\right)\left\{W_t\left(b_1+n\right)/\left(a_1 n\right)\right\}^{b2/b1} \qquad [42]$$

Finally, the specific root length SRL is obtained as function of W$_t$

$$SRL\left(W_t\right) = L_t/W_t = \left(a_2 n\right)/\left(b_2+n\right)\left\{\left(b_1+n\right)/\left(a_1 n\right)\right\}^{b2/b1} W_t^{b2/b1-1} \qquad [43]$$

Equation (53) 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 3.20)

$$RtDiamAV_{ij} = \left[\frac{Rt\_CLrv_{ij}\sqrt{Rt\_CDiam} + Rt\_TLrv_{ij}\sqrt{Rt\_TDiam}}{Rt\_CLrv_{ij} + Rt\_TLrv}\right]^2 \qquad [44]$$

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:

$$EffLrvC_{ij} = LrvC_{ij}\left[1 + \frac{Inffrac\;.HypLeng\;.\sqrt{HypDiam}}{\sqrt{RtDiamC}}\right] \quad [45]$$

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.

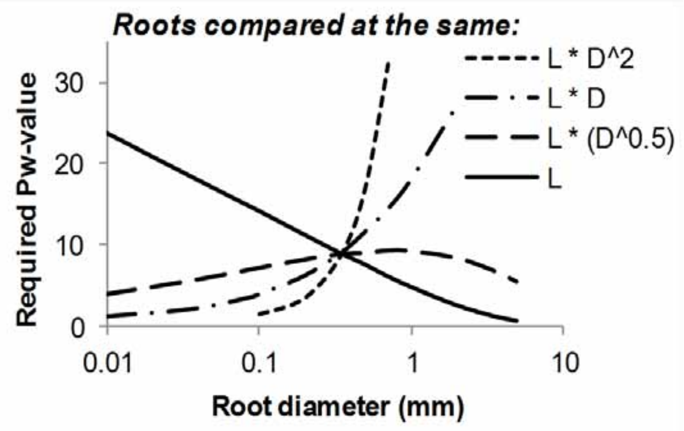


Figure 3.20. Effect of root diameter on potential uptake when root systems of different diameter are compared at equal length, root surface area or volume (weight); the smallest effect of root diameter exists when root length times the square root of the root diameter is used (Van Noordwijk and Brouwer, 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 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) (Figure 3.21).

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 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.

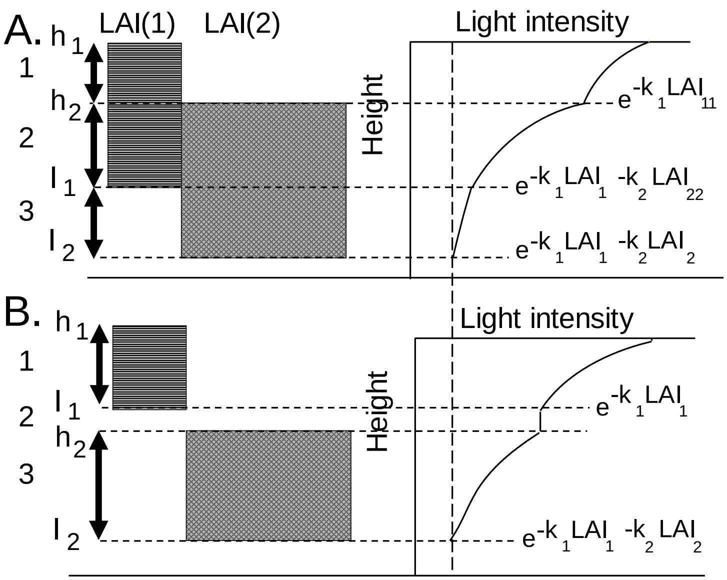


Figure 3.21. Light capture in a two-component leaf canopy, as used in WaNuLCAS; three zones can be distinguished: an upper zone with only one species, a middle one with both and a lower one with only one (usually not the same as in the upper zone); total light capture in the shared zone may be apportioned relative to the leaf area index of both species in that zone (compare Kropff and Van Laar, 1993).

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% (Figure 3.22)

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

1. sort the four values (three trees plus crop) of upper canopy boundary ($CanU_{pi}$),
2. calculate the canopy boundary values $CanBound_j$ 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:

$$LAI_{ij} = LAI_i\left(MIN\left(CanUp_i, CanBound_j\right) - MAX\left(CanLow_i, CanBound_{j+1}\right)\right)/\left(CanUp_i - CanLow_i\right) \quad \textbf{[46]}$$

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

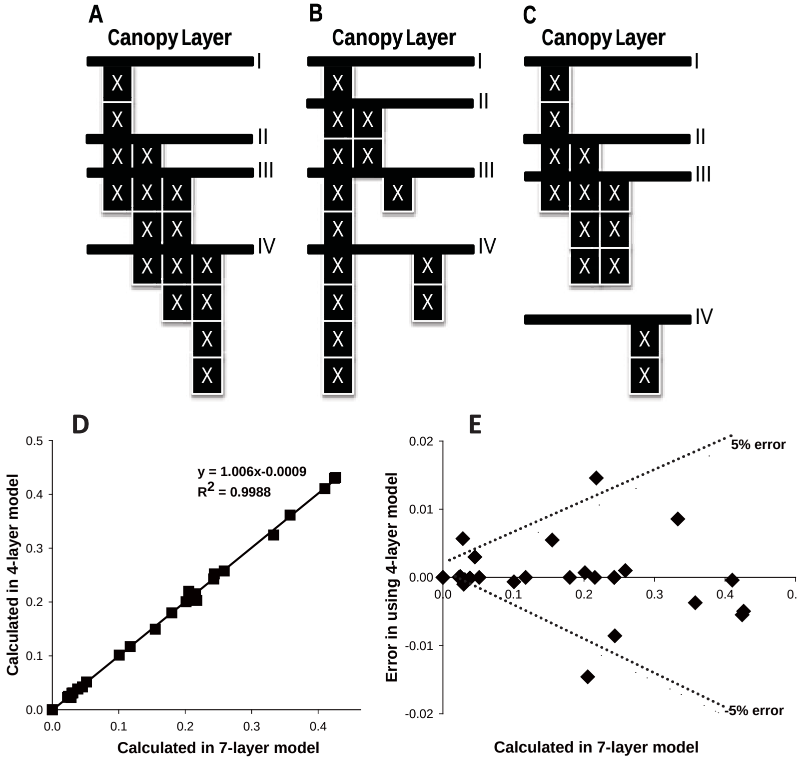


Figure 3.22. A, B and C Three examples of canopy distribution of four plant types within a given zone and the way they are represented in the canopy layers for calculating light capture; D and E Comparison of light capture calculations per component (tree or crop) according to the 4-layer canopy model used in WaNuLCAS and that in a theoretically more correct 7-layer model.

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:

$$TotLightCap_j = 1 - \sum_{k=1}^{j-1} TotLightCap_k - e^{-\sum_i (kLLight_i * LAI_i - kBLight_i * BAL_i)} \qquad [47]$$

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,

$$LightCap_{ij} = TotLightCap_j \frac{kLLight_i LAI_{ij}}{\sum_i (kLLight_i * LAI_i - kBLight_i * BAI_i)} \qquad [48]$$

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 (Figure 3.23) 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. There is an option to specifically define maintenance respiration. This option enabled weed to be shaded by tree (see 3.7.3 on Maintenance Respiration)
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.
9. calculation of litterfall, if the actual LAI of the crop exceeds the maximum (C_LAImax, which is crop type dependent), a proportional part of the stem and leave biomass is transferred to the litter layer.

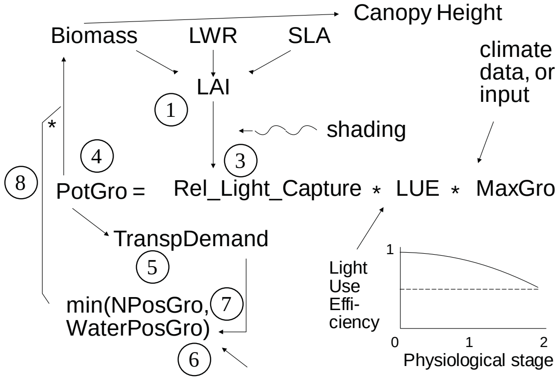


Figure 3.23. Major relationships in the daily cycle of calculating crop biomass accumulation.

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 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 3.24 and 3.25 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 WaNHELP.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]= leaves biomass in dry weight (kg ha^{-1} day^{-1})
DwSt[time]= stem biomass in dry weight (kg ha^{-1} day^{-1})
DwSo[time] = storage biomass in dry weight (kg ha^{-1} day^{-1})
SLA[time] = specific leaf area in m^2 g^{-1}
Cq_kLight = light extinction coefficient, as fixed value over time

Derivations:

DwTot[time] = total dry weight biomass = DwLv + DwSt + DwSo
GroMax = maximum daily increment in aboveground plant biomass = max(DwTot) (kg ha^{-1} day^{-1})
LWR[time] = leaf weight ratio = DwLv[time]/(DwLv[time] + DwSt[time])
TimeVeg = length of vegetative stage period = time of flowering or last day before first value of DwSt is recorded
TimeGen = length of generative stage period = time to harvest - TimeVeg
Stage = Increased of plant growth stage = time/TimeVeg for time<TimeVeg and (1 + (time - TimeVeg)/TimeGen) for time $\geq$ TimeVeg

Deriving apparent light use efficiency:

Calculate daily increment in total dry weight (logarithmic average over preceding and subsequentperiod):
BiomInc[time] = exp(0.5*(ln (dDwTot/dt)preceding + ln (dDwTot/dt)subsequent)
Calculate daily relative light capture, the factor 10 000 converts from ha to m^2:
RelLightCap[time] = 1 - exp(-k * DwLv * SLA/10000)
Calculate 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)

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: 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.

As illustrated in Figure 3.26 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.

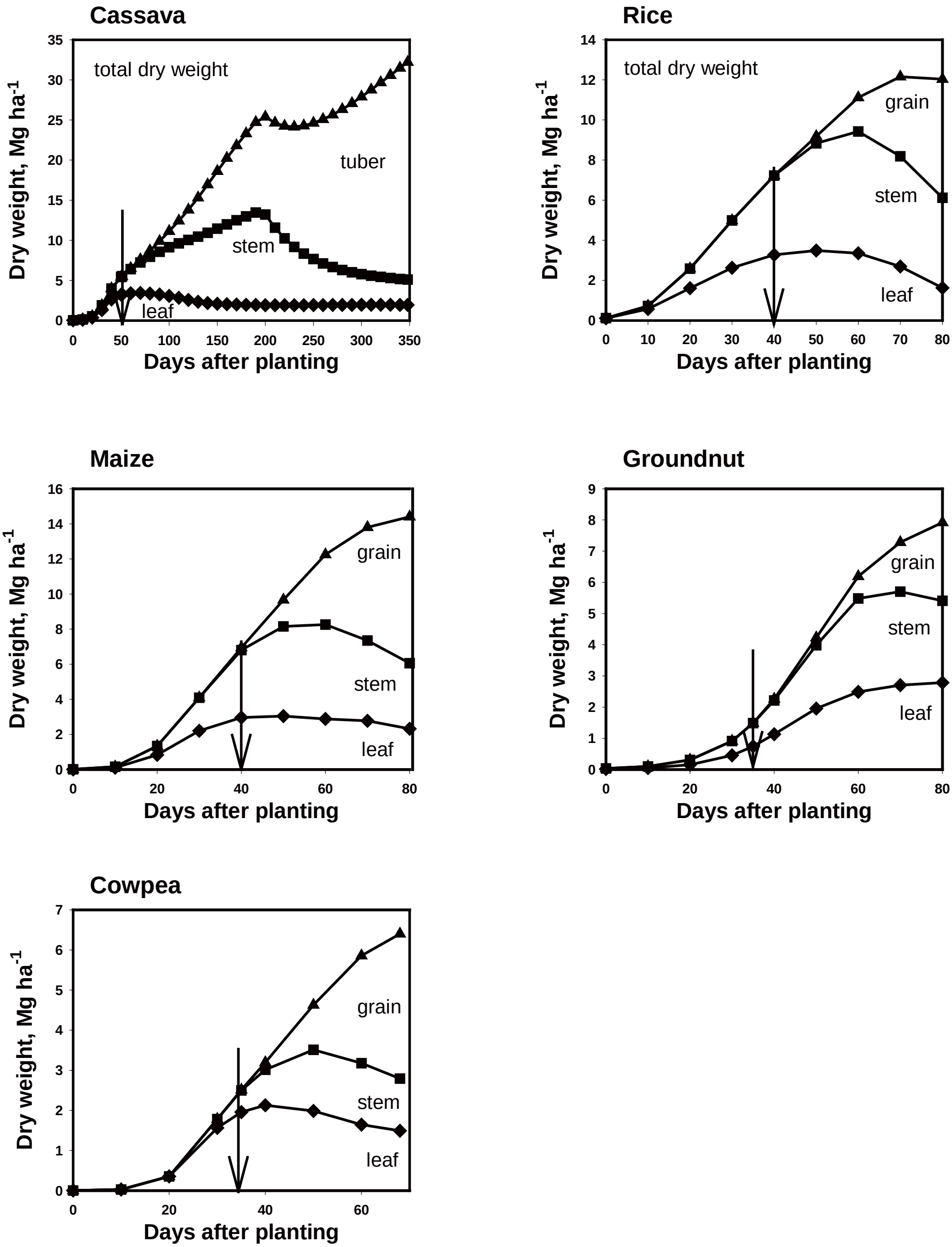


Figure 3.24. Examples of basic allocation functions derived from the Wofost model using climate data from Lampung (Indonesia) and 'standard' parameter settings for cassave, (upland) rice, maize, groundnut and cowpea (data provided by Dr. P. de Willigen, AB-DLO Haren the Netherlands). Arrows denote the starts of generative stage (Cq_Stage=1).

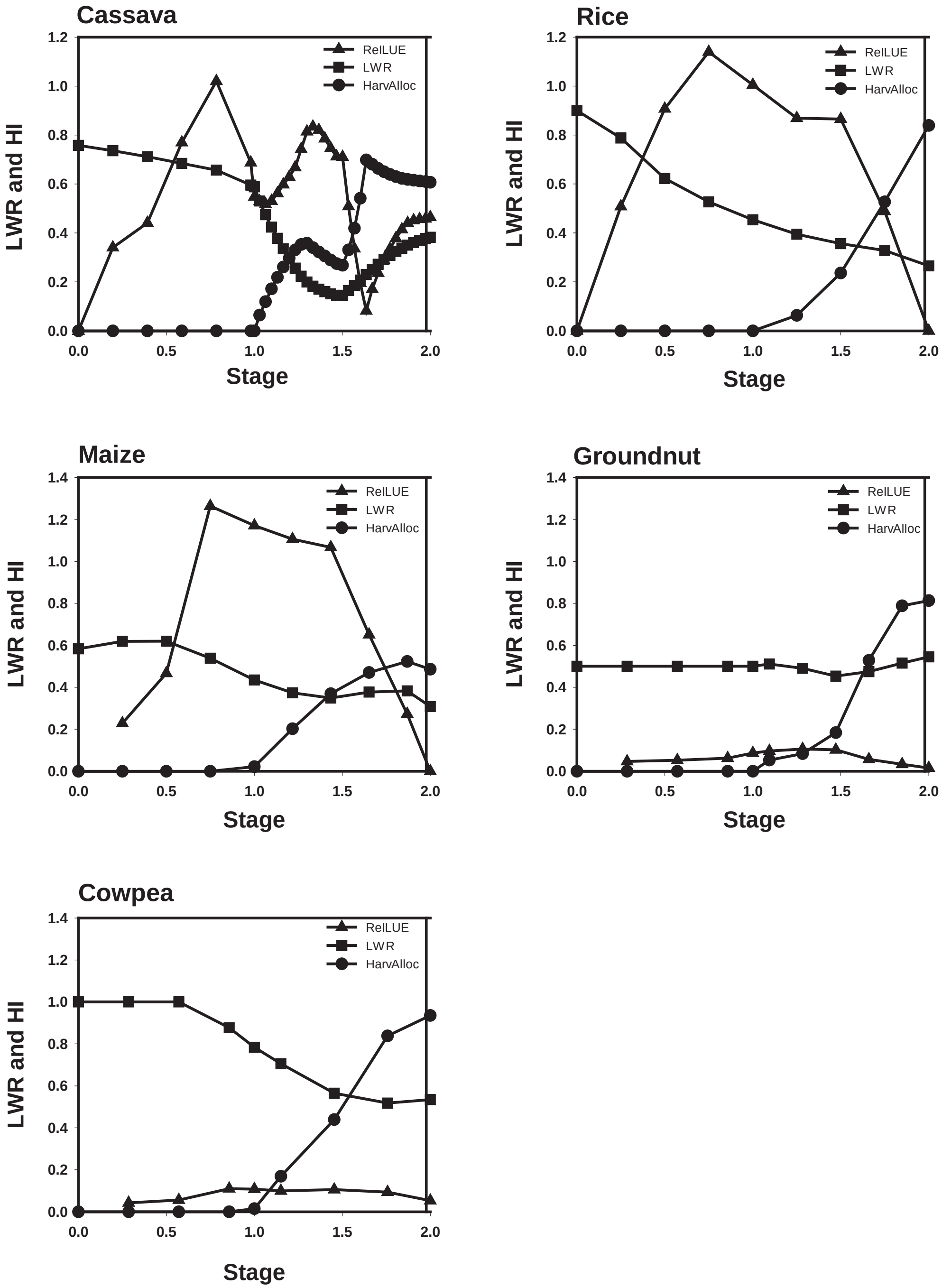


Figure 3.25. Leaf weight ratio, harvest allocation and relative light use efficiency rate as a function of time for the model output of figure 3.24.

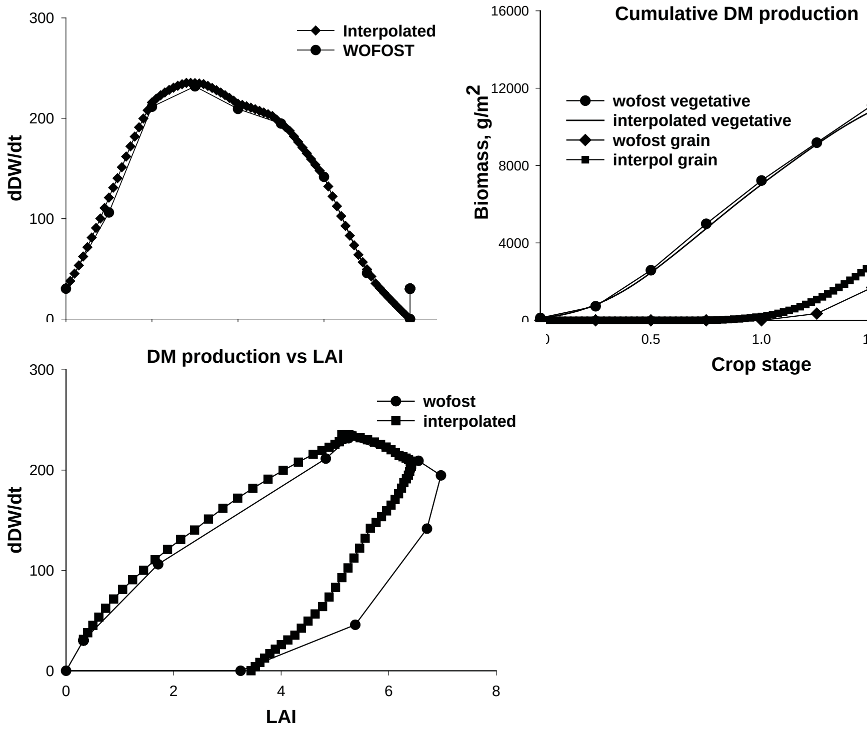


Figure 3.26. Comparison of potential production as derived per 10-day interval from the WOFOST model, and the daily interpolated values derived in the Wanulcas.xls spreadsheet: A. daily growth rates, B. accumulative dry matter production, C. trajectory of the relation between growth rate and LAI.

3.7.3. Maintenance respiration

Maintence repiration in WaNULCAS is specifically address the ability to ‘shading out weeds’. We use two additional concepts:

1. maintenance respiration from the growth reserve pool, at a rate of X % of current biomass per day, that leads to a ‘compensation point’, or light level below which the crop will start to decrease in reserves,
2. if growth reserves (dry weight) are zero the plant will die

We implement it by using the following additional parameters:
C_ApplyMaintResp? is a on/off switch for applying the maintenance respiration; for a default value of 0 all the rest is ignored
C_RespPerBiomass is the relative use of resources for maintenance respiration per unit biomass
C_RelRespRt is the relative weighting factor for roots as part of total biomass as used for maintenance respiration
C_RelRespStLv is the relative weighting factor for stem&leaves as part of total biomass as used for maintenance respiration
C_RelRespCurrHarv is the relative weighting factor for developing fruits as part of total biomass

as used for maintenance respiration
C_RelRespGroRes is the relative weighting factor for growth reserves as part of total biomass as used for maintenance respiration
C_RespTemp is a graphical relation between temperature and maintenance respiration
C_GroResMobFrac is the fraction of growth reserves that is used for growth of plant organs such as stems&leaves on a daily basis

These parameters are set within the **STELLA** model and not yet part of Crop Library in Excel.

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'

$$\Delta Biom = \Delta Canopy + \Delta Support + \Delta Litterfall \quad [49]$$

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.

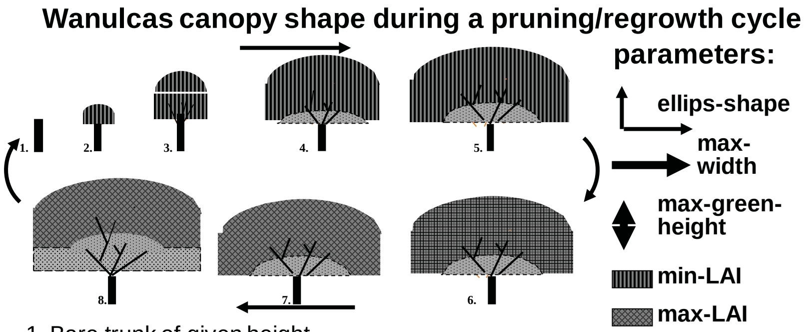
Within the canopy, the increment in leaf biomass is calculated from:
- LWR (leaf weight as fraction of total biomass in the canopy),
- SLA (specific leaf area, or leaf area per unit leaf weight).

$$\Delta Leafarea = \Delta Canopy * LWR * SLA \quad [50]$$

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 Figure 3.27. 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).



1. Bare trunk of given height

2..4. Lateral expansion of canopy with a fixed LAI-canopy, and constant LWR inside the canopy, and constant width/height ratio

5. When canopyheight exceeds max-greenheight, litterfall ~ inner ellips

6,7. When maximum canopy-width is obtained, the LAI inside the canopy may increase to its maximum value, still at constant LWR

8. Beyond this point the canopy will increase in height, with concommittant litterfall and formation of 'thick stem' category

Figure 3.27. Tree canopy shape during a pruning - regrowth cycle

$$R = Leafarea / LAI_{\min} \quad [51]$$

$$H = R / S \quad [52]$$

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}.

$$\Delta height = leafgrowth / (LAI_{\max} * Maxwidth) \quad [53]$$

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 3.10.7.

3.8.4. Tree diameter and allometric biomass allocation rules

A number of allometric biomass equations (of the general form: $Y = aD_b$) 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 Branch Analsysis’ (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

$$T\_BiomAG = T\_BiomDiam1\ T\_StemDiam^{T\_BiomDiamSlope} \quad \textbf{[54]}$$

can be inverted to obtain

$$T\_StemDiam = \left(T\_BiomAG / T\_BiomDiam1\right)^{1/T\_BiomDiamSlope} \quad \textbf{[55]}$$

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:

$$T\_TargetLeafTwig = T\_LeafTwigDiam1\ T\_StemDiam^{T\_LeafTwigDiamSlop} \quad \textbf{[56]}$$

$$T\_BiomBranch = T\_BranchDiam1\ T\_StemDiam^{T\_BranchDiamSlope} \quad \textbf{[57]}$$

$$T\_LargeWood = T\_Wood - T\_BiomBranch \quad \textbf{[58]}$$

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. Tree phenology

In WaNuLCAS we treat the physiological water use efficiency (dry matter production per unit water used, in situations without nutrient stress) as a constant, to be specified for each crop type or tree species, but not varying with plant age. The model predicts that this water use efficiency will be reduced under nutrient stress, as such a stress (beyond a tolerance limit) affects dry matter production but not water use. The main differentiation in physiological water use efficiency implemented so far is a generic difference between C3 and C4 crops.

Measurements of instantaneous water use efficiency at leaf level, e.g. with IRGA equipment, generally show considerable variation in this efficiency between individual leaves, partly linked to position of leaves in the canopy and leaf age. During ‘ageing’ leaves tend to become less efficient for a number of reasons. Where trees differ substantially in average age of current leaves (e.g. in a comparison between trees that are evergreen and those that regularly shed leaves in a dry or cold season) a difference in ‘average leaf’ water use efficiency should be expected. One step further would be to keep track of the average age of current leaves in a canopy and assign a water use efficiency on the basis of a generic ‘ageing’ function.

In calculating the average age of a leaves in a canopy we may simply impose a phenological pattern on a tree based on the time of year that leaf flush starts and litterfall is completed (either the same dates every year, or differentiated according to weather records and e.g. a temperature sum), or trigger these events by relations inside the model. Since WaNuLCAS version 2.1 rules are included for a drought-induced litterfall, with a minimum waiting period for leaf re-emergence if the water stress disappears (e.g. as a consequence of reduced demand after litterfall).

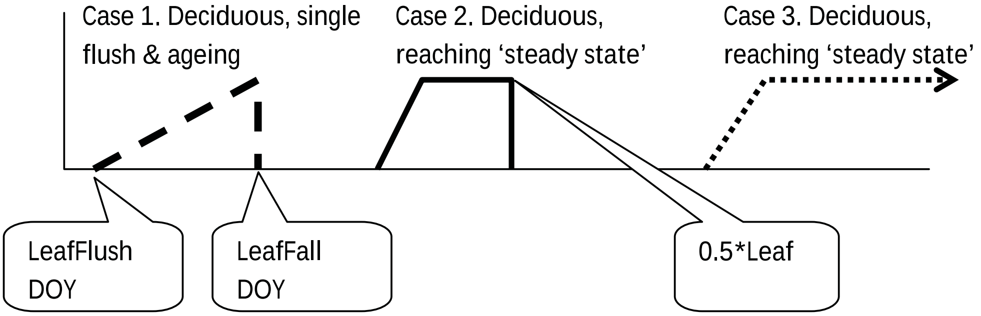


Figure 3.28. Three parameters are used to describe the leaf age over time, allowing the 3 cases to be paremeterized.

3.8.6. Cumulative litterfall

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:

$$L(D) = L_{min} + a_1 (D - D_{min}) \qquad [59]$$

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 Lmin two branches etc.; from equation [59] 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:

$$D_{x2} = \left((1-q) D_x^2 / \alpha \right)^{0.5} \qquad [60]$$

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}:

$$CumLittfall(D0) = \int_{D\,min}^{D\,max} (a_l / L_{min})\, BiomD1 \left\{ \sqrt{(1-q)} D^2 / \alpha \right\}^b dD =$$

$$= \frac{a_l\ BiomD1((1-q)/\alpha)^{0.5b}}{L_{min}(b+1)} \left(D_{max}^{b+1} - D_{min}^{b+1} \right)$$

[61]

For any D_{max} value more then 2.4 Dmin the error made when ignoring the D_{min} term in the equation is ignored is less than 5% and for D_{max} > 3.7 Dmin 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 (Figure 3.29A); the position of the cross-over point is (again, if the D_{min} term can be ignored):

$$D = \frac{L_{min}(b+1)}{a_l((1-q)/\alpha)^{0.5b}}$$

[62]

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

$$AllocLit(D) = \frac{dCumLittFall}{dD} = \frac{a_l BiomD1((1-q)/\alpha)^{0.5b}}{L_{\min}}$$

[63]

while allocation to the Biomass pool will be:

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

[64]

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 (Figure 3.29B).

$$RelLitFallAlloc(D) = \frac{a_l((1-q)/\alpha)^{0.5b} D}{a_l((1-q)/\alpha)^{0.5b} D + bL_{min}}$$

[65]

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 [62]. If so, new leaves and twigs can grow unimpeded until the former canopy biomass is regained.

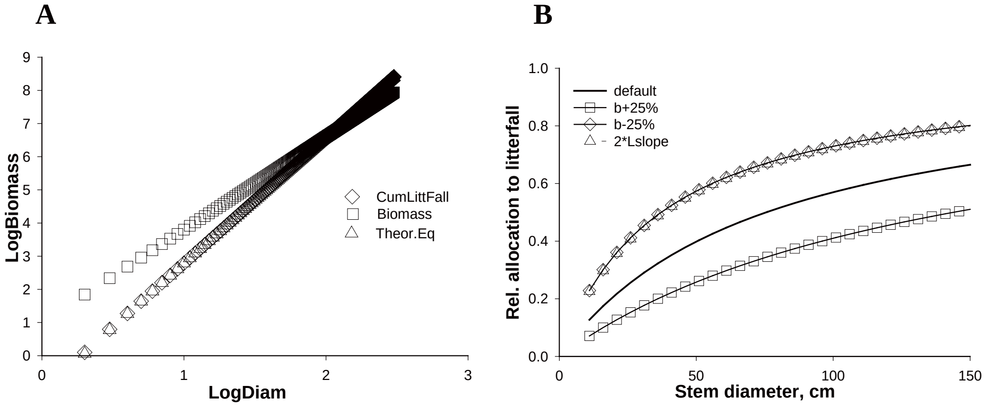


Figure 3.29. A. Comparison of biomass and cumulative litterfall as a function of stem diameter comparing a numerical integration with results of eq.[54]; **B**. Relative allocation of current biomass production to litterfall as a function of stem diameter for a default parameter set and in situations where the slope of the biomass allometric equation is increased or decreased by 25%.

3.8.7. 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

3.8.8. Oil palm growth

A new option is available to simulate fruiting mechanism in oil-palm (Figure 3.29). Palms differ from most dicotyledonous trees in a number of ways that are relevant for the current model: they have a much more rigid development pattern in which leaves are formed and emerge continuously (rather than with the seasonality or flushing of many trees), gradually forming a stem which normally does not branch and that does not show secondary growth in diameter (as the leaf area supported by the stem is virtually constant over time there is no need for more transport or support tissue, but inversely, the lack of secondary meristems in the existing stem can be a constraint on branch development). Flowers are formed in axillary buds, one for every leaf and have a long development trajectory that starts much before the adjacent leaf emerges, and that includes phases where the sex of the flowers is determined, in response to physiological conditions in the palm. The long development phases from bud to flower to ripe fruit causes a large number of developing bunches to be present on the same palm, interacting in their demand for growth resources.

This general pattern applies to oil palm, coconut, peach palm and date palm. For the sago and sugar palm, however, flower development is delayed and the palm stores large amounts of internal resources; in sago these are directly harvested (and the palms loose all their value in years that the climate-related trigger for flowering is expressed), for sugar palm the stored resources are intercepted on their way to the developing flowers, once the palm starts to flower (and flowers develop in a top-down sequence, opposite to their age).

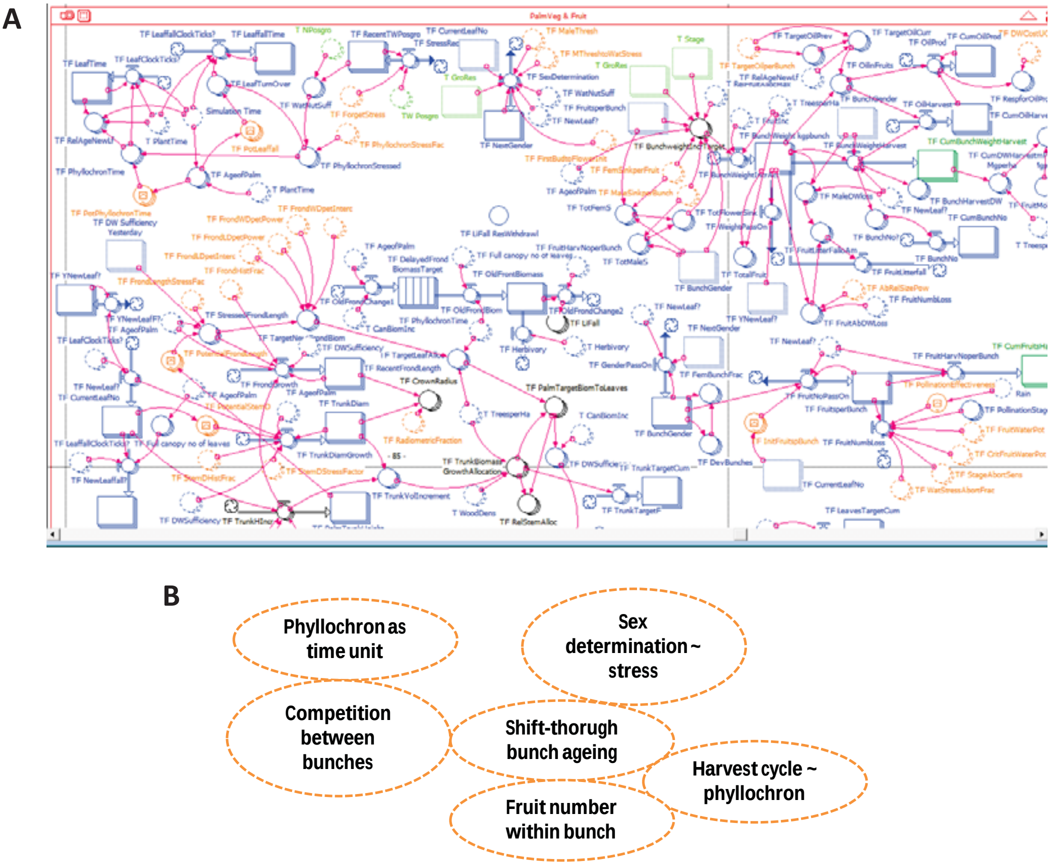


Figure 3.30. Diagram (A) and schematic map (B) of the new tree fruit module developed to represent palm fruit development in the various bunch stages.

Focussing on oil palm and leaving further model adaptations to other palms for a later treatment, the following model elements were identified for the model:

- **phyllochron** time keeping: the time interval between the emergence of two leaves, or phyllochron, determines the basic unit of time for floral and fruit development as well. For current oil palm germplasm a phyllochron unit is about 14 days.
- **sex determination** of flowers is related to the internal condition of the palm, based on its internal growth reserves, as well as in response to current water stress; as in the model the switch between male and female bunches is set at a single day, we do it on the basis of a moving average of the past water stress levels; because of the link with internal growth

reserves the module can account for the tendency to male flowers caused by tapping for palm wine, as is common practice in W. Africa.

- **simultaneous development and resource competition** between the various male and female flowers and bunches present at any point in time, with an age-dependent relative sink strength,
- **abortion** of individual fruits in a bunch, in response to water stress,
- **book keeping** of the dry weight and fruit number individual bunches as they shift through the stages from flower to ripe bunches,
- **harvest of one (potential) bunch at the end of each phyllochron unit.**

Figure 3.30 shows the palm oil module in WaNuLCAS, sink strength for male and female bunches and the sensitivity to drought stress leading to fruit abortion depend on bunch development stage.

3.8.9. Harvesting latex or resin from tress

Tapping rubber (*Hevea brasiliensis*) or jelutung (*Dyera costulata*) trees for their latex, or *Acacia senegalensis* for its gum-arabic or any other tree for its resin, implies a direct drain on the Growth Reserves in the tree. WaNuLCAS can simulate the consequences for tree growth and yield of products in the short and longer time frames, of various intensities and frequencies of tapping. As implemented in WaNuLCAS 4.0, the assumption is made that all N and P stay behind in the tree and only dry matter is affected. The description is given here in terms of tapping rubber, but the same routines could be used for other tree products after adjustment of parameter values.

The conversion of Tree Growth Reserves (T_GroRes) into harvested product is described as a two-step process: formation of latex and building up a stock of latex, and the actual tapping (Figure 3.31). The first conversion is controlled by inherent properties of the trees (T_Rubber?, an on/off switch that is part of the tree library), and a dynamic allocation fraction (T_LatexFormAlloc) that depends on a number of tree parameters (than can be differentiated for rubber clones) such as a maximum mobilization fraction, bark thickness and a saturation feedback if the latex stock (T_LatexStock) approaches its maximum capacity (Figure 3.32).

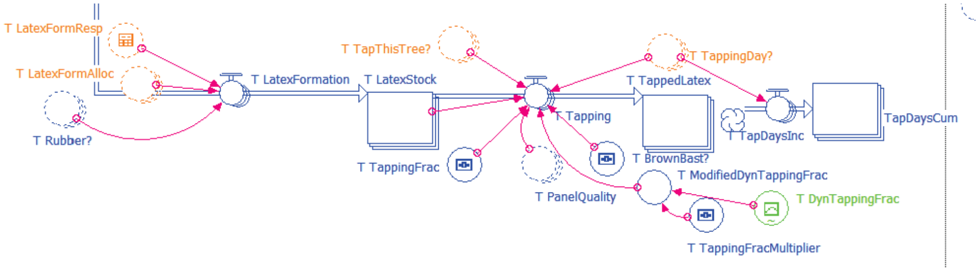


Figure 3.31. Latex formation diagram in WaNuLCAS model

The second step, tapping into the actual tapping (T_TappedLatex) pool can influence the rate of latex formation. There are a number of controls here:

- Whether the tree has reached the minimum girth at which tapping starts (T_GirthMinforTappingcm),
- Whether the date matches the annual tapping period (e.g. avoid dry season and wettest period),
- Whether it is a 'tapping day', depending on the tapping schedule selected (T_TappingDay?) (Figure 3.33),
- Whether there is sufficient 'tapping panel' left (bark below the maximum tapping height that has not been tapped before, or has sufficiently recovered since an earlier tapping cycle, governed by a recovery rate) (T_PanelQuality) (Figure 3.34),
- Whether the panel is affected by the 'BrownBast' condition (a fungal infection) (T_BrownBast?),

Whether recent tapping events provided economically attractive returns to labour (this is based on a comparison of labour investment, dry weight of latex obtained and prices for a day of labour and a kg or dry rubber). This function reflects farmer decisions to selectively tap as long as it gives adequate yield or otherwise rest a tree and focus on others in the same stand (T_TapThisTree?) (Figure 3.31).

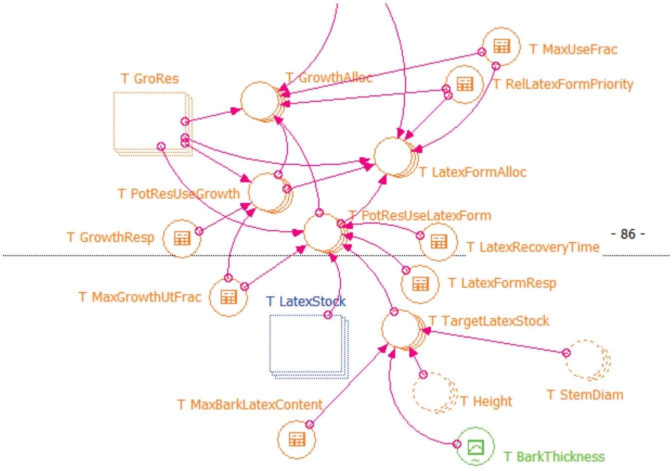


Figure 3.32. Diagram that show number of tree parameter controls a dynamic of latex allocation fraction (T_LatexAllocForm).

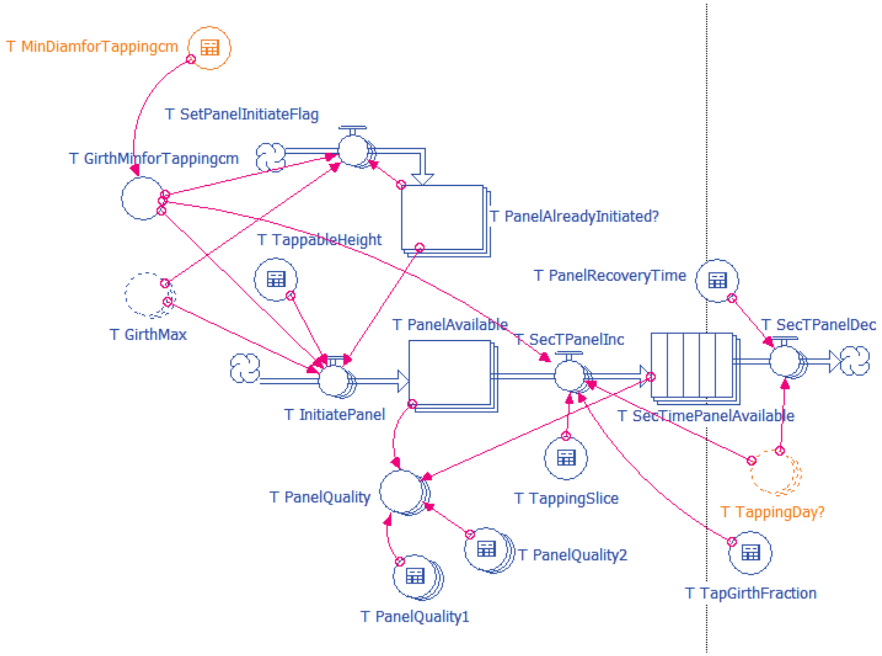


Figure 3.33. Diagram that show dynamic of available tapping panel and its influence factors
The latter ratio is derived in a section of the model that also converts the latex yield per tree to a dry weight of rubber per ha, using the appropriate area scaling factor.

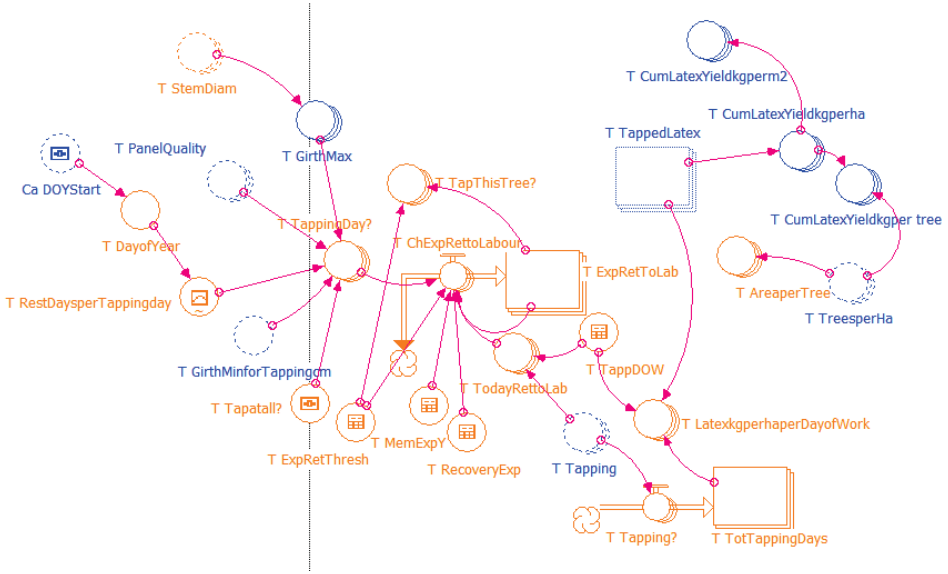


Figure 3.34. Diagram that show influence factors for tapping schedule selected and farmer decisions to tap the tree.

This module has been developed as part of the PhD research of Dr. Yahya Abdul Karim, and was paramaterized by him for rubber clone comparisons in Malaysia.

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).

An option is introduced to initialize on the basis of the Corg/Cref ratio, where Cref is either derived from a pedotransfer function (Type = 2) or specified by the model user (Type = 3). The relative allocation of Corg to the slow, active and passive pool is driven by the Corg/Cref ratio for Types 2 and 3.

1. for MC_SOMInitType = 1 the user can specify all pool sizes for all zones,
2. for MC_SOMInitType = 2 the user can specify the size of all pools relative to those for a forest soil (Cref) that is calculated from soil texture data,
3. for MC_SOMInitType = 3 the user specifies the Corg and Cref directly, but otherwise follows the procedure of Type 2

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.

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:

$$k = 0.14 * (1 - .75 * Mc\_SiltClay) * Mc\_TempLim * Mc\_TethaLim[Zone] \qquad [76]$$

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.

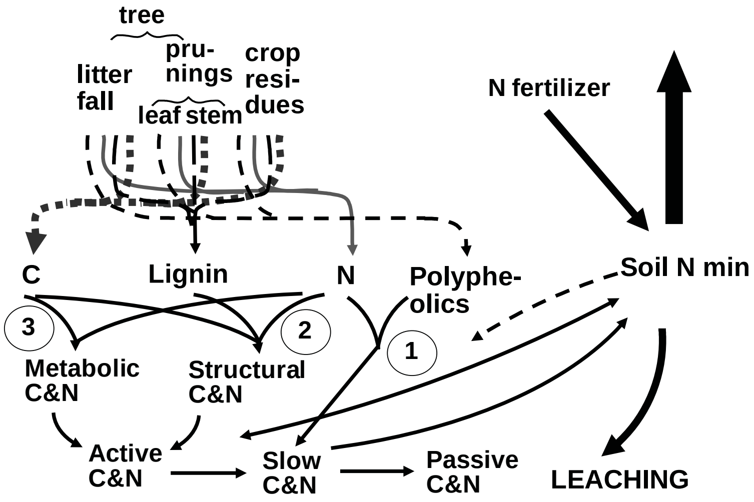


Figure 3.35. Major relationships in N immobilization and N mineralization from organic residues; the basic C and N pools are similar to the Century model, but plant polyphenolics are added as litter quality parameter.

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 CO_2, 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). Currently, we can kill, replant then kill of any tree on acertain zone up to 3 times on 1 length of simulation.

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:

$$\Delta FenceQuality = Lcurr(M - Q)^2 / (KM + Lcurr(M - Q)) \quad \textbf{[67]}$$

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.

3.10.8. Tillage

This option relates to Soil Erosion and transfer of litter to SOM pools. Tilling can be specified from a calendar, or be automatically implemented at X days before planting a new crop.

3.10.9. Timber Harvesting

Timber can be harvested, specified in Excel sheet Tree Management. When timber is harvested all canopy biomass and fruit are removed from plot. T_WoodHeight will decreased depending on fraction of timber removed.

3.10.10. Grazing

Grazing will affect crop/grass only and 2 types of grazing pressure can occur, field and patch level.

Field-level grazing pressure depends on two factors:
1. stocking rate in standard livestock units as a function of simulation time.
2. daily intake requirement per animal.

Patch-level grazing pressure depends on field-level grazing pressure, relative attractiveness of grass/crop in the patch and total fodder availability in the field. Relative attractiveness of grass is a function of standing biomass, N concentration and growth stage. Input parameters related to this module are:
1. Graphical inputs specifying the attractiveness on the basis of biomass (G_BiomDep), N concentration (G_Ndep) and growth stage of the grass (G_StageDep).
2. A graphical input defining the stocking rate as a function of time (G_StockrateperHa)
3. Daily requirement per standard livestock unit=SLU (G_DayDempDayKg, default value 2.5% per dry weight SLU)
4. Standard live stock unit (G_SLU, default value 450 kg)

The possible output are cumulative biomass grazed, G_GrazedBiomCum(in dry weight) and its nutrient content). For future modifications, we plan to have rule for relating stocking rate to standing biomass as result of actual grazing success. This would reflect farmer decision making in managing the system.

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:

$$NPV = \sum \frac{-\cos t + return}{\{1 + DiscountRate/365\}^{Time}} \qquad [68]$$

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 are listed in Table 3.7.

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

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):

$$N\_LocFF_{ij}[Nutrient] = Upt_{ij}[Nut]/(Upt_{ij}[Nut] + Loss_{ij}[Nut]). \qquad [69]$$

$$N\_LocFF_{ij}[Nutrient] = Upt_{ij}[Nut]/(Upt_{ij}[Nut] + Loss_{ij}[Nut]). \qquad [70]$$

$$N\_TotFF[Nut] = TotUpt[Nut]/(TotUpt[Nut] + TotLoss[Nut]) \qquad [71]$$

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:

$$N\_TotFF[Nut] = S_i\ S_j\ N\_TotFF_{ij}\ [Nut] =$$
$$= \Sigma_i\ \Sigma_j\ Upt_{ij}[Nut]/(UptTot[Nut] + LossTot[Nut]) \qquad [72]$$

The N_TotFFij 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):

$$N\_EdgeFF[Nut] = \Sigma_{k=edg}\ UptEdge_k[Nut]/(UptTotEdge[Nut] + LossTotEdge[Nut]) \qquad [73]$$

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.

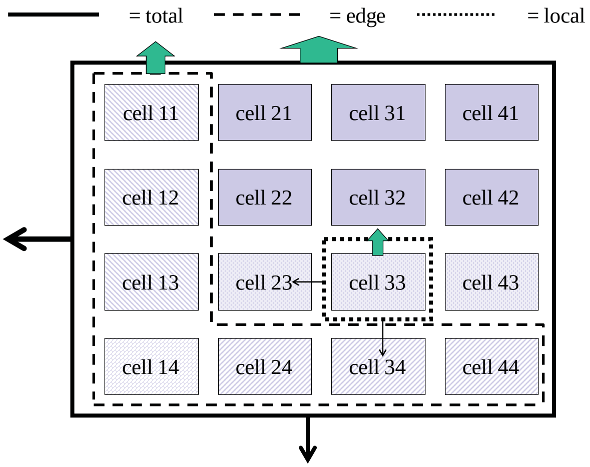


Figure 3.36. Filter functions (or safetynet functions) are defined as uptake/(uptake +loss) at three scales: local (as example here for cell 3.3), edge (uptake from zone1+layer4, net losses from the edge equal net losses from system as a whole) or system as a whole

3.11.4. Number of days plants has growth limitation

We defined this as fraction of days (out of the length of simulation days) tree or crop is limited by water, nitrogen or phosphorous.

Chapter 4

Examples of model applications

We first explore a simulation based on the 'default' parameters of version 3.0 and see how crops, trees and weeds interact and compete for N, P, water and light on soil rich in organic matter but with limited rooting depth due to subsoil acidity.

After that, five examples of model applications (made with version 3.0) are presented, 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 safety net 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 and some more examples of WaNuLCAS application on the agroforestry research.

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.stm 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 "Return to DEFAULT value" 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. The default settings simulate an alley cropping system of maize and *Peltophorum dasyrrachis*. Figure 4.1 gives the biomass production results for a 'default' run of 2 years duration in which the trees are always pruned before planting a new crop. In the first cropping period there is little difference in crop growth between the three zones. In the first cropping season of year two, crop growth starts to differ significantly between zones and the crop in zone 2 (close to the hedgerow) produces less biomass compared to zones 3 and 4, as it faces more competition in terms of water, nutrient and light. During fallow period the hedgerow trees start develop more biomass until the next cropping season when the hedgerows are pruned; the woody part of the hedgerows is maintained, so overall aboveground tree biomass can gradually reach a higher level.

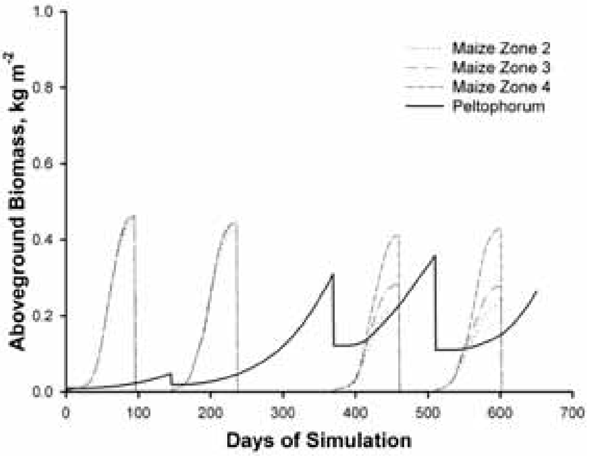


Figure 4.1. Biomass development of crop and tree for a WaNuLCAS simulation using 'default' parameter settings

If you click on 'To 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 5812 mm (i.e. 2606 mm year^{-1}), 79 mm was used to recharge the soil (which was initialised below field capacity), 3723 mm drained from the soil profile, 174 mm became surface run-off, 636 mm evaporated from the soil surface, 146 mm evaporated from interception by crop and tree canopy, 731 mm was transpired by the crop and 324 mm by the tree. The BW_NetBal result of 4.5 10^{-13} 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 247 to 227 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 1.65 g m^{-2}, while 9.5 g m^{-2} was lost through leaching and 7.6 g m^{-2} was exported with crop harvest products. At the end of the run N the tree biomass was 2.2 g m^{-2} and the error term of the N balance was –5.68 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 57 to 55 g m^{-2}. In contrast to N, however, leaching losses have been very small (0.14 g m^{-2}). The error term of -1.8 10^{-13} 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 67 and 98% for N and P, respectively. A substantial part of this overall filter function was located in the 'Edge': filter function horizontally was 17 and 73% for N and P, respectively; filter function vertically was 7 and 2% for N and P, respectively. 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 (2679 to 2438 g m^{-2} or 27 to 24 Mg ha^{-1}), while total photosynthesis of the tree is more than half of that by the crop (319 and 536 g m^{-2}, respectively), most of which was lost in respiration. At the end of the two years simulation, 335 g m^{-2} has been exported from the field in crop products, while the current tree biomass is 111 g m^{-2}. The error term of the C balance is negligibly small at 0, while the 'time-averaged C stock' is 2641 g m^{-2} (or 26 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, current tree biomass harvested comes from tree biomass pruned (8 Mg ha^{-1}).
The maize grain yield of 0.94 kg m^{-2} or 9.4 Mg ha^{-1} (3.3, 3.1, 2.2 and 2.2 Mg ha^{-1} per crop, respectively) is quite good. During the simulation N, P and water limited crop growth 37, 64 and 0 % of days in the cropping period, and tree growth for 34, 13, and 0 % of the year.

The 'light' output shows crop growth limitation by light capture. The value 0.99 means the growth of the crop was hardly limited by light.

The 'soil balance output' gives result for the amount of soil loss and current topsoil thickness. As the default value for slope 0%, topsoil thickness after two years simulation is the same to the initial value means no soil was lost during the simulation.

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 4.2 A-K show the tree and crop biomass results for such runs.

Figure 4.2 A-C shows the crop biomass as a result of changing tree species and absence of the tree. The presence of the tree (comparing Fig 4.2.A-B and C) affects crop growth in zones closer to the tree. Using *Peltophorum* (comparing Fig 4.2.A and C) crop growth starts to differ between zones at year 2. Changing the tree type from *Peltophorum* to *Gliricidia* in the Excel sheet 'Tree parameters' (comparing Fig. 4.2.A and B), the impact of tree on crop growth starts earlier, that is on the second crop season of the first year. The decrease of total tree biomass during a cropping period is due to pruning and use of internal reserves in the tree. For *Gliricidia* (Fig. 4.2.B), the total tree biomass decreases during fallow period (no crop). This is due to litter fall caused by drought, as *Gliricidia* is more sensitive to drought than *Peltophorum*.

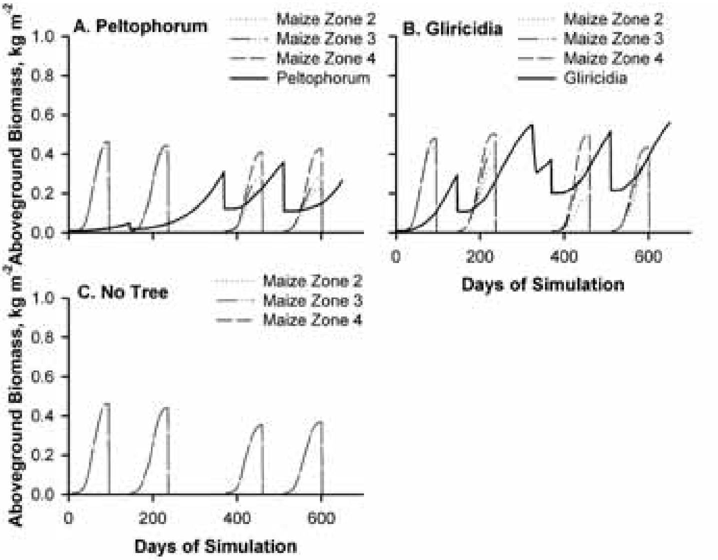


Figure 4.2A…C. Aboveground biomass for a simulation based on default parameters setting in WaNuLCAS using tree type D (=Peltophorum) or E (=Gliricidia) or none (set the slider AF_AnyTrees? to 0)

Figure 4.2 D…G shows the tree and crop growth without water, N or P limitations. Figure 4.2 D…G. indicate that removing the impacts of P limitation has by far the strong impact on overall crop growth. In its normal condition, crop growth during the second year is severely limited by P.

Figure 4.2 H and I show the impact of tree and weed presence in the systems. Current default settings are without weed and with tree. 'Weed growth' can be simulated by specifying the slider AF_SimulateWeeds? in Run and Output section to 1. To set with or without a tree situation, specify the slider AF_SimulateTrees? in Run and Output section to 1 or 0.

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. Weeds only grow during the fallow periods (no crop) 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 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.

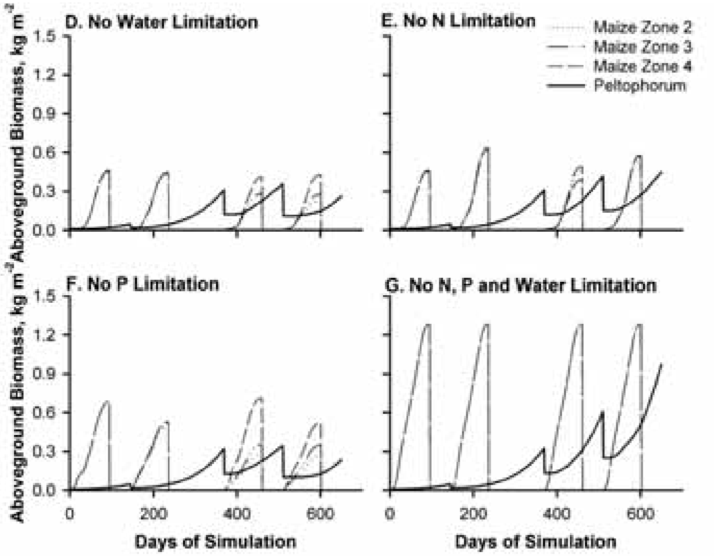


Figure 4.2.D...G. Aboveground biomass for a simulation based on default parameters setting in WaNuLCAS as impact of N, P and water limitation

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 slider AF_AnyTrees? in 'Run and Output' section to 0 and change the crop types on the 'crop management' sheet in the excel file (Maize in zone 1, Cassava in zone 2, Ground nut in zone 3 and Rice in zone 4). Note that when a tree is added to the systems (set the slider AF_AnyTrees? back to 1), as shown in Figure. 4.2.K, it will be pruned every time prior to planting crop. The presence of the tree significantly affects the biomass of maize that grows closer to the tree.

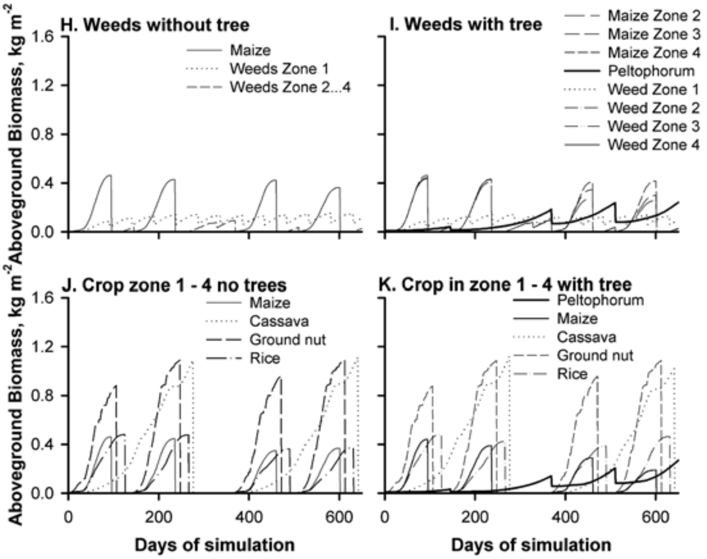


Figure 4.2 H...K. Aboveground biomass for the simple modification (less than 5 mouse clicks) of the default parameter setting in WaNuLCAS 3.0; for explanation see text

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 four N fertilizer regimes (0 in zone 1, 60 in zone 2, 90 in zone 3 and 120 in zone 4, kg N ha^{-1} crop^{-1}), by specifying Ca_FertApply?[N] as 1. The amount of N fertilizer equals to 0, 3.5, 4.5 and 6 g m^{-2} that applied twice, half at planting time and half at a month after planting time. For simplicity, we used the same amounts for P fertilizer by specifying Ca_FertApply?[P] as 1. It is applied once at planting time. Figure. 4.3 the simulation beside run at the different of fertilizer application also knows the impact of reducing 50% of soil organic matter content by reducing Mn_InitAct, Mn_InitPass and Mn_InitSlw 50% (see table 4.1 for details of changes from the default parameter setting).

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

Parameter		**Input Section (Link Location in Excel)**
INPUT	New Value	
AF_AnyTrees?	0	Run and Output Section
Ca_FertOrExtOrgAppYear	0, 0, 0, 1, 1, 1, 1, 1, 1, 2, 2,2	(Crop management/Fertilizer and organic input schedule)
Ca_FertOrExtOrgAppDoY	305, 306, 335, 81, 82, 111, 305, 306, 335, 81, 82, 111	(Crop management/Fertilizer and organic input schedule)
Ca_FertApply?[N] Ca_FertApply?[P]	1, 0, 1, 1, 0, 1, 1, 0, 1, 1, 0, 1 0, 1, 0, 0, 1, 0, 0, 1, 0, 0, 1	(Crop management/Fertilizer and organic input schedule)
Ca_FertOrExtOrgAmount[Zn1...4] N1[Zn1,2,3,4] N2[Zn1,2,3,4]	 0,30,45,60 0,30,45,60	(Crop management/Fertilizer and organic input schedule)
Ca_FertOrExtOrgAmount[Zn1...4] P[Zn2,3,4]	 0,60,90,120	(Crop management/Fertilizer and organic input schedule)
Mn2_InitAct[Zn1...4]	0.0455	Soil Organic Matter/Initial C & N in SOM Pool
Mn2_InitSlw[Zn1...4]	0.505	Soil Organic Matter/Initial C & N in SOM Pool
Mn2_InitPass[Zn1...4]	0.364	Soil Organic Matter/Initial C & N in SOM Pool

The simulation (Figure. 4.3) was extended to two years, with four consecutive crops of maize. For unfertilised plots with default soil organic matter, crop biomass development started with a good initial crop biomass (with a total biomass of over nearly 0.5 kg m^{-2} (= 5 Mg ha^{-1}), but the biomass declined to 20% of the first year's value in year 2. By reducing 50% of soil organic matter, crop biomass declined to 30% of default value of soil organic matter.

By applying different amount of fertilizer for N and P, the results show that the higher fertilizer, the higher crop biomass. Reducing 50% of soil organic matters does not show significant different on the crop biomass when N and P fertilizer was applied together. Response of the reducing soil organic matter on crop biomass is obtained when only P fertilizer was applied.

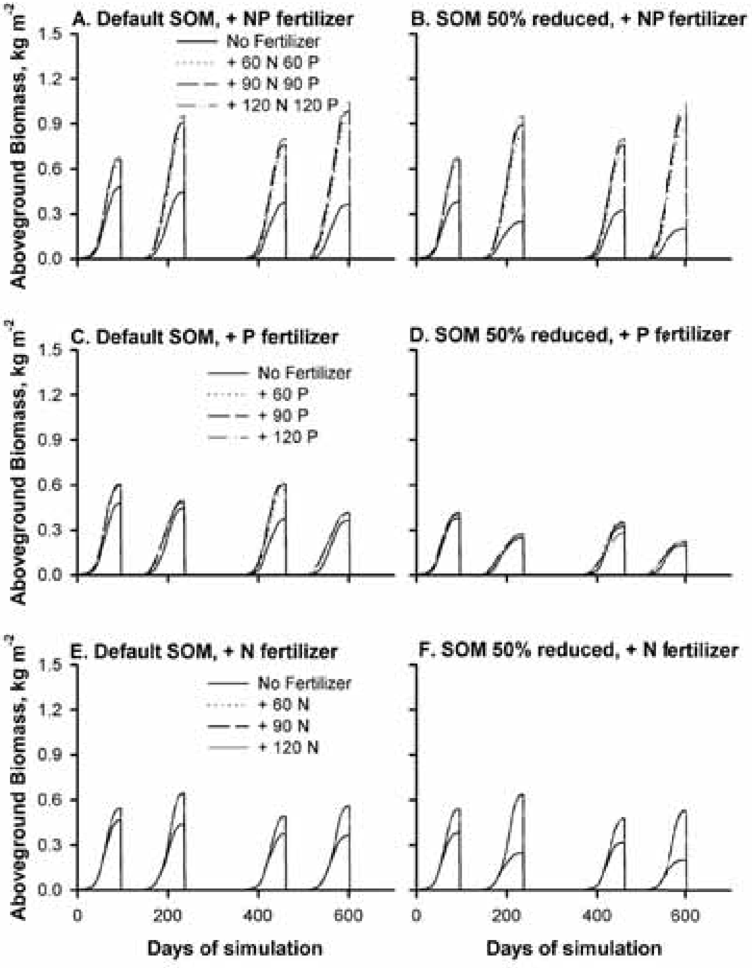


Figure 4.3. A…F. Simulated crop development (total aboveground biomass) for maize with a Lampung climate and default parameters setting (for changes in parameter settings from the default values, see Table 4.1), with or without N fertilizer (at 60, 90 or 120 kg N ha^{-1} $crop^{-1}$, with split application (50% at planting, 50% at 30 days later). We also used the same amounts for P fertilizer; it is applied once at planting time. The simulation also knows the impact of reducing 50% of soil organic matter content.

4.4. Hedgerow intercropping: pruning regime and hedgerow spacing

Based on different tree characteristics ('P' and 'G' in Figure 4.4), the model predicts different pruning frequencies to be applied (one per crop for P and two to three times per crop for G) by making modifications from the default settings as indicated in Table 4.2. 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). The simulations presented here were made with version 3.0 as a first approximation of long-term hedgerow intercropping experiments in Lampung (Indonesia); details of the experiments that form the inspiration for these simulations can be found in Van Noordwijk *et al*. (1998a).

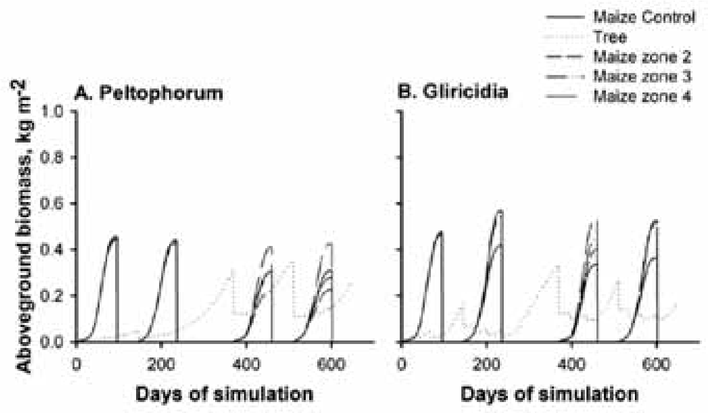


Figure 4.4. Model predictions with WaNuLCAS of development of hedgerow tree canopy and crop biomass (on a whole field basis) over four cropping seasons in two years, for three crop zones (2, 3 and 4) within the alleys (the P and G trees approximate *Peltophorum* and *Gliricidia*, respectively, as used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

The WaNuLCAS model can also 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 4.3. The simulations presented here were made with version 3.0 as a first approximation of long-term hedgerow intercropping experiments in Lampung (Indonesia); details of the experiments that form the inspiration for these simulations can be found in Van Noordwijk *et al*. (1998a).

Compared to the maize series of Figure 4.1 and 4.2 which we include as 'control', the P trees can partly alleviate the yield decline over time, while the G trees the second crop in each year produces more biomass than the first crop. Averaged over four crops and expressed on a whole-field basis, predicted crop yields for the P hedgerow intercropping system are similar to this control crop while for the G hedgerow intercropping system are slightly higher than 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.

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.

Table 4.2. Input parameter modifications to generate example 4.4

Parameter		Input /Output Section location
INPUT	New Value	
T_PrunLimit	0.1	Management/Pruning Events

Table 4.3. Input parameter modifications to generate example 4.5.

Parameter I		Input /Output Section location
INPUT	New Value	
Same settings as above with different AF_ZoneTot		Agroforestry zone
AF_ZoneTot	4, 8, 16, 32	
AF_Zone[Zn1]	0.5, 0.5, 0.5, 0.5	
AF_Zone[Zn2]	1, 1, 1, 1	
AF_Zone[Zn3]	1, 1, 1, 1	
AF_Zone[Zn4]	1.5, 5.5, 13.5, 29.5	
T_PrunLimit	0.1, 0.3	Management/Pruning Events

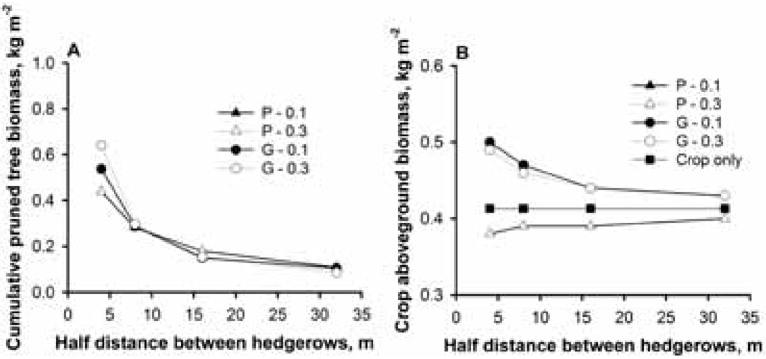


Figure 4.5. Predicted effect on cumulative pruned tree biomass (A) average crop biomass of four cropping seasons (B) if the distance between two hedgerows is gradually increased; results are given for P and G trees (compare Fig. 4.2 and two values of the 'prune limit', i.e. the hedgerow canopy biomass at which hedgerows are pruned back (For details see Table 4.3); and control refers to a whole field planted with crops

The G parameterisation (wider canopy shape, lower LAI within the canopy, shallower roots, N fixation) leads to crop yields that are substantially above the control yields due to biomass pruned from Gliricidia higher than Peltophorum. From the third crop onwards, however yields in zone 3 as well as 2 will be 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.

If the distance between hedgerows is gradually increased (Fig. 4.5), 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. Crop biomass with the G tree tends to be decrease with increasing of the distance between hedgerows but still above the control value while with the P tree crop biomass slightly increase although below the control value.

The P trees with different prune limit does not give significant different on the crop biomass, while the G tree with high prune limit (G = 0.3) crop biomass lower than G tree with lower prune limit (G = 0.1).

In contrast to Figure. 4.2, the results of Figure. 4.5 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. Tree fallow - crop rotations

The WaNuLCAS model can also be parameterised 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, broader zones of tree growth replace hedgerows and the pruning regime is modified, but otherwise the processes of tree-soil-crop interactions are the same.

The simulations presented here were made with version 3.0 based on default setting with not applying fertilizer. Parameters modification needed to simulate the system are shown in Table 4.4. The simulation requires two runs in which output from the 1st run becomes input for the 2nd run. Notice also that output values from the tree zone should become the input values in crop zone and vice versa. The soil nutrient content of the tree zone can be directly used as input for crop zones while we need to start the tree zone with the weighted average of output from crop zones. Here is an example of how to do that for initial N in 1st soil layer.

For the 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 the crop zone:
N_Init1[Zn2] = N_Init1[Zn3] = N_Init1[Zn4] = N_Soil1[Zn1]
The soil organic matter pools increased is size during a fallow period (in the model mainly by litter fall, 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).

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 that 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 Figure. 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.

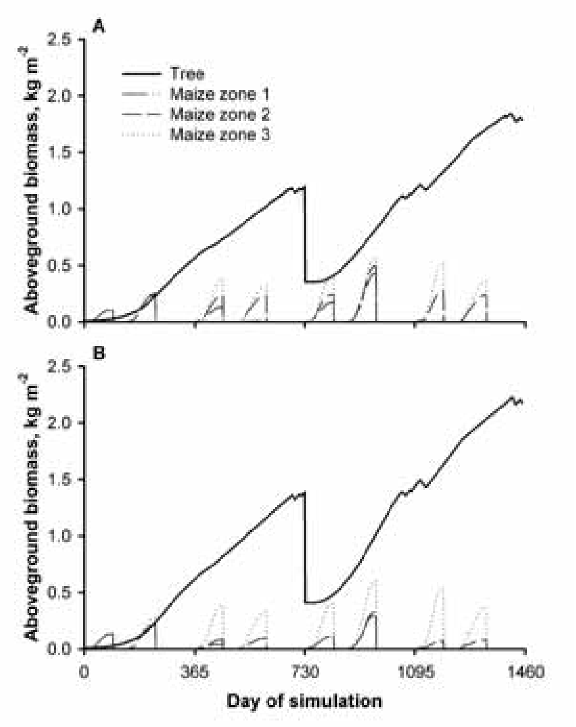


Figure 4.6. Predicted development of a tree fallow vegetation as well as the simultaneous yield of crops with increasing distance to this fallow plot, over two cycles of a two year fallow and 2 years of cropping (4 crops/ cycle); A. tree root length density decreases by a factor 0.6 from zone 1 to zone 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 4.4. Input parameter modifications from default to generate example 4.6 and output parameters to retain.

Parameter for 1st run		**Location on WaNuLCAS Input/ Output Section**
INPUT	New Value	
AF_Zone[Zn1] AF_Zone[Zn2] AF_Zone[Zn3]	10 2 3	Agroforestry zone
AF_ZoneTot	20	Agroforestry Zone
Ca_PlantYear[Zn2…4]	0, 1, 1, 2, 2, 3, 3, 4	Crop Management
Ca_PlantDOY[Zn2…4]	304, 80, 304, 80, 304, 80, 304, 80	Crop Management
T_CanHMax	5	Tree Library/Canopy
T_CanWidthMax	12	Tree Library/Canopy
T_PrunPlant?	0	Management/Pruning Event
T_PrunYear	2	Tree Management
T_PrunDOY	300	Tree Management
T_PrunFracD	0.7	Tree Management
Ca_FertOrExtOrgAppYear	100	Crop Management
	Graph A	**Graph B**
Rt_TLrvL1[Zn1…4]	4, 1.6, 0.64, 0	4, 4, 4, 0
Rt_TLrvL2[Zn1…4]	1, 0.4, 0.16, 0	1, 1, 1, 0
Rt_TLrvL3[Zn1…4]	0.5, 0.2, 0.08, 0	0.5, 0.5, 0.5, 0
Rt_TLrvL4[Zn1…4]	0.1, 0.04, 0.016, 0	0.1, 0.1, 0.1, 0
OUTPUT	**Remarks**	
Mn_Act[Zone]	Use Values at the end of run as initial values for the 2nd run	
Mn_Slw[Zone]		
Mn_Pass[Zone]		
Mn_Struc[Zone]		
Mn_Metab[Zone]		
Mn2_Act[Zone]		
Mn2_Slw[Zone]		
Mn2_Pass[Zone]		
Mn2_Struc[Zone]		
Mn2_Metab[Zone]		
W_Thetai[Zone]/ W_FieldCapi[Zone]		
N_Soili[SlNut,Zone]		

Parameter for 2nd run		Location on WaNuLCAS Input/ Output Section
INPUT	New Value	
Same setting as 1st run with additional below		
AF_Zone[Zn1]	5	Agroforestry Zone
AF_Zone[Zn2]	3	
AF_Zone[Zn3]	2	
AF_ZoneTot	20	Agroforestry Zone
Ca_PlantYear[Zn1…3]	0, 1, 1, 2, 2, 3, 3, 4	Crop Management
Ca_PlantDOY[Zn1…3]	304, 80, 304, 80, 304, 80, 304, 80	Crop Management
Mn_Act[Zone]	Use Values resulted from 1st run. Make sure result from crop zones become input from tree zone and vice versa (see explanation in text)	
Mn_Slw[Zone]		
Mn_Pass[Zone]		
Mn_Struc[Zone]		
Mn_Metab[Zone]		
Mn2_Act[Zone]		
Mn2_Slw[Zone]		
Mn2_Pass[Zone]		
Mn2_Struc[Zone]		
Mn2_Metab[Zone]		
W_Thetai[Zone]/ W_FieldCapi[Zone]		
N_Soili[SlNut,Zone]		
OUTPUT		
T_Biom		Table 1 page 1
C_Biom[Zn1…3]		

4.6. Contour hedgerows on sloping land

Figure 4.7B gives initial results for a contour hedgerow system on sloping land, cumulated over four crops. The simulations presented here were made with version 1.1. 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 4.7C 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'

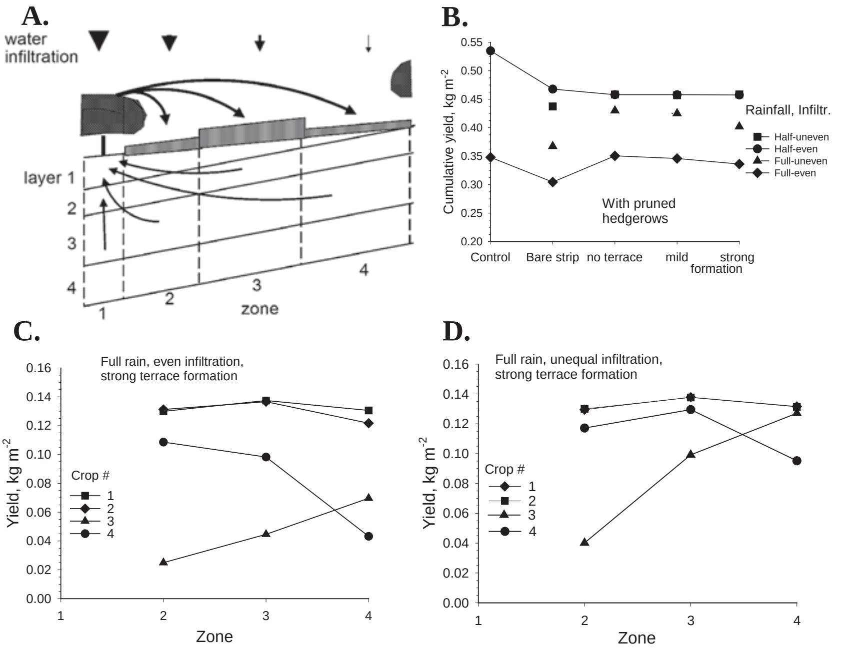


Figure 4.7. Calculations with the WaNuLCAS model (Van Noordwijk and Lusiana, 1999) of crop yield in a contour hedgerow system on sloping land; A. Model scheme for applications on sloping land; B. Cumulative yield over four crops (2 years) for a humid (3 000 mm/year) and sub-humid (1 500 mm/year) climate, with and without uneven infiltration of rainfall over the respective zones; C. and D. results per crop and zone.

4.7. 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 (Figure 4.8).

For these runs the soil profile consisted of four layers (5, 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 water holding 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 where 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 litter fall 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 using WaNuLCAS, we focus here on grain production (actual harvest index was between 36 and 41%), stem wood production for the tree (treating crop residues, litter fall, 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 the first crop in the pure crop control effectively exhausted supply in the soil 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.

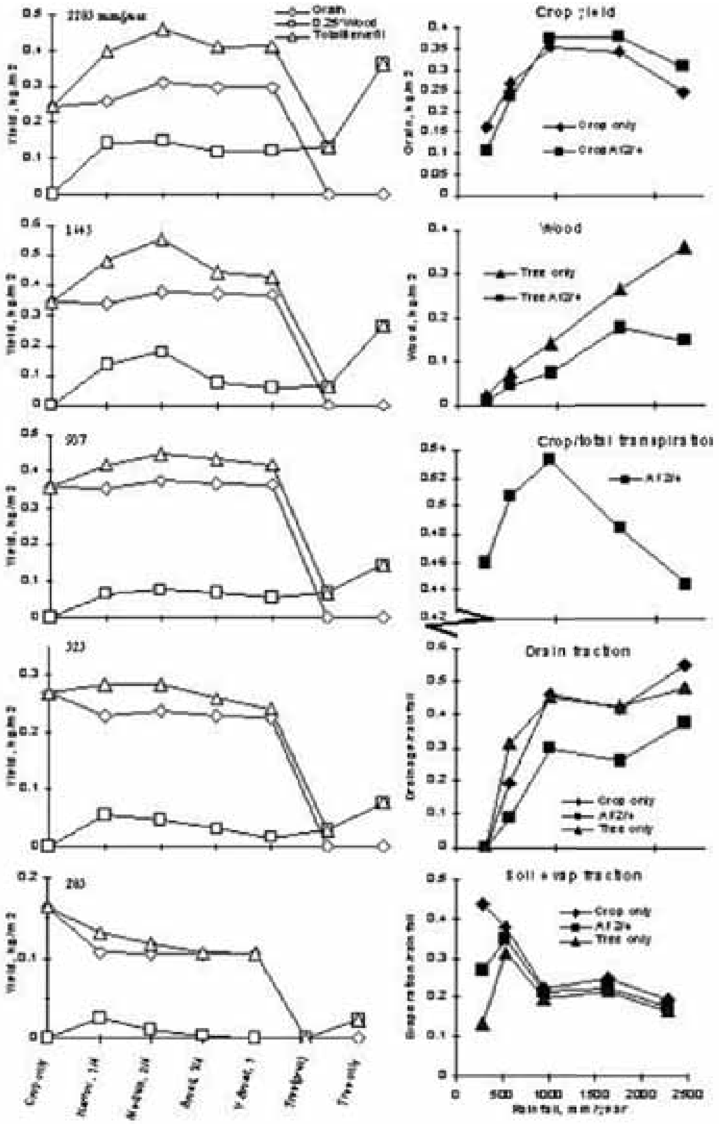


Figure 4.8. Calculations with the WaNuLCAS model of grain and wood production and water use for a range of annual rainfall conditions in an agroforestry system with isolated trees which are pruned when a crop is sown, resembling an early stage of a parkland system; production is accumulated over 2 years, 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).

Total yield for the agroforestry system can be calculated if the value of wood can be expressed relative to that of grain. In Figure. 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 affected 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.

4.8. Model parameter sensitivity for P uptake

WaNuLCAS model was used to explore the effect of root density and presence of mychorriza on phosphorous uptake in agroforestry systems (van Noordwijk, *et al*., 1999).

The predicted P uptake for both tree and crop (Figure. 4.9A and B) respond to changes in root length density (L_{rv}) 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 (Figure. 4.9C 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.

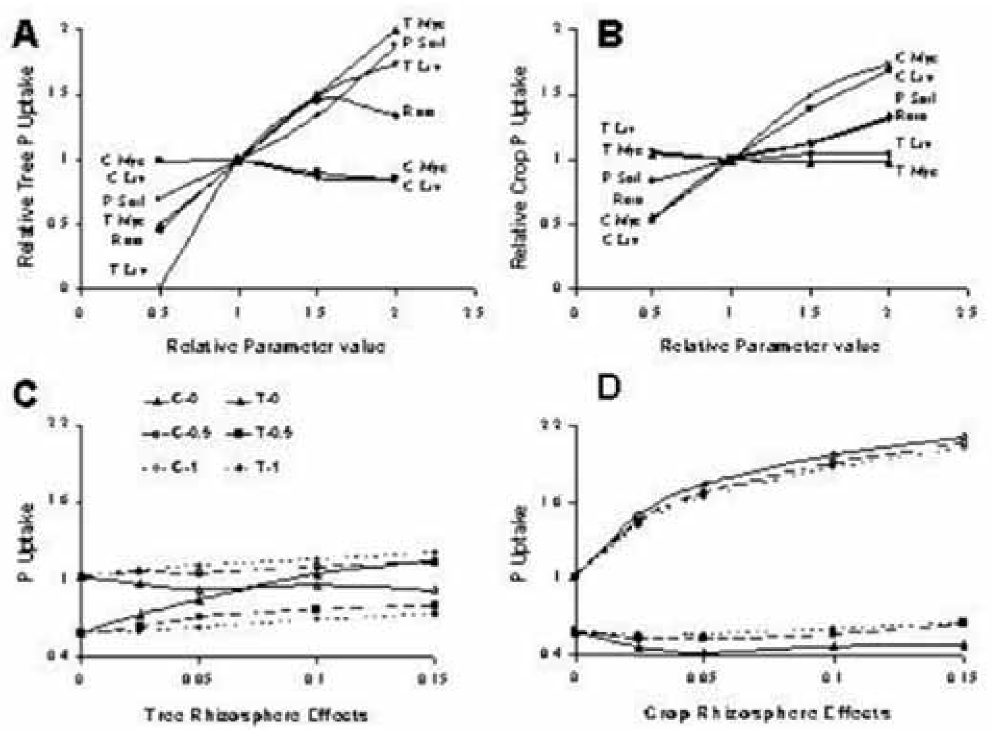


Figure 4.9. Preliminary calculations with the WaNuLCAS model after incorporating a P balance. A and B Sensitivity of predicted P uptake by tree (A (and crop (B) to changes in parameters for root length density T_Lrv and C_Lrv, respectively), mycorrhiza (C_Myc and T_Myc), soil P content (P_Soil) and rainfall. 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).

4.9. 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 safety net 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 version 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 safety net 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 from trials in Lampung (Rowe *et al*., 1999), are in line with this model.

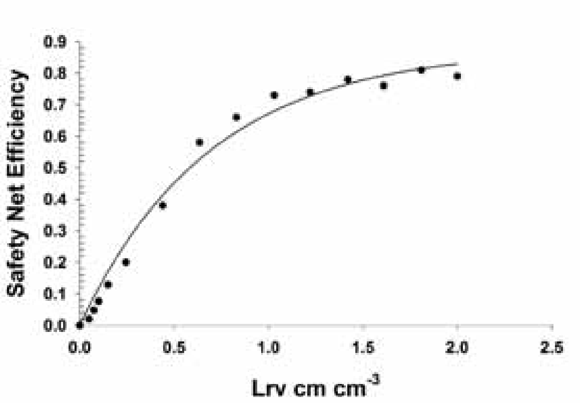


Figure 4.10. Use of the WaNuLCAS model to estimate the tree root length density in the subsoil required for efficient functioning of a 'safety net' (modified from) Cadisch *et al*. (1997); model runs were made with an N adsorption constant Ka of 0.2, reflecting a nitrate-dominated situation as can be expected at high soil pH values.

4.10. Water and nutrient use efficiency in agroforestry systems

Farming systems purely based on annual food crops during and directly after deforestation generally lead to degradation of soil. Establishment of timber and/or fruit trees in cropped fields is feasible and offers better prospects in term of its sustainability. The efficiency of water and nutrient use in agroforestry systems can be used as an indicator of systems sustainability. In this study WaNuLCAS was used to assess the water and nutrient use efficiency in three alley cropping systems (Suprayogo,*et al*., 2002) The crop component is maize and the tree components are: *Paraserianthes falcataria, Hevea braziliensis* and *Swietenia mahagony*.

In this study water use efficiency is defined as: E_{water} (%) = $(T_c + T_t)/R * 100$, where:
E_{water} = water use efficiency,
T_c = crop transpiration,
T_t = tree transpiration
R = amount of rainfall.

Nutrient use efficiency is defined as: $E_{Nutrient}$ (%) = $(N_c + N_t)/(N_{Leach} + N_c + N_t) * 100$, where:
N_t = tree nutrient uptake
N_c = crop nutrient uptake
NL_{each} = amount of nutrient leached

Result shows that water use efficiency in tree based systems tend to increase with increasing age of the tree (Figure 4.11). *Paraserianthes*-maize is the systems with highest water use efficiency while Hevea-maize is the systems with lowest water use efficiency. Presence of trees in the system also reduced runoff and increased supply to ground water stores.

N-use efficiency in tree-based systems also tends to increase with increasing age of the tree (Figure 4.12). *Mahogany* – maize is the systems with highest N-use efficiency while Paraserianthes-maize is the systems with lowest N-use efficiency. The use of N fertilizer caused the N-use efficiency to decrease since N leaching becomes higher. On the other hand, P-use efficiency tends to decrease with increasing age of the tree. This is because P is an immobile nutrient that stimulates accumulation of P in the soil producing low P leaching.

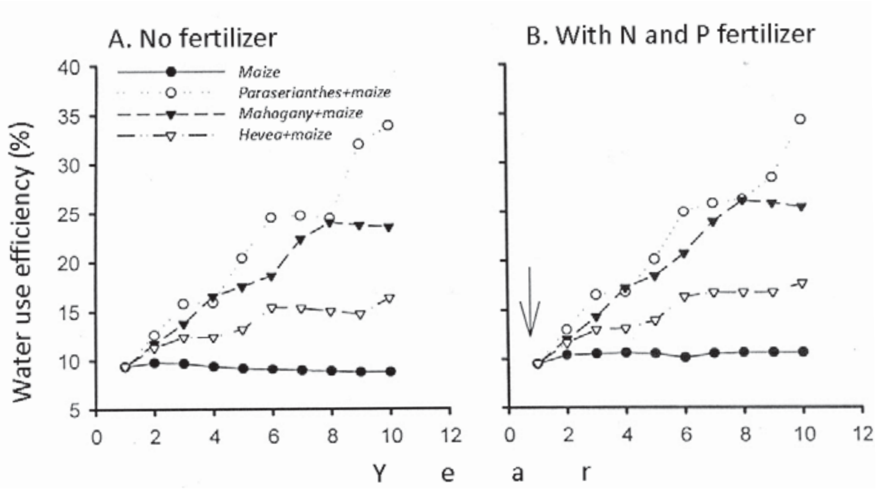


Figure 4.11. Water use efficiency at different agroforestry systems: maize monoculture, *Paraserianthes* + maize, *Mahogany* + maize and *Hevea* + maize. (A) no fertilizer and (B) with N and P fertilizer.

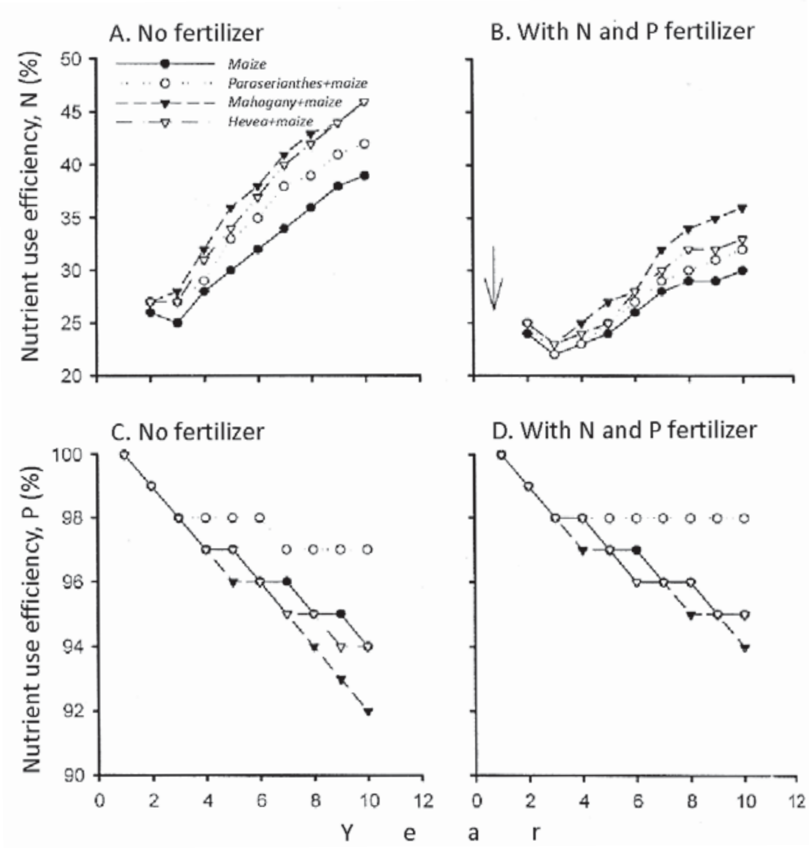


Figure 4.12. Nutrient (N and P) use efficiency in the different agroforestry systems : maize monoculture, *Paraserianthes* + maize, *Mahogany* + maize and *Hevea* + maize. (A and C) no fertilizer and (B and D) with N and P fertilizer.

4.11. Management options for agroforestry parkland systems in Sapone (Burkina Faso): separating the tree-soil-crop interactions using WaNuLCAS

Trees in the parkland systems of West Africa provide food and income, but also interact with the grain crops. Competition and complementarity in resource use between the components of these systems need to be better understood. The effects of crown pruning of agroforestry parkland systems in terms of resource capture and utilization either were investigated in an agroforestry parkland system in Burkina Faso or was analysed using the Water Nutrient and Light Capture in Agroforestry Systems (WaNuLCAS) (Bayala , *et al*, 2004).
The tree was focus on two species *Vitellaria paradoxa C.F. Gaertn (karité)* and *Parkia biglobosa (Jacq.) Benth. (néré)* with associated crops of *Pennisetum glaucum (L.) (millet)* and *Sorghum bicolor (L.) Moench (sorghum)*. Three treatments of crown pruning (totally-pruning, half-pruning and no-pruning) were applied to karité and néré. The area under each tree was divided into four concentric tree influence zones before pruning the trees (Zones A: up to 2 m from the tree trunk, B: up to half of the radius of the tree crown, C: up to the edge of the tree crown and D: up to 2 m away from the edge of the tree crown).

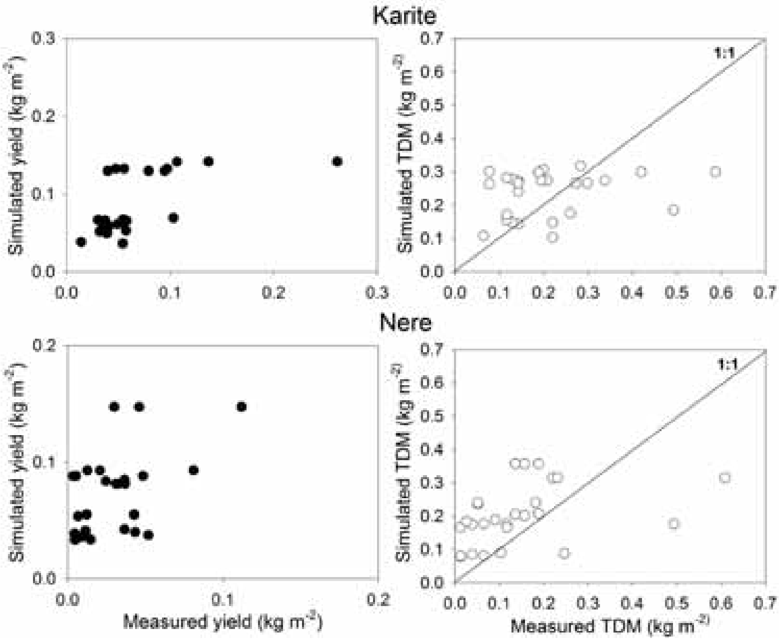


Figure 4.13. Scatter plots of measured and simulated crop yield and total dry matter (TDM) under karité (Vitellaria paradoxa) and néré (Parkia biglobosa) trees in a parkland agroforestry system in Saponé, Burkina Faso.

Figure 4.13 shows crop performance for the various zones and pruning regimes tended to be overestimated, indicating that not all limitations occurring tin the field were adequately represented and/or that resource capture for the resources included in the model (light, water, N and P) was overestimated. Simulation with WaNulCAS indicated that the plant components differed in the key limiting factors. For the Karite, with a relatively shallow root system and ability to fix atmospheric nitrogen, water limitation dominated for (29%, 27% and 33% of the simulation period for unpruned, half-pruned and totally pruned trees, respectively). Water limitation was also found to restrict crop growth under this species (26% of the time in unpruned and half-pruned trees, and 30% of the growing season for totally pruned) trees. P limitation restricted crop growth only 8% of the season in unpruned and half-pruned trees and 4% in totally pruned trees. Water limitation under karite is probably due to its shallow root system indicating its high dependency on rainfall water and probable less access to the ground water table. For the Nere tree the main limitations were water (11 to 32% of the simulation time) and P (15 to 42 of the simulated time). Crop growth under Nere was mainly limited by P (32 to 50% of the simulated growing season) corroborate to the findings of Tomlinson *et al*. (1995) and Bayala *et al*. (2002).

4.12. Long time effect of Legume Cover Crop (LCC), sugarcane harvest residue (trash) and *Bagas* (sugarcane processing waste) on soil carbon and sugarcane yield

Ultisols is a typical soil type in North Lampung, Indonesia. It is low in soil organic matter content as well as N, P and exchangeable cations. It also has high concentration of Al and Mn. Thus, the main problem in soils of North Lampung is low fertility.

Soil organic matter is the key factor to soil fertility. One way to prevent more soil degradation is to maintain soil organic matter. Maintaining soil cover throughout the year, either by cover crop or by mulch, can do this. A continuous biomass is required to stabilize the organic matter content of the soil. According to Young (1989) about 8.5 Mg ha^{-1} annual input of aboveground biomass is required in order to maintain soil carbon content of 2 %.

One of the main crops in North Lampung is sugarcane. Sugarcane yields tend to drop rapidly if there is no fertilizer input. A potential source organic input to the systems is sugarcane harvest residue (*trash*) and *Bagas* (sugarcane processing waste). *Thrash* is normally burnt after harvest and *Bagas* (sugarcane processing waste) is normally piled up around the sugarcane factory creating high risk of fire.

Brawijaya University-Indonesia had conducted an experiment to test the effect LCC, sugarcane harvest residue (trash) and Bagas (sugarcane processing waste) on sugar cane growth and production. The following applications of organic materials were tested on a soil that had been cropped for more than 10 years after forest conversion: (1) without organic materials as a control, (2) bagas 8 Mg ha^{-1}, (3) bagas 16 Mg ha^{-1}, (4) sugarcane trash (harvest residue) 8 Mg ha^{-1}. The whole plot was planted a mixed of legume cover crops (LCC) *Mucuna pruriens var. utilis* and *Centrosema pubescens* (1:1) and was given rock phosphate 1 Mg ha^{-1} at the first year and followed by sugarcane for another 2 years.

Based on this experiment, we simulate the systems using WaNuLCAS model to see the long-term effect of the organic inputs on soil fertility (Hairiah, *et al*., 2003). Three different scenarios were used: (1) external organic input given only at first year and N and P fertilizer every years with similar dosage, (2) external organic input gave every three years and N and P fertilizer every years with same dosage, (3) external organic input gave every three years and N and P fertilizer every years with different dosage (ratio dosage/years = 1.2:0.9:0.9 from default value and start from third years).

The simulation predicted that additional organic input do not significantly affect the long-term amount of organic carbon of the systems (Figure 4.14). The organic matter content at 0 – 5 cm depth decrease by 0.04 – 0.07% per year, which is faster compare to 0.02 – 0.03 % per year at depth 5-20 cm.

The results also predicted that application of sugarcane residues to the soil lead to a slower declining rate of sugar cane yield if accompanied by application of N fertilizer (Figure 4.15). Without N fertilizer application, returning sugarcane residues will cause N immobilization in the soil causing a decrease in sugarcane yield.

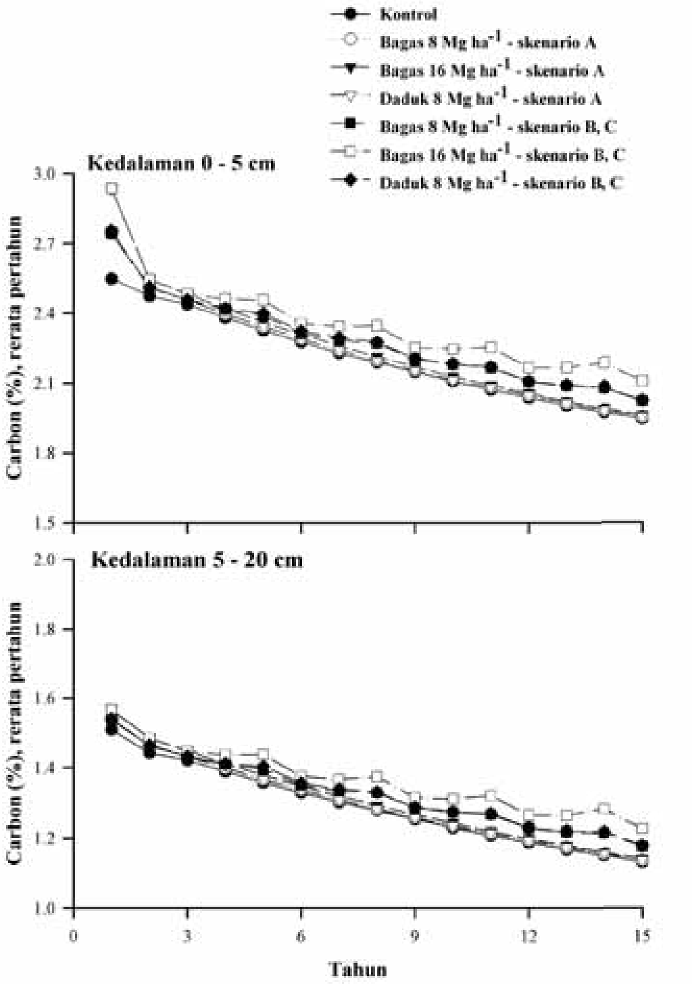


Figure 4.14. Soil organic matter content (average per year) at depth 0 – 5 and 5 – 20 cm of soil.

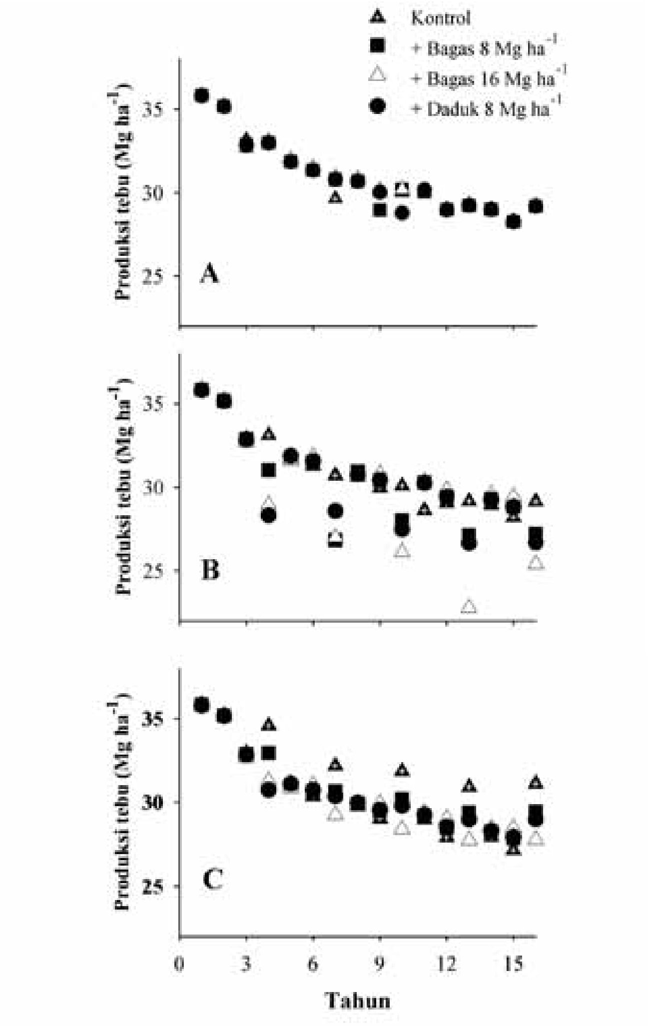


Figure 4.15. Sugarcane yield (in dry weight stem, Mg ha-1) for 16 years in different treatment and scenario.

4.13. The effect of agroforestry systems based on differing leaf phenologies on water balance and tree and crop growth

In Thika and NaroMoru, West of Mt. Kenya introduction of tree species into the cropping systems might aggravate the crop since water limitation is an important factor for the crop performance and yield. The differences of crop performance and yield may have relation to the tree water uptake that is corroborate to the tree leaf phonologies. The WaNuLCAS model was used to simulate water balance of the agroforestry systems based on differing leaf phenologies (Muthuri, 2003). The tree was focus on three species *G. robusta, A. acuminata* and *P. fortunei* associated with maize. *G. robusta* is evergreen, *A. acuminata* is semi-deciduous and *P. fortunei* is deciduous in term of tree water uptake.

Figure 4.16 and 4.17 shows the components of the water balance by the trees and crops using different leaf phenology for the Thika and Naro Moru site. The simulations of the water balance between Thika and Naro Moru site shows was not too different. Changing leafing phenology from evergreen, through semi-deciduous to deciduous generally decreased water uptake by the trees and interception of rainfall by all three trees species. Simulated total water uptake was never greater in all agroforestry systems than in sole maize, although the estimated water uptake by the crop component in the agroforestry systems was close to that for sole maize, especially when the deciduous leafing phenology scenario was adopted.

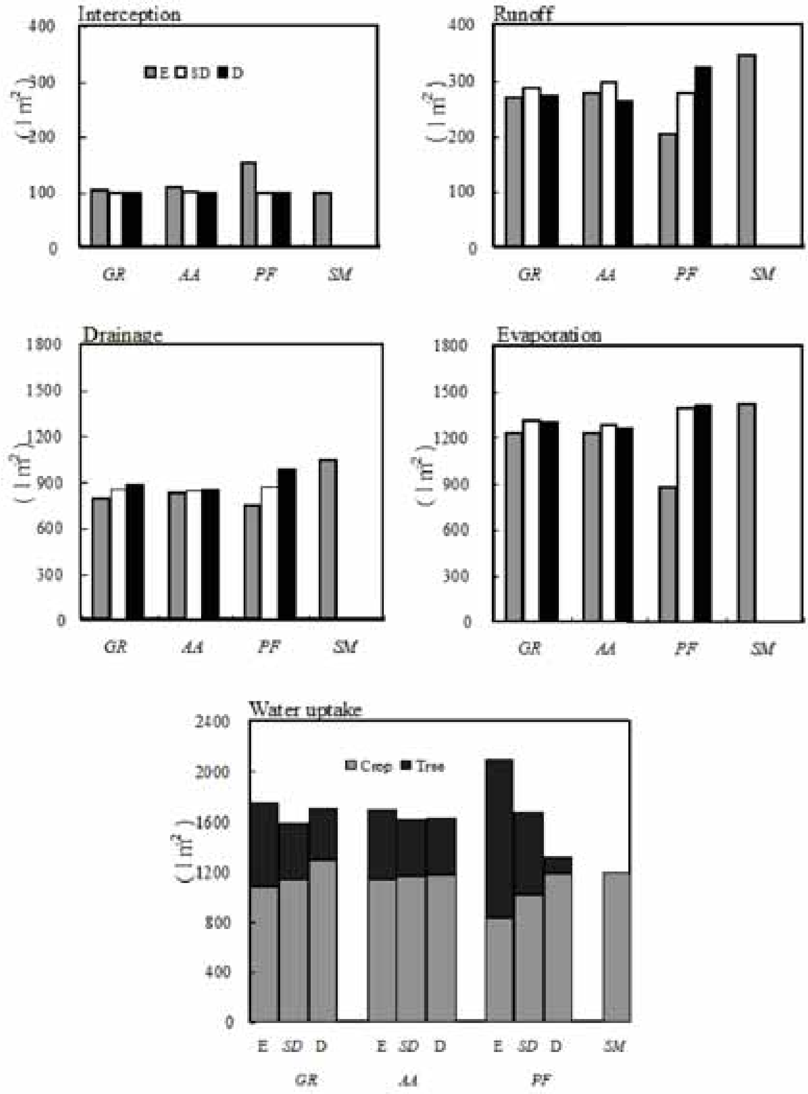


Figure 4.16. Simulated values for water balance components in (SM) sole maize and agroforestry systems containing (GR) *G. robusta*, (AA) *A. acuminata* and (PF) *P. fortunei* in five year simulation involving (E) evergreen, (SD) semi deciduous and (D) deciduous leaf phenology scenarios at Thika.

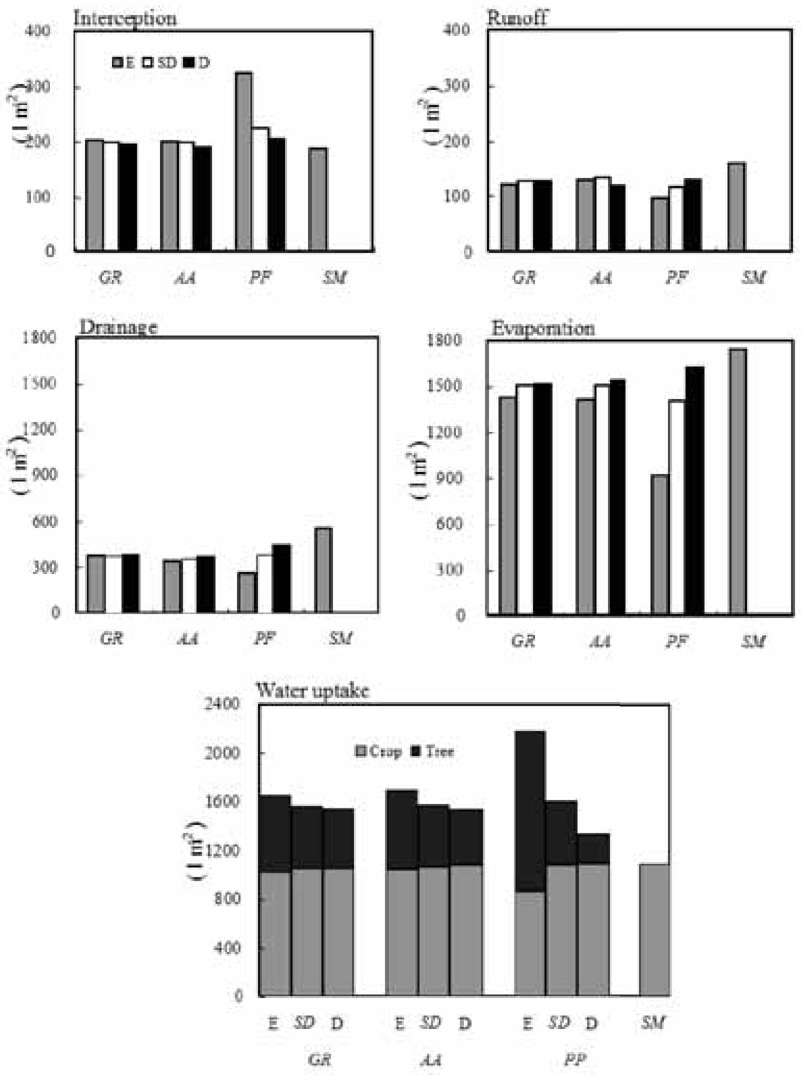


Figure 4.17. Simulated values for water balance components in (SM) sole maize and agroforestry systems containing (GR) *G. robusta*, (AA) *A. acuminata* and (PF) *P. fortunei* in five year simulation involving (E) evergreen, (SD) semi deciduous and (D) deciduous leaf phenology scenarios at Naro Moru.

4.14. Safety net efficiency – effect of root length density and distribution

The presence of hedgerow tree in the crop field may lessen nutrient leaching. For nutrients of higher mobility leaching could be reduced if tree have a relatively dense root system beneath the crop root zone (a safety net). Cadisch *et al.*, 1997 have explore how such safety net function may depend on tree root length density in the layer underneath the crop root zone. WaNuLCAS was used to test the positive (safety net functions) and negative (competition for water and N) impacts of simultaneous tree roots on maize yield by separating relative tree root distribution from absolute root length density for topsoil and subsoil (van Noordwijk and Cadish, 2002).

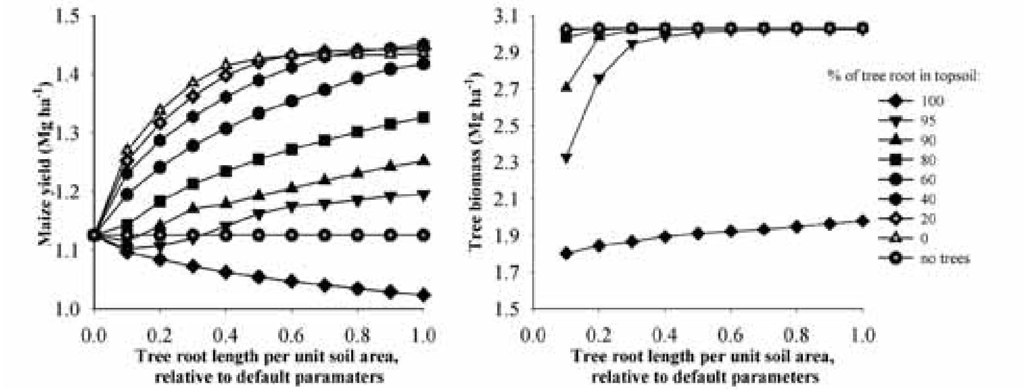


Figure 4.18. Predicted maize yield (A) and tree biomass (B) for the default rainfall situation (2318 mm year $^{-1}$), when relative distribution of tree roots with depth as well as total amount of tree roots are varied independently. Whereas the 'default' tree roots system had 21.5% of its roots in the top layer, a series of data was made that had 0 – 100% of its roots in the top layer and the remainder allocated to the deeper layers in proportion to the root length densities of the default case (the relative distribution over the four zones with increasing distance to the tree was not modified). For each of these root distributions, the total amount of roots was varied from 0.1 – 1 times the default, while maintaining the relative value.

Figure 4.18 shows that negative effect of the tree can be expected from trees that have all their roots in the topsoil, and from trees with only 0 – 10% of their roots in the subsoil, at low overall tree root length. These same relative tree root distributions at higher total root length (i.e. higher absolute root lengths in both top and subsoil) can have a moderate positive effect on maize yield, while tree root systems with 20% or more of their roots in the subsoil were consistently positive for crop, the higher the total root length, the more positive the impact on maize.

A remarkable feature of these results is that at default value for total root length, the tree root systems with 60% of their roots below the top soil led to (slightly) higher maize yields, than those with more (up to 100%) in the subsoil, while at total root systems size the 100% in subsoil (0% in top soil) was better for the maize. Although this effect is much too subtle to be recognized in any field data, it seems counter-intuitive.

4.15. Tree root systems dynamic – root functional and local response

Simulation models can represent belowground resource capture process at different levels of sophistication (van Noordwijk and De Willigen, 1987):

- Level 0.
  models 'without roots' using empirical resource capture efficiency coefficients for the relation between water and nutrient supply in the soil and the dynamics of plant growth,

- Level 2.
  models that differentiate between soil layers and use empirical data on relative root distribution to predict resource capture potential in each zone; root distribution can be schematised via an exponential decrease with depth (Jackson *et al*. 1996) or its 2-dimensional elliptical variant (Van Noordwijk *et al*., 1995), or they can be provided as 'independent' parameters for each layer or zone; change of root length densities with time can be imposed on the basis of crop age,
- Level 3.
  models that consider plants as organisms with the capacity to adjust the total amount of roots to the internal balance between above and belowground resource capture, and the location of new root growth to the parts of the root system with the best opportunities for uptake of the resource that is most limiting overall plant growth.

WaNuLCAS model can predict competition for water and nutrients between trees and crops at 'level 0' and 'level 1'. It can also be used at 'level 2' using spatial root distribution that restrictedly follows the exponential-decrease-with-depth or elliptical distributions. Stress of nutrient (N, P) or water is an important factor for the crop growth. When nutrient (N, P) or water stress occurs, the relative allocation of growth reserves to root can increase quickly.

The WaNuLCAS model was used to explore the change of root patterns due to local response (van Noordwijk, *et al*., 2003). A series of simulations was made for a moderately deep soil (1 m) with an annual rainfall of 1000 mm. Rainfall patterns ranged from '1 = every day 3 mm of rain' and '2 = every second day 6 mm', to '6 = every 32 days 96 mm'. As the potential evapotranspiration was assumed to be 4 mm day^{-1}, this environment would not provide enough water to avoid water stress, even if all rainfall were to be fully used. Figure 4.19 shows the rainfall patterns lead to situations of permanent moderate stress (rainfall pattern 1), alternations of sufficient water and severe water shortage (rainfall patterns 5 and 6) or intermediate patterns. In the overall water balance, with a decrease in the number of rainy days (through patterns 1 to 6), a decrease in the values for the interception and soil evaporation terms can be noted, while the contribution to groundwater (deep infiltration) and runoff increases but remains small in absolute value. Cumulative tree water use tends to increase through rainfall patterns 1 to 6. If a grass sward is added to the simulations, canopy interception increases and thus the amount of soil water available to either tree or grass is reduced. The grass water use is predicted to benefit more from rainfall patterns 5 and 6 than the tree causing a bell-shaped response curve for the tree.

A sensitivity analysis was carried out on the two key parameters for the functional shoot/ root balance and root distribution: 'Root_Allocation_Responsiveness' and 'local response'. Higher values of 'Root_Allocation_Responsiveness' lead to a more rapid shift of current growth resources to roots, at the expense of shoot growth, when the total uptake of water and/or nutrients falls short of current 'demand'. With increasing 'local response', root distribution shifts towards the soil layer and spatial zone in which roots are most successful (per unit root length) in taking up the most limiting resource.

'Local response' is simulated in WaNuLCAS by a gradual change in the parameters of the elliptical root distribution, and constrained by the total new length of roots that can be produced with the carbohydrates allocated. The intensity of change depends on the T_DistResp parameter and on the degree to which effective uptake per unit root length of the currently limiting resource differs between soil layers and zones. If roots in deeper layers are more effective (e.g. in case of water stress), the root distribution can shift to a more gradual decrease of root length density with depth (or even an inverse pattern), if roots in topsoil are more effective (e.g. when P uptake is overall limiting plant growth and the topsoil has sufficient water content to keep the P mobile) roots will expand (mainly) in topsoil.

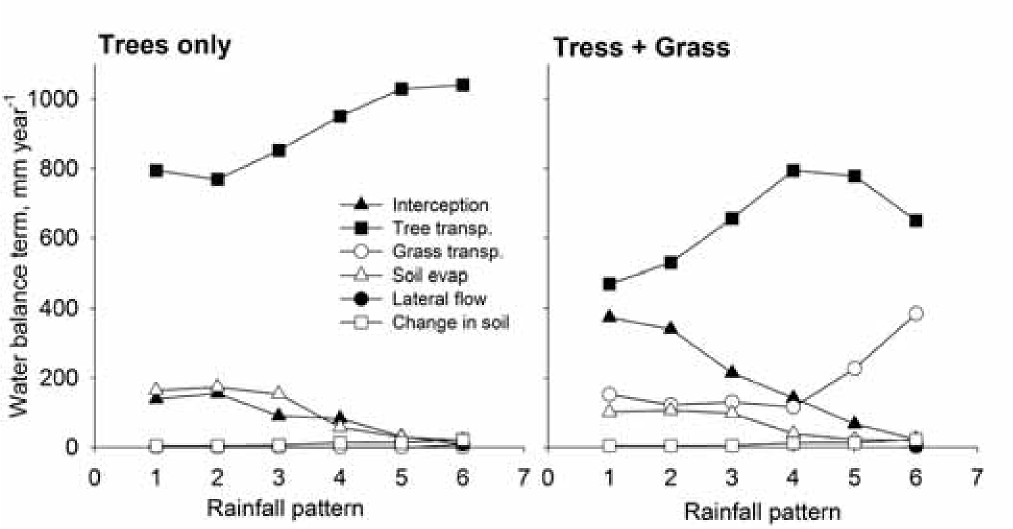


Figure 4.19. Water balance for a range of WaNuLCAS simulations, in the absence of functional or local response of the tree, with and without a grass sward.

The general patterns of root and shoot response in the simulations can be understood from the re-wetting patterns of the soil (Figure 4.20). In the absence of a competitor, a stronger root allocation leads to a larger root system, but only in rare situations to a larger shoot biomass or total water use. For rainfall patterns 1-4 the 'local response' rules lead to a shallower tree root system, as the rainfall events are insufficient to rewet the whole soil profile and superficial roots are thus more effective in water uptake than deep ones. For rainfall pattern 5 and 6, however, the local response rule leads to a deeper root system. In the presence of a competing grass sward, total water use by the tree is expected to decrease substantially and the tree biomass will consequently be lower. A marked difference with the previous simulations, however, is that now a larger root allocation can actually increase tree water use and shoot biomass. The competitor is predicted to enhance the increase in the fraction of tree roots in the topsoil for rainfall pattern 1-4. For rainfall pattern 5 the presence of a grass sward is predicted to drive the tree root to a more superficial pattern, rather than the deeper pattern of the monoculture.

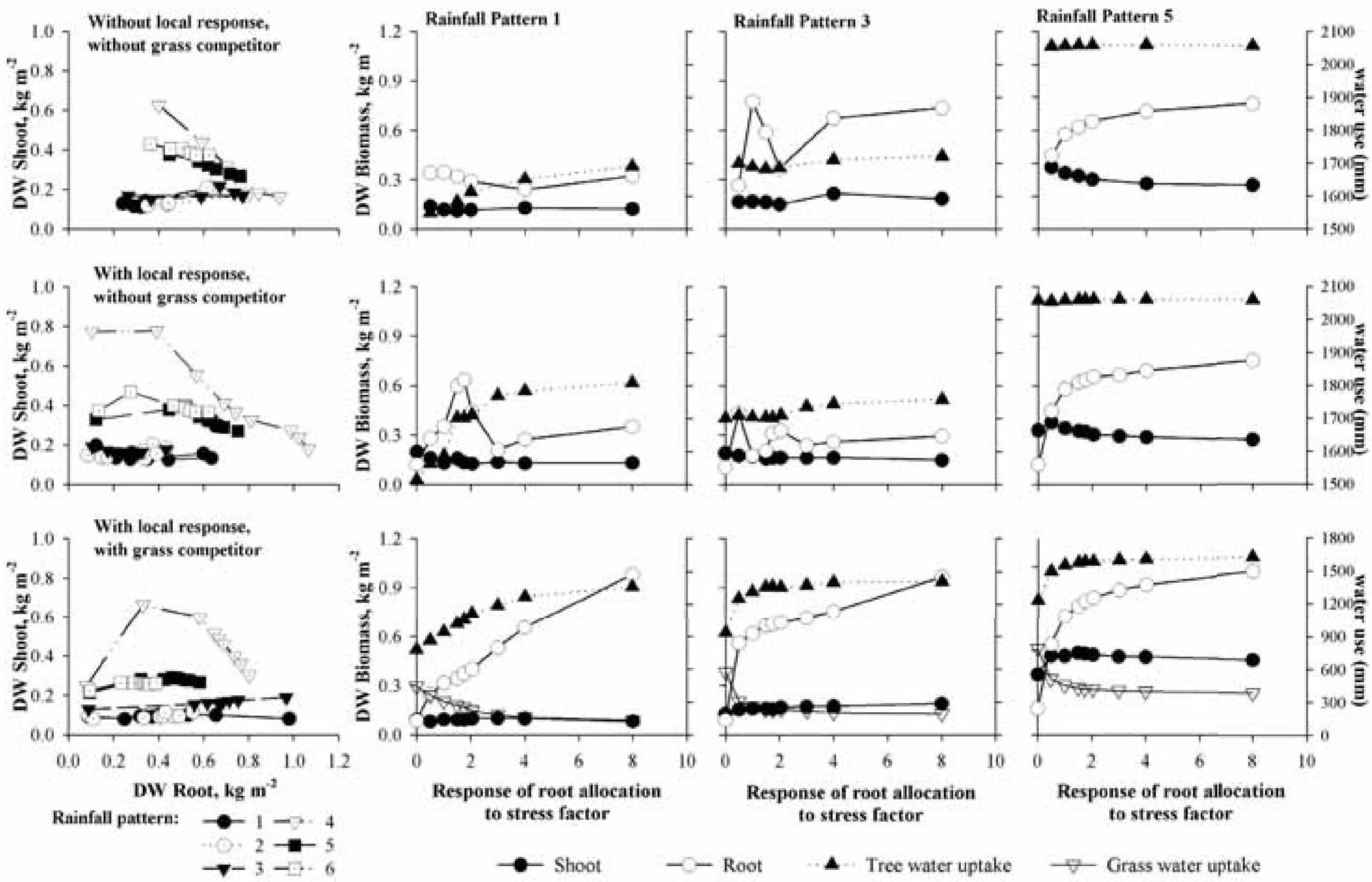


Figure 4.20. Simulation results for shoot and root dry-weight (DW) biomass and tree (and grass) water use, for three rainfall patterns and a range of parameter values for the ‘root_Allocation_Responsiveness’ parameter (see explanations in text, this Box). Simulations include situations with and without ‘local response’ (see text, this Box), and with and without competition from a grass sward

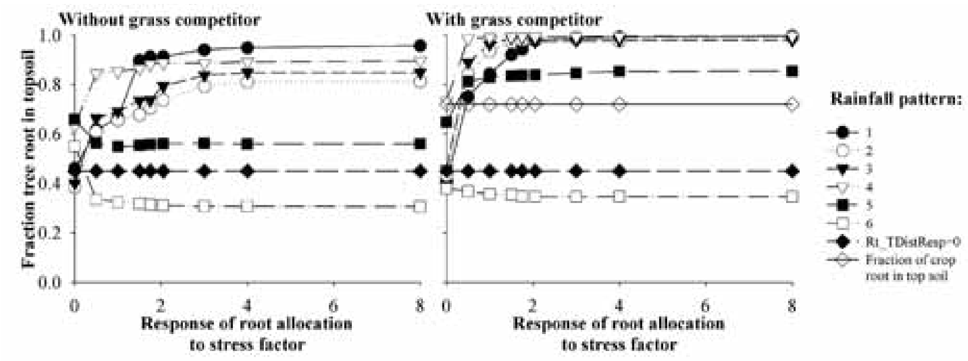


Figure 4.21. Relative tree root biomass in the upper 25 cm of the soil profile for a range of values of the factor that governs the response to stress of the biomass allocation to roots, with (right) and without (left) a competing grass; the grass is assumed not to show a functional or local response, so it has a constant fraction of its roots in the topsoil; the line Rt_TdistResp = 0 indicates a situation without 'local response', so the 'response to stress' can modify total root biomass, but not root distribution for this setting.

4.16. Improved options for tree spacing and tree-crop intercrop patterns

Transformations from degraded soils and landscapes to agroforestry mosaics can benefit from the potential complementarity between the early stages of tree-based production systems and crop growth. Decisions by farmers managing such transition involve strategic (multi-year) decisions on the choice of tree species, the number of trees per ha and the spacing, while tactical (shorter term) decisions relate to the choice of intercrops, tree canopy pruning and/or tree root pruning. Based on the current experience in Lampung (Indonesia) through SAFODS (Smallholder agroforestry options for degraded soils: Tree establishment in cropped fields) project, we use WaNuLCAS model to explore these choices.

Increasing the space between tree rows makes longer intercropping possible – but also reduces the expected yield from the trees. An efficient way of considering the trade-off is to plot crop versus tree yield (Figure 4.22).

Most of the tree- crop combinations are substantially above the straight trade-off curve, suggesting that there is indeed a benefit to be obtained by the combination when compared to separate monocultures. However, the points for *A. mangium* suggest virtually no intercropping advantage. For the slower growing trees (mahogany and rubber), maximum tree yield can be obtained at about 20% of the potential long-year crop yield. After accounting for this intercept, a slight positive curvature remains when tree spacing is widened. *P. falcataria* has a low intercept (low crop yield opportunity when maximum wood volume is the target), but clear intercropping advantage at lower tree population density. This may therefore well be the most promising 'agroforestry' tree at intermediate densities.

As a first approximation of the dynamic effects of tree root pruning, we can compare simulations with and without the presence of tree roots in the various soil layers of the 'crop zone'. We assume that tree root pruning will have little effect on tree roots in the deeper layers, although the specific impacts on root distribution depend on tree species, time of pruning and soil conditions. According to the WaNuLCAS model set up for conditions in Lampung, we expect a direct negative effect of such tree root pruning on tree growth, and only a small positive effect on crop growth (Figure 4.23).

Tree root pruning will, according to the model, only have a substantial positive effect on opportunities for crop production in mahogany (*S. macrophylla*) and sengon (*P. falcataria*). The negative effects on tree growth will make this intervention not very attractiv4e, even before we account for the additional labour involved. Tree root pruning is a poor substitute for starting at an appropriate tree spacing.

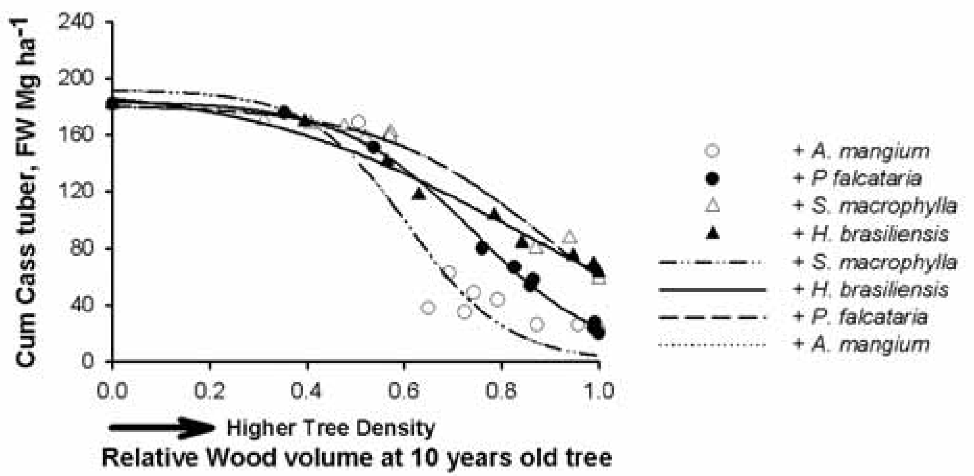


Figure 4.22. Predicted tradeoff between cumulative cassava yield and wood volume at various tree species and densities in Lampung.

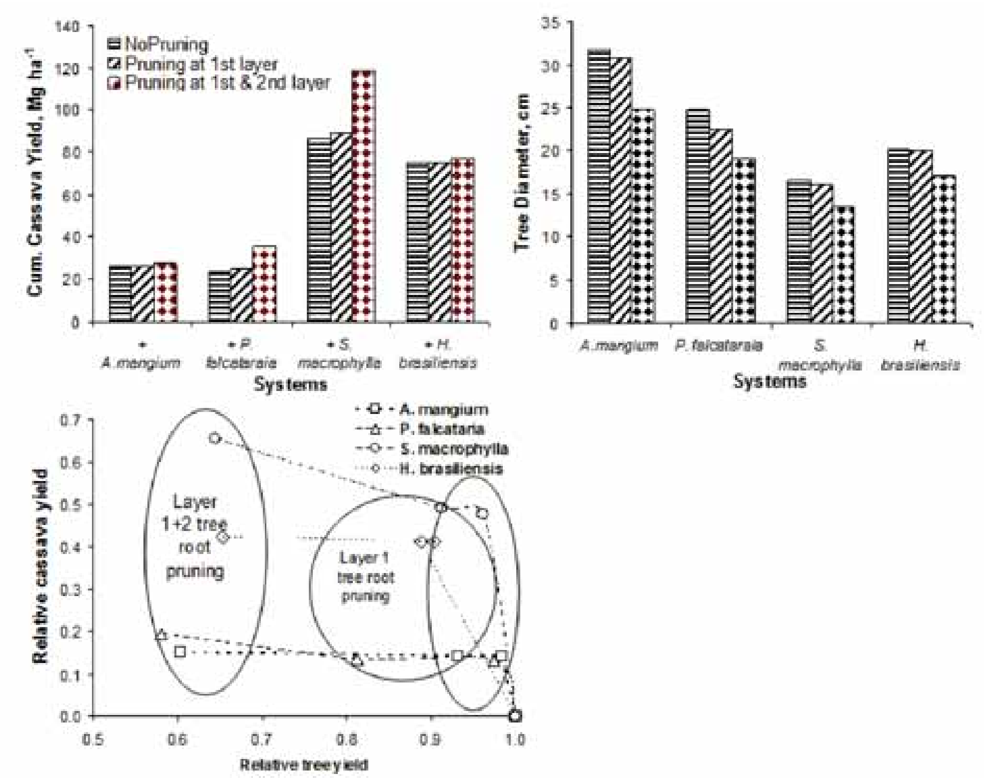


Figure 4.23. Upper limit of effects of tree root pruning on predicted performance of a cassava crop (A), tree growth (B) and on the tradeoff (C) between expected tree and crop yield under Lampung conditions; the simulation compared default conditions with situations without tree roots in the first or the first two layers fro all cropped zones

4.17. Recommendations for shade-based Imperata control during tree establishment

Technically, Imperata as a weed can be controlled and Imperata grasslands can be converted to more productive systems. The first steps in technically controlling Imperata in the agroforestation of grasslands can be achieved by either mechanical or chemical control. Farmers employ a range of techniques from herbicide or soil tillage to 'pressing', depending on their resources and the current cost of the technique. Food crops can be used in the first few years of most tree crops or agroforestry systems to maintain income and pay for the suppression of Imperata regrowth. However, the gap between the last food crop interplanting and canopy closure leads to a major risk of Imperata regrowth and fire occurrence. The current analysis of shade-based Imperata control by agroforestation is largely focussed on the duration of this 'Imperata regrowth window', and the way its duration depend on the planting pattern and species choice of the trees.

Through SAFODS (Smallholder agroforestry options for degraded soils: Tree establishment in cropped fields) project, we compared WaNuLCAS model scenarios between tree species to estimate the Imperata regrowth window as the period between 50 and 15% of ground-level light availability.

Results of the WaNulCAS model simulations first of all confirmed a well-known fact: young trees of most species are not able to compete with Imperata and partial weeding around the tree stem base is absolutely necessary to get most trees started, with the possible exception of *Paraserianthes falcataria*. Although *Acacia mangium* is a fast growing tree, a more intensive weeding regime will double tree growth. The improvement of initial tree growth speeds up tree canopy closure and reduces subsequent Imperata regrowth window is 2 to > 5 years according to the model, with periods longer than 5 years associated with slow initial growth rates (Figure 4.24).

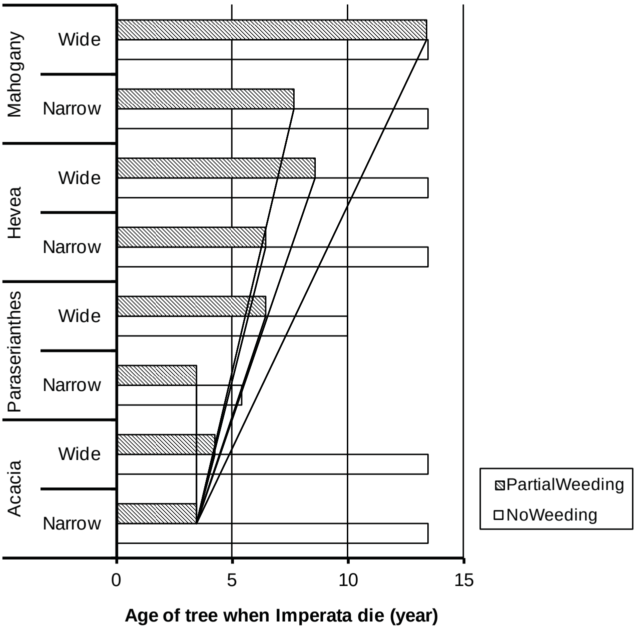


Figure 4.24. The age of the tree when Imperata die of four tree species under different weeding regime (partial and no weeding) and different tree spacing, narrow (timber trees : 4*2, 3*3, 4*4 m; rubber : 6*3, 5*3, 4*4 m) and wide spacing (timber trees : 8*4, 8*8 m; rubber : 6*6, 12*6m).