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WaNuLCAS, a model of water, nutrient and light capture in agroforestry systems

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Abstract. Models of tree-soil-crop interactions in agroforestry should maintain a balance between dynamic processes and spatial patterns of interactions for common resources. We give an outline and discuss major assumptions underlying the WaNuLCAS model of water, nitrogen and light interactions in agroforestry systems. The model was developed to deal with a wide range of agroforestry systems: hedgerow intercropping on flat or sloping land, fallow-crop mosaics or isolated trees in parklands, with minimum parameter adjustments. Examples are presented for simulation runs of hedgerow intercropping systems at different hedgerow spacings and pruning regimes, 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.

Introduction

A focal point in the analysis of where and how agroforestry systems work is still whether or not tree-crop systems can utilise resources of light, water and/or nutrients which would not be available in a simpler tree or crop system (Cannell et al., 1996). A sufficient amount of detail in the description of above- and below-ground resource capture by the component species is needed to evaluate both competition and complementarity or facilitation (Ong and Huxley, 1996; Sanchez, 1995; Vandermeer, 1989).

Interactions occur both in space and time. In sequential agroforestry systems neighbourhood effects in a landscape mosaic still have a spatial element, while simultaneous systems often have at least an element of zonation. The dichotomy between sequential and simultaneous agroforestry systems may thus have been overstated in the past (Sanchez, 1995; Van Noordwijk and Purnomosidhi, 1995) and a modelling framework is desirable in which they are endpoints of a continuum of spatio-temporal interactions.

In modelling agroforestry systems, a balance should be maintained between process and pattern, between temporal and spatial aspects. Existing crop growth models tend to be detailed in processes, but simple in spatial patterns, (implicitly) assuming a homogeneous minimum representative area, with a one-dimensional variation between soil layers. Most GIS (geographical information systems) applications do not incorporate spatial interactions and only apply a stratified sampling approach. Full-scale detail on spatial interactions may not be achievable for any reasonable process description. As a compromise, a system of zoning can be used, which can relate many types of spatial patterns to a model still covering essential aspects of real-world behaviour.

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

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

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

The total balance for below-ground resources (water or nutrients) inputs into an agroforestry system is:

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

The term $Upt_{tree, noncomp}$ represents the safety-net function of tree roots for nutrients and water leaching and percolating below the zone of crop roots and/or outside of the crop growing season (Van Noordwijk et al., 1996; Rowe et al., this issue), as well as a nutrient pump role for resources stored in the subsoil for longer periods of time (Young, 1997). Empirically it is no easy task to separate these components of total resource capture for any given system, let alone cover the wide range of possible system configurations and variations induced by management. In a conceptual process-based model, the terms of Eq. (1) can be quantified as indicated in Table 1.

A major problem in linking a number of single-species resource capture models into a multi-species resource capture model with a single accounting system for the resources, is one of priority assignment in the calculation sequence. Models which consistently assign priority to one of the components may vastly overestimate its resource capture, while the solution of some models of alternating priorities is not very satisfactory either (Caldwell et al., 1996). For a more balanced approach, the resource capture of the various components should be further integrated and applied simultaneously, avoiding priority assignment. One way of doing this is adding the roots (for water and nutrients) and leaves in a common layer or zone, calculating a total resource capture and sharing this out over the two components in proportion to their root length density or leaf area. As resource capture is in most cases a non-linear function of root length or leaf area, this approach to resource sharing gives a different result from adding resource capture for the two components (the latter may overestimate potential uptake rates).

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

1. integrate knowledge and hypotheses on below- and aboveground resource

Table 1. Representation of resource capture (Eq. 1) in a simple tree-crop agroforestry system, where the crop roots are confined to the 'topsoil' and the tree roots explore the 'subsoil' as well.

	Water	Nitrogen	Light
Input	Rainfall + irrig – runoff+runon	Fertilizer + org. imports	Sum of daily radiation
Recycle	Hydraulic lift into crop root zone	Litterfall, tree prunings, crop residues	–
$Uptake_{Crop}$	$\sum$ W_Uptakecrop	$\sum$ N_Uptakecrop	$\sum$ Lightcap_crop
$Uptake_{Tree, Comp}$	$\sum_{top}$ W_Uptaketree	$\sum_{top}$ N_Uptaketree	$\sum$ $Lightcap\_tree_{1, 2}$
$Uptake_{Tree, Noncomp}$	$\sum_{sub}$ W_Uptaketree	$\sum_{sub}$ N_Uptaketree	$\sum$ $Lightcap\_tree_{3}$
Losses	$\sum$ Percolation from lowest zone	$\sum$ Leaching from lowest zone	1 – $\sum$ Lightcap
Storage	Δ Water content	Σ (Nmin + Soil Organic Matter)	–

capture by trees and crops (or any two types of plants) at patch scale as a basis for predicting complementarity (facilitation) and competition;
2. build on well-established modules (models) of a soil water, organic matter and nitrogen balance, and crop and tree development to investigate interactions in resource capture;
3. describe the plant-plant interaction term as the outcome of resource capture efforts by the component species, as determined by their above- and below-ground architecture (spatial organisation) as well as physiology;
4. be applicable to spatially zoned agroforestry systems as well as rotational systems;
5. be testable on the basis of independently measured parameters;
6. be flexible in exploring management options within each type of agroforestry system;
7. be useful in estimating extrapolation domains for proven agroforestry techniques, as regards soil and climate properties, as well as tree and crop architecture;
8. be user-friendly and allow non-modellers to explore a range of options, while remaining open to improvement without requiring a complete overhaul of the model;
9. generate output which can be used in existing spreadsheets and graphical software;
10. make use of readily available and tested modelling software.

In view of objectives 8, 9 and 10 we chose the Stella Research modelling shell (Hannon and Ruth, 1994) linked to Excel spreadsheets for data input and output. The current model should be seen as a prototype; in the Stella environment it is relatively easy to modify or add modules or relationships. Here we will outline the main assumptions underlying the WaNuLCAS model and give some examples of model output. A more complete model description as well as computer versions of the model and parameter settings used for the examples given here can be obtained from the authors.

Model description

A key feature of the model is the description of uptake of water and nutrients (at this stage only N) on the basis of root length densities of both the tree and the crop, plant demand factors and the effective supply by diffusion at a given soil water content. Underlying principles were described by De Willigen and van Noordwijk (1987, 1989, 1991, 1994) and Van Noordwijk and Van de Geijn (1996).

The model represents a four-layer soil profile (vertical), with four spatial zones (horizontal), a water and nitrogen balance and uptake by a crop and a tree (Figure 1A). The user can define the width and depth of each zone and adjust it to the type of system simulated. The model can be used both for simultaneous and sequential agroforestry systems and may help to understand the continuum of options ranging from improved fallow via relay planting of tree fallows to rotational and simultaneous forms of hedgerow intercropping. The model explicitly incorporates management options such as tree spacing, pruning regime and choice of species or provenances. The model includes various tree characteristics, such as (dynamic) root distribution (over the 16 cells; four layers * four zones), canopy shape (above the four spatial zones), litter quality, maximum growth rate and speed of recovery after pruning.

If applied to hedgerow intercropping, the model allows for the evaluation of crop growth at different distances from the hedgerow for different pruning regimes and hedgerow tree spacings or fertiliser application rates. When applied to rotational fallow systems, the edge effects between currently cropped parts of a field and the areas where a tree fallow is growing can be simulated, by letting the first zone represent a fallow plot and zone 2, 3 and 4 represent three zones in a neighbouring cropped field. For isolated trees in parkland systems, equidistant zones around individual trees can be pooled (Table 2).

A number of inputs to the soil surface can be distributed proportional to the relative surface areas or heterogeneously. In this way, we can for example account for surface runoff of rainfall in one zone and its infiltration in another. Separately, patch-level net run-on or run-off can be implemented. Similar weighting factors are used for allocating litterfall, tree prunings, fertilisers and crop residues to the various zones, while conserving their overall mass balance.

The model assumes the same crop to be grown in all three zones, simultaneously. Sequencing of crops is possible by specifying the crop type, planting year and day of year for each subsequent crop. The vegetative and generative duration of that crop (at standard temperature) is used as an input, and modification of phenological development by actual temperature can be accommodated. Each crop should be specified on the basis of its maximum dry matter production rate per day, expressed in kg m^{-2} day^{-1}, and a graphic or tabulated input of its relative light use efficiency (dry matter production per unit light intercepted) and its leaf weight ratio as a function of crop stage. These parameters may be derived for a given location from more specific models, such as the DSSAT family of crop growth models.

Trees can be pruned in the model to a specified degree, on the basis of two criteria: concurrence with a crop on the field and tree biomass above a prune limit. Alternatively, calendar dates for pruning events can be given as

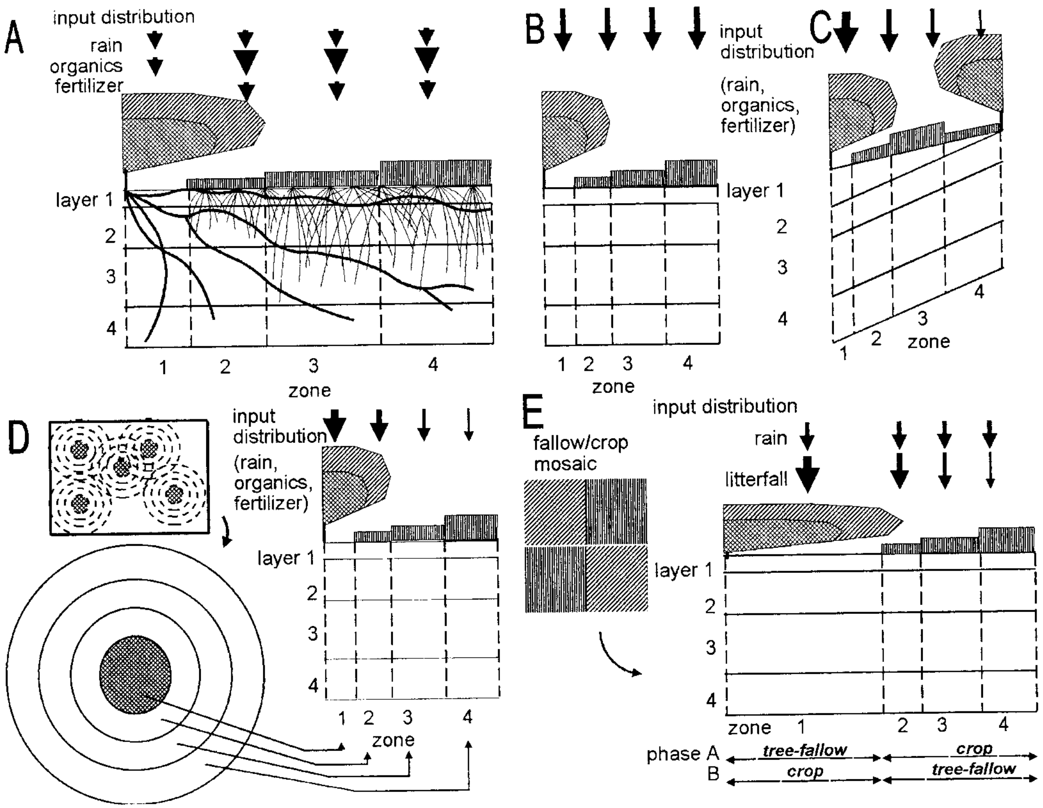

Figure 1. General layout of zones and layers in the WaNuLCAS model (A) and applications to four types of agroforestry system; B) Alley cropping; C) Contour hedgerows on slopes, with variable topsoil depth; D) Parkland systems, with a circular geometry around individual trees; E) Fallow-crop mosaics with border effects.

Table 2. Characteristic settings for four types of agroforestry system.

	Geometry	Tree canopy	Topsoil depth	Water infiltration	Time sequence
Alley cropping on flat land	Linear	Zone 1-4	Homogeneous	Homogeneous	Continuous
Alley cropping on slopes	Linear	Zone 1-4 + symmetrical canopy 4-1	Gradient (runoff + run-on)	Heterogeneous	Continuous (soil redistribution can be simulated)
Parkland trees	Circle	Zone 1-4	Homogeneous	Heterogeneous	Continuous
Tree fallow/mosaic	Linear	Zone 1 (fallow plot size)	Homogeneous	Homogeneous	Switching between fallow and crop stage

input. Prunings can be returned to the soil as organic input (in the standard case with regular distribution over the zones).

Soil and climate input data

Climate effects are mainly included via daily rainfall data which can be either read from a spreadsheet or generated on the basis of a daily probability of rainfall and an expected monthly rainfall total. Average temperature and radiation are reflected in potential growth rates which are used as input, but thermal time (temperature sum) is reflected in the speed of phenological development inside the model. Temperature effects on organic matter decomposition are incorporated according to the Century model (see below). Parameters influencing potential evapotranspiration (windspeed, VPD) are not explicitly required, only the resulting potential soil evaporation rate.

Soil is represented in four layers, the depth of which can be chosen, with specified soil physical properties and initial water and nitrogen contents, for all sixteen compartments. For calculating water infiltration to the soil, a layer-specific estimate of the field capacity (soil water content one day after heavy rain) is needed. No capillary rise or abiotic water redistribution other than during rainfall events is included in the model in its current form. For calculating potential water uptake a table of the soil's matric flux potential is needed, which integrates unsaturated hydraulic conductivity over soil water content (De Willigen and Van Noordwijk, 1994). The model also needs the relationship between water potential and soil water content, to derive the soil water content equivalent to a certain root water potential. As these relationships are not generally measured for all soils where we may want to apply the WaNuLCAS model, pedotransfer functions are used (Arah and Hodnett, 1997). We derive parameters of the Van Genuchten equations of soil physical properties via a pedotransfer function from soil texture, bulk density and soil organic matter content. The function selected was developed by Wösten et al. (1995). As this pedotransfer function is based on soils from temperate regions, one should be aware of its possible poor performance on soils with a low silt content, as the combination of clay + sand at low silt contents is much more common in the tropics than in temperate regions.

Water balance

The water balance of the system includes rainfall, with the option of exchange between the three zones by run-on and run-off, surface evaporation, uptake by the crop and tree and leaching. Only vertical transport of water is included (so far). For the description of the soil water balance in soil-plant models a number of processes should be combined which act on different time scales:

1. rainfall or irrigation (with additional run-on) and its allocation to infiltra-

tion and surface run-off (and/or ponding), on a seconds-to-minutes time scale;
2. infiltration into and drainage from the soil via a cascade of soil layers, and/or via bypass flow, on a minutes-to-hours time scale;
3. subsequent drainage and gradual approach to hydrostatic equilibrium on a hour-to-days time scale;
4. transfers of solutes between soil layers with mass flow;
5. evaporation from surface soil layers on a hour-to-days time scale, as modified by soil water content and vegetative cover;
6. water uptake on a hour-to-days time scale, but mostly during day time when stomata are open;
7. hydrostatic equilibration (hydraulic lift and sink) via root systems on a hour-to-days time scale, but mostly at night when plant transpiration is negligible;
8. hormonal controls (drought signals) of transpiration on a hour-to-weeks time scale;
9. changes in macropore volume (and connectivity) based on swelling and shrinking of soils closing and opening cracks, and on creation and destruction of macropores by soil macrofauna and roots; this acts on a day-to-weeks time scale.

The WaNuLCAS model currently incorporates points 1 to 7 of this list, but aggregates them to a daily time step; drainage to lower layers is effectuated on the same day as a rainfall event occurred. An empirical infiltration fraction (as a function of rainfall intensity, slope and soil water deficit) can be implemented at patch scale. Between the zones of the WaNuLCAS model, surface run-off and run-on resulting in redistribution among zones can be simulated on the basis of a user-specified weighing function for effective rainfall in the various zones. Upon infiltration a tipping bucket model is followed for wetting subsequent layers of soil, filling a cascade of soil layers up till their effective field capacity. Field capacity is estimated from the water retention curve. Soil evaporation from the surface layer depends on ground cover (based on LAI of trees and crops) and soil water content of the topsoil.

Hydraulic lift and sink

An option exists to simulate hydraulic lift and hydraulic sink phenomena in tree roots, transferring water from relatively wet to relatively dry layers. Hydraulic continuity via root systems can lead to transfers of water between soil layers, on the basis of water potential and resistance. If the subsoil is wet and the surface layers are dry, this process is called hydraulic lift (Dawson, 1993). The reverse process, transfers from wet surface layers to dry subsoil is possible as well and has recently been observed in Machakos (Kenya) (Smith et al., 1998; Burgess et al., 1998). Although the total quantities involved in these water transfers may be relatively small, it can be important in the competition between shallow and deep rooted plants. Hydraulic lift can re-wet nutrient-rich dry topsoil layers and thus facilitate nutrient uptake. The reverse process, deep water storage by deep rooted plants after moderate rainfall which only infiltrates into the topsoil, can increase their overall resource capture vis-a-vis shallow rooted plants.

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

$$F_i = \frac{\sum_{j=1}^{n} \frac{\psi_i - \psi_j}{r_i r_j}}{\sum_{j=1}^{n} r_j^{-1}} \tag{2}$$

where ψ_i and ψ_j refer to the root water potential in soil compartment i and j respectively (from a total of n soil compartments), and r_i and r_j to the resistance to water flow between the soil layer and stem base. This equation assumes a zero transpiration flux at night.

Nitrogen balance

The nitrogen balance of the model includes inputs from fertiliser (up to four applications, specified by amount and time of application), atmospheric N fixation (see above) and mineralisation of soil organic matter and fresh residues. Uptake by crop and tree is allocated over yields (exported from the field/patch) and recycled residues. Leaching of mineral N (nitrate) is driven by the water balance, the N concentrations and the apparent adsorption constant for nitrate in each layer (thus allowing for a chemical safety-net by subsoil nitrate adsorption). Decomposition of soil organic matter is represented by a three-pool model, following the terminology and concepts of the Century model (Parton et al., 1994).

Growth

Growth of both plants (crop and tree) is calculated on a daily basis by multiplying potential growth (which depends on climate and current plant size) with the minimum of four stress factors, one for shading, one for water limitation, one for nitrogen and one for stress history. The latter factor ensures for example that plants will not directly resume their maximum growth rate the day after they have been exposed to full sunlight after pruning the trees. The half-life time of the stress can be chosen by the model user, but experimental data for this parameter are scarce; a value of a few days appeared to be adequate.

The major relationships in the daily cycle of calculating crop biomass accumulation are:

– 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, $m^2\ g^{-1}$);
- calculation of canopy height on the basis of biomass and physiological stage (assuming height growth to stop at flowering);
- calculation of the relative light capture on the basis of LAI of both tree and crop;
- calculation of the potential growth rate of the crop for that day, PotGroRed, by multiplying relative light capture based on LAI and shading with the light use efficiency (dry matter production per unit light captured) and maximum net growth rate (kg m^{-2} day^{-1}), which is an input to the model and can be derived from more physiologically explicit models of potential crop growth under the given climate. The maximum net growth rate is supposed to include respiration losses for maintenance of existing tissues as well as for the formation of new ones. It may be desirable to split this term in its components, but we chose at this stage to take these values from existing calibrated crop models rather than duplicating these inside WaNuLCAS;
- 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;
- calculation of whether actual water uptake can meet this transpirational demand, the crop water stress factor WPotGro is determined as the ratio of actual water use and transpirational demand;
- calculation of the N limitations on growth on the basis of the ratio of current N content and the target N content (80% of demand, see above), NPotGro;
- calculation of real dry matter production as the product of PotGroRed and the minimum of NPosGro and WPosGro.

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

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 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 (thermal time) rather than by time.

WaNuLCAS uses a simple description of tree canopy shape, aboveground biomass production and litterfall. 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.

$$\Delta \text{ Biom} = \Delta \text{ Canopy} + \Delta \text{ Support} + \Delta \text{ Litterfall} \quad (3)$$

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).

$$\Delta \text{ Leafarea} = \Delta \text{ Canopy} * \text{LWR} * \text{SLA} \quad (4)$$

Tree canopy shapes are approximated by a half ellipse on a stick (forming an umbrella), 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}.

Growth of the canopy in a lateral or vertical direction can be continuous, but for light capture the canopy is at any point in time discretized on the basis of the zones it covers under a vertical projection, with even distribution within each zone.

Uptake

Uptake of both water and nitrogen by the tree and the crop is driven by demand but within limits set by a zero-sink uptake model (De Willigen and Van Noordwijk, 1987, 1991, 1994) on the basis of root length density and effective diffusion constants in each compartment where the plant has roots:

$$\text{uptake} = \text{minimum (demand, potential uptake)} \quad (5)$$

For water the potential uptake is based on the matric flux potential (De Willigen and Van Noordwijk 1987, 1991, 1994). If the sum of potential uptake over all roots of a plant exceeds what is currently needed, actual uptake from each compartment is reduced proportionally.

Demand for nitrogen uptake is calculated from empirical relationships of maximum N uptake and dry matter production under non-limiting conditions (5% N in dry matter up to a closed crop canopy is reached at an aboveground biomass of 2 Mg ha^{-1}, 1%N in new dry matter after that point; De Willigen and Van Noordwijk, 1987), A luxury uptake is included in the demand, stating that growth will not be reduced until N content falls below 80% of the above defined maximum uptake. The demand for uptake can be increased to compensate for past uptake deficits, and can be decreased if the plant is able to fix N from the atmosphere (driven by the Ndfa parameter, indicating the part of the N demand which can be met from atmospheric fixation).

Competition for water and nitrogen

Competition is based on sharing the potential uptake rate on the basis of relative root length multiplied by relative demand:

$$\mathrm{PotUpt}(i) = \min\left[\frac{L_{rv}(i) * \mathrm{Demand}(i) * \mathrm{PotUpt}(\sum L_{rv})}{\sum_{j=1}^{n}(L_{rv}(i) * \mathrm{Demand}(i))}, \mathrm{PotUpt}(L_{rv}(\mathrm{i}))\right] \quad (6)$$

The potential uptake rate PotUpt($\sum L_{rv}$) is calculated on the basis of the combined root length densities for all plants in a given soil compartment (a general formulation is chosen, although currently we only deal with n = 2 types of plants for each soil compartment, a tree and a crop). This potential uptake rate is allocated to the plants i (from a total of n) on the basis of their share in total root length in the compartment, multiplied by plant demand. The latter factor was introduced to avoid situations where tree roots in the absence of current demand by the tree (e.g. directly after pruning) would negatively affect the predicted uptake by the crop. A safety valve (in the form of the ‘minimum’ function) is built into the procedure to ensure that the uptake by a component of the mixture can never be more than it would have been without roots of surrounding plants.

Equation 6 refers to potential uptake rate. The actual uptake rate will be a fraction (between 0 and 1) of this potential, depending on the sum of potential uptake by a given plant and its current demand.

Water uptake from any compartment is shared between all components having roots in a given compartment, with the share based on effective root length density (corrected for root diameter), plant demand and the degree to which plant demand can be met from other compartments in which a plant is rooted.

Root growth

Root growth is represented for the crop by a logistic increase of root length density in each layer up till flowering time and gradual decline of roots after that time. A maximum root length density per layer is given as input. The model thus does not (yet) incorporate functional equilibrium responses on shoot/root allocation of growth, nor does it allow for a local response to shift root growth to favourable zones. These elements can however be incorporated in a later stage. The tree root length density in all zones and layers is assumed to be constant, thus representing an established tree root system with equilibrium of root growth and root decay. The model can be modified to make tree root length density in each compartment a function of time or dependent on tree size or age.

Light capture

Light capture is treated on the basis of the leaf area index (LAI) of both components and their relative heights, in each zone. Potential growth rates for conditions where water and nutrient supply are non-limiting are used as inputs (potentially derived from other models), and actual growth is determined by the minimum of shade, water and nutrient stress. Three strata can be distinguished: an upper canopy (with only one type of leaves), a mixed one (with both types of leaves present) and a lower one (with one only). Total LAI for each plant in each zone is fractionated according to the relative heights of tree and crop, thus ensuring symmetry in the relations and the possibility of crops shading trees depending on relative heights. Light capture is calculated from the LAI in each canopy layer and a plant-specific light extinction coefficient. These equations should give a reasonable approximation for any canopy geometry (Kropff and Van Laar, 1993).

Management options

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 modeller 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.

Tactical options represented in the model are:

- Tree pruning: predetermined dates or based on a prune-limit;
- Use of fertiliser and organic inputs and their distribution over the zones;
- Crop residue removal.

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 below-ground.

Examples of model applications

Four examples of model applications are presented here, to test the objective that the model can be applied to a wide range of agroforestry research questions. Results are not compared to specific data sets and no parameter fitting has occurred. Examples are presented for simulation runs of 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.

Hedgerow intercropping: pruning regime and hedgerow spacing

The WaNuLCAS model can predict crop yields in different strips (zones) within the alleys in a hedgerow intercropping system (Figure 2). The results presented here are derived as a first approximation of long term alley-cropping experiments in Lampung (Indonesia); details of the experiments which form the inspiration for these simulations can be found in Van Noordwijk et al. (1998). Based on different tree characteristics ('P' and 'G' in Figure 2; compare Van Noordwijk, 1996a), the model predicts different pruning frequencies to be applied (one or twice per crop for P and three or four times per crop for G). The figure includes a yield prediction for an unfertilised field of crops only (control), which are predicted to decline rapidly under the high rainfall (2200 mm/year) regime and under declining soil organic matter levels, not maintained by the use of crop residues only. Crop yields for the P alley-cropping system are similar to this control crop (and 25% lower when compensating for the area in zone 1) in the first cropping season, but they are more than double the control yields for crop 2 and 3. The overall trend in crop yields is negative, however, as the system is gradually depleting its N stocks, in the absence of atmospheric N fixation. In the long term field experiments crop yields for the control indeed declined rapidly, but no such yield decline was recorded for the treatments including P-type trees; this raises questions about additional sources of N in the field trials, not accounted for in the WaNuLCAS model. The G parameterisation (wider canopy shape, lower LAI within the canopy, shallower roots, N fixation) leads to crop yields which are substantially below the control yields for the first crop, but which are maintained with time. In the longer run alley-cropping with G trees is predicted to lead to substantial gains over the pure crop control, but this applies to situations where the pure crop control would not have been planted with maize by any sensible farmer. The square shape in the tree canopy data occurs when the tree (leaf + fine branch) canopy reaches its maximum value (determined by canopy size and maximum LAI); further tree dry matter production is then allocated to stem growth and litterfall. Model results for crop yield are sensitive to the pruning regime implemented (the threshold of current canopy size), as well as the initial soil fertility. For well-specified pruning

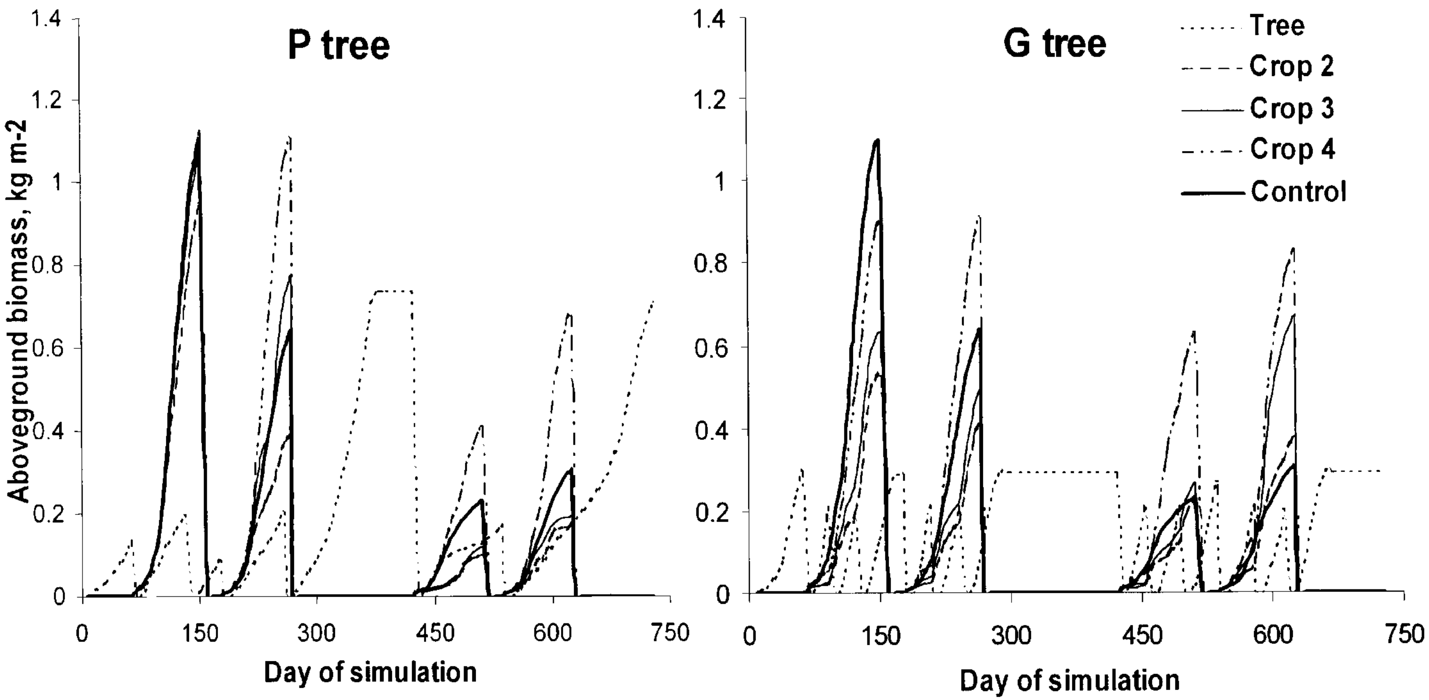

Figure 2. Model predictions of development of hedgerow tree canopy and crop biomass (on a whole field basis) over four cropping seasons in two years, for three crop zones (2, 3 and 4) within the alleys [the P and G trees approximate Peltophorum and Gliricidia, respectively]; zones 1, 2 and 3 are 1 m wide each, and zone 4 is making up the rest of the field; soil type, rainfall pattern and potential maize production inputs were derived from the Lampung site, Indonesia.

regimes on soils of low-intermediate N fertility, hedgerow intercropping can result in an increase of predicted crop yield. However, there are many situations where negative effects by competition will dominate over positive effects of soil fertility increase. The window of opportunity for positive effects of alley-cropping on crop yields at low soil N supply and adequate soil water supply described by the algebraic shade/mulch model with growing seasons as time step (Van Noordwijk, 1996a) can be confirmed by this model on a daily time step. The algebraic solution suggested an optimum distance between hedgerows with monotone rising and declining functions on either side, the WaNuLCAS model indicates that more complex responses can occur. If the distance between hedgerows is gradually increased (Figure 3) crop yield will increase as light competition effects are reduced. Under certain parameter conditions the predicted yield will gradually approach the level of a no-tree-control plot; under other conditions the predicted yield will increase above this control level and reach a maximum at a certain hedgerow spacing. Interestingly, the model predicts that yields can drop below control levels at a wider spacing of the hedgerows: in this situation the hedgerows keep scavenging the crop zones for nutrients, but the biomass of the hedgerows stays below the pruning limit (expressed on a per ha basis) and nutrients are not recycled. In fact, the response of crop yields to a continuously changing hedgerow spacing will show discontinuities at points where pruning frequency is responding. Further exploration of pruning criteria (on a per tree rather than per area basis) will be needed. In contrast to Figure 2, the results of Figure 3 can not be compared with any existing experiments we know of, as hedgerow spacing has seldom been systematically evaluated in alley cropping experiments.

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. WaNuLCAS calculations (Cadisch et al., 1997) 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 trees 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 are currently collected from trials in Lampung (Rowe et al., this issue), which can test these model predictions.

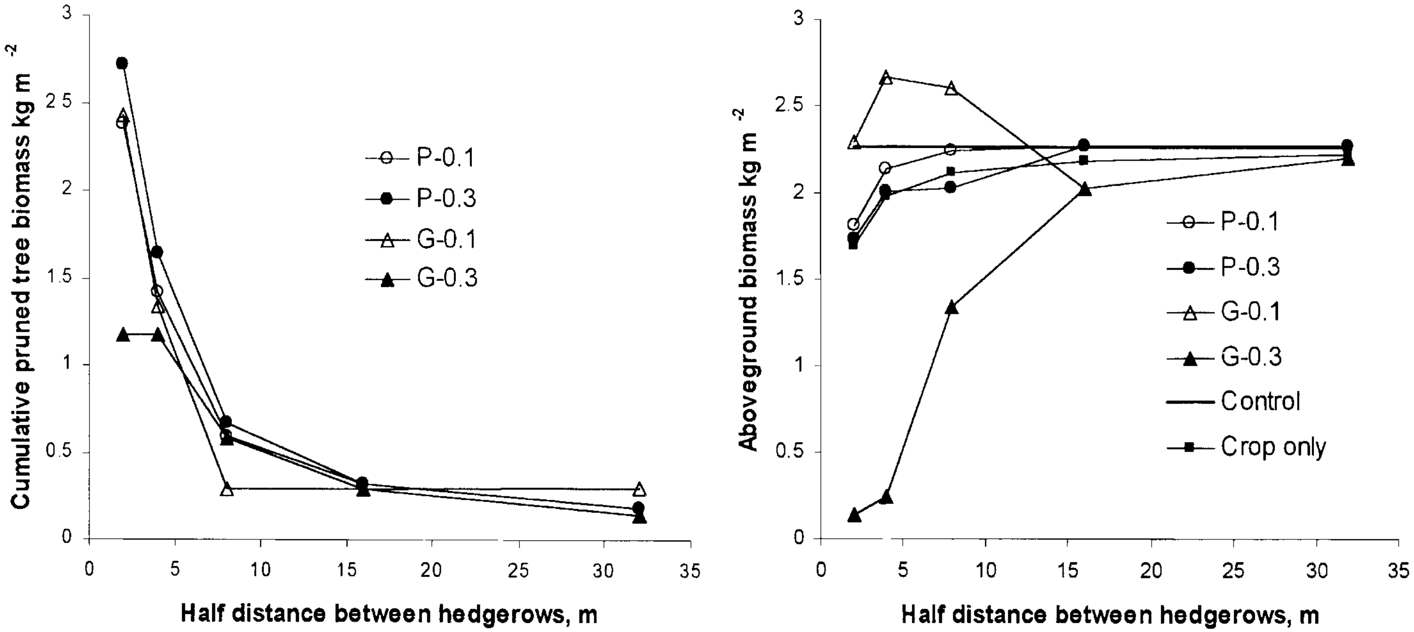

Figure 3. Predicted effect on cumulative crop yield if the distance between two hedgerows is gradually increased; results are given for P and G trees and two values of the 'prune limit', i.e. the hedgerow canopy biomass at which hedgerows are pruned back.

Tree fallow – crop rotations: effects of plot size

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, hedgerows are replaced by broader zones of tree growth and the pruning regime is modified, but otherwise the processes of tree-soil-crop interactions are the same. Model results show a potentially considerable effect of lateral root extension from the fallow plots into the currently cropped area (Figure 4A comparison between crop zones) and a relatively small effect of shading when tree root distribution is homogeneous under the cropped plot (Figure 4A versus B). The yield decline for consecutive crops is to be expected in crop-fallow rotations where the soil organic matter supplies are increased during a fallow period (in the model mainly by litterfall, which is supposed to be mixed through the upper soil layer by abundant faunal activity) and depleted during cropping. The WaNuLCAS model may offer the first opportunity to consider crop-fallow mosaics as a coherent system, instead of only regarding the sequential effects on plots which are supposed to be spatially isolated. These 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. Unfortunately, no tree root length densities are known for these (or similar) teak stands.

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 5). The soil profile consisted of four layers (15, 15, 50 and 30 cm thick, respectively) and had a sandy texture (61% sand, 11% silt, 28% clay) and a bulk density of 1.3 Mg m^{-3} and thus had a rather low 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 (one month of 30 mm, followed by three months of 60 mm and one month of 30 mm; in practice the average was 285 mm for the runs presented here);
- annual average 450 mm (one month of 75, followed by three months of 100 and one month of 75 mm; in practice the average was 525 mm);

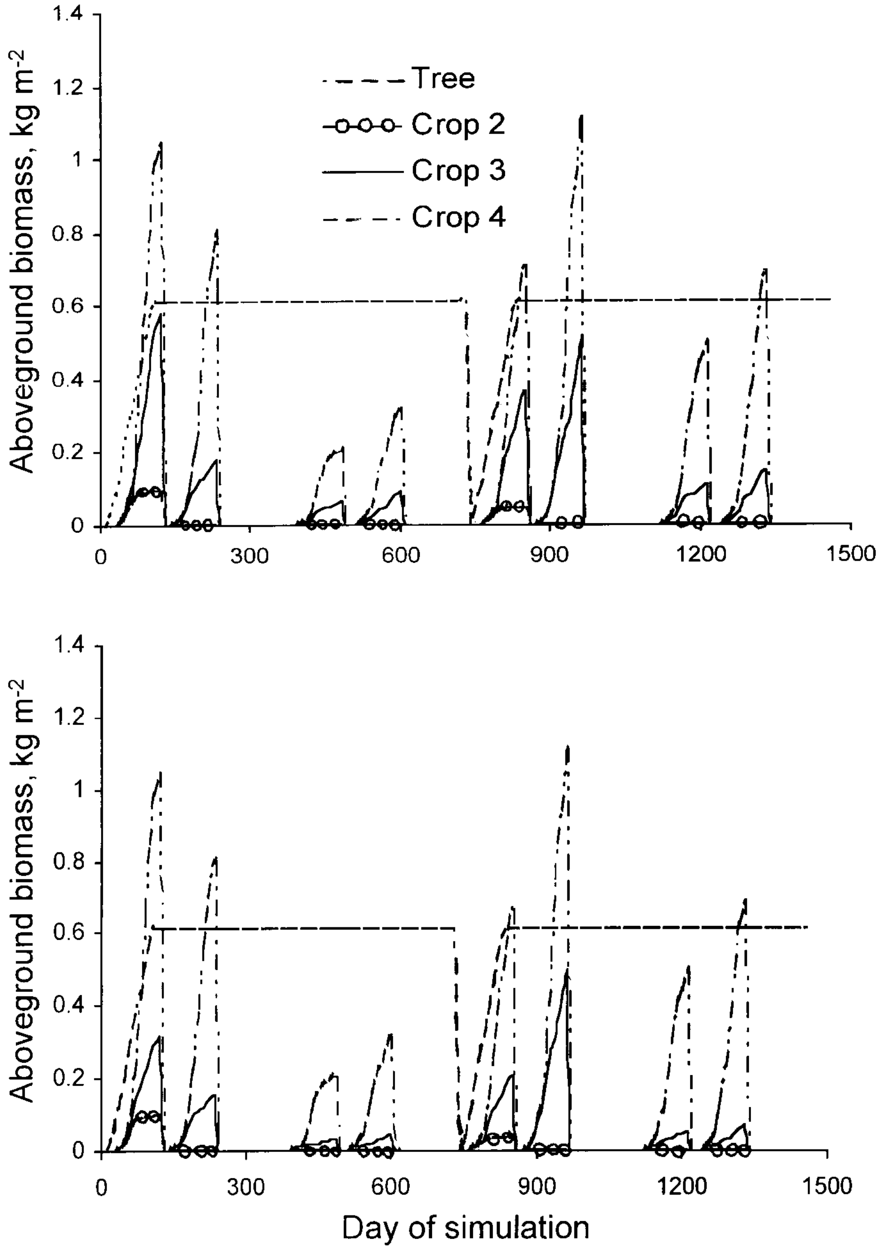

Figure 4. Predicted development of a tree fallow vegetation as well as the simultaneous yield of crops with increasing distance to this fallow plot, over two cycles of a two year fallow and two years of cropping (four crops/cycle); A) Tree root length density decreases by a factor 0.6 between neighbouring zones (so relative values are 1, 0.6, 0.36, 0.22 for zones 1-4 respectively); B) Tree root length density under crop zones equal to that under the tree fallow.

– annual average 1000 mm (one month of 125, followed by five months of 150 and one 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 two years, and two crops were grown per year for the 1500 and 2400 mm rainfall zone. Simulations for pure crops (covering the whole field) were compared with those of trees only (unrestricted tree growth) or agroforestry systems were trees occupied the inner circle and crops the remainder of the land. The trees were pruned at sowing time for each crop, and a second time during the crop if their biomass exceeded a set value of 0.2 kg m^{-2} (averaged over the whole field). For comparison a set of simulations was included where the tree was pruned in the same way as in the agroforestry system, but where no crop was grown. Four variants were considered for the agroforestry system, indicated by 'narrow', 'medium', 'broad' and 'very broad' tree canopies with a crown diameter of 1, 2, 3 or 4 quarters of the diameter of the whole system. Note that all zoning is relative to tree size and no absolute distances have to be specified. Tree root length density was 2, 1.5, 0.6 and 0.2 cm cm^{-3} for the four depth layers directly under the tree, respectively, and 0.6, 0.36, 0 times that value in the three other zones, respectively; thus tree roots were confined to a circle of 3/4 the total diameter. The tree was able to derive 40% of its daily N demand by atmospheric nitrogen fixation and tree N could be transferred to the crop via litterfall and tree prunings, based on a gradual N mineralisation. 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 fertiliser was used.

From the simulation results we focus here on grain production (actual harvest index was between 36 and 41%), stem wood production for the tree (treating crop residues, litterfall, pruning and current tree canopy as intermediate components of the system) and the water balance (Figure 5). The simulation involved a gradual shift from water to nitrogen as the major factor limiting crop production. At high rainfall the total N supply in the soil was effectively exhausted by the first crop in the pure crop control and the three following crop yields were low. Under these conditions the agroforestry system could increase crop yield (by up to 8%), by supplying at least some N for the later crops, thus compensating for the area without a crop and competition effects on crop growth. The medium tree canopy shape (2/4) gave the highest crop yield of all agroforestry systems in the three wettest climates. For the simulations at 450 and 240 mm rainfall, crop yields were reduced in agroforestry by 11 and 35% respectively, as competition for water dominated

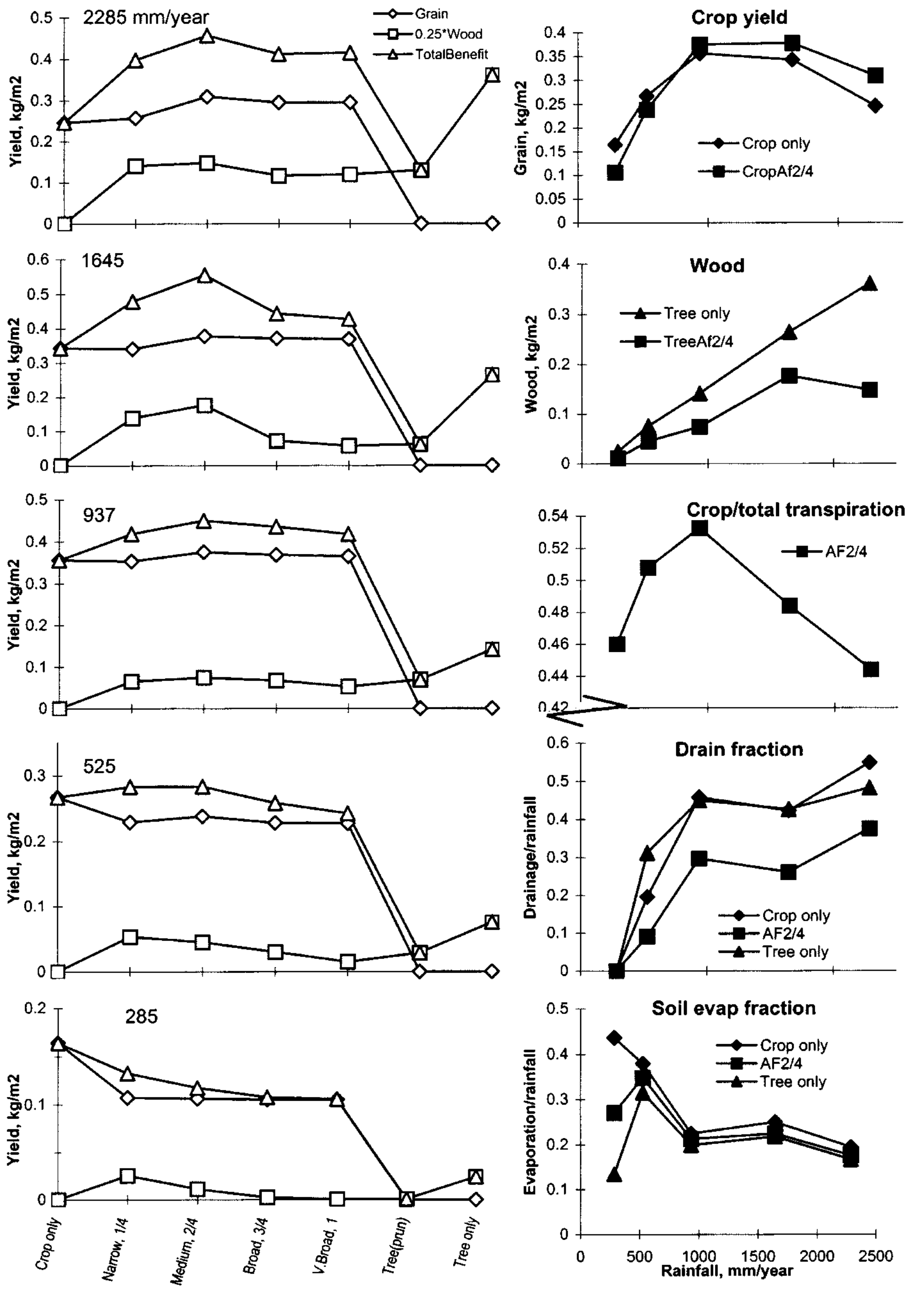

Figure 5. Calculations with the WaNuLCAS model of grain and wood production and water use for a range of annual rainfall conditions in an agroforestry system with isolated trees which are pruned when a crop is sown, resembling an early stage of a parkland system; production is accumulated over two years, involving four (at 2285 and 1645 mm/year) or two crops of 98 days duration, on a sandy soil with limited N mineralisation from soil organic matter.

over positive effects on N supply; at 450 mm the four agroforestry systems gave equal grain yields, while at the 240 mm run, the narrow tree morphology was best. In contrast to grain yield, wood production was always higher in the pure tree system than in the agroforestry system. The narrow tree morphology produced more wood, as it invested less resources in a leaf + fine branch canopy. Total yield for the agroforestry system can be calculated if the value of wood can be expressed relative to that of grain. In Figure 5 a 1:4 ratio is used. In the driest simulations any agroforestry system will reduce total yield, while the curve for the 450 mm zone is nearly flat (but 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 than 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 below-ground.

Discussion

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

Even at validation levels a and b, however, model development can not be more than a few steps ahead of empirical data collection (Van Noordwijk, 1996b). The WaNuLCAS model is now in a testing stage, with the experiments described by Rowe et al. (this issue) and Cadisch et al. (1997) as the most critical test so far. Testing the water balance model will be possible especially for data sets where the water flow in vertical and horizontally oriented roots has been measured separately (Howard et al., 1997; Lott et al., 1996).

In making comparisons across climatic zones (Fig. 5) we realised that a number of relevant processes is not represented in the WaNuLCAS model and may have to be included in future to make the model more realistic, especially for drier climates:

- tree litterfall induced by drought;
- crop failure to germinate and crop death induced by severe drought;
- effects of drought on biological N fixation;
- temperature effects on crop performance;
- maintenance respiration for woody parts of the tree;
- nutrient remobilization before leaf fall;
- a more explicit linking of fractal branching analysis (Van Noordwijk and Purnomosidhi, 1995) to the above- and below-ground tree architecture descriptions.

The treatment of canopy structure and light interception may be reasonable as a first step in the tropics with a predominantly vertical light orientation, but would have to be modified for temperate zone applications where orientation becomes more important. More detailed models exist which could provide inspiration for this step (Sinoquet et al., 1997; Mobbs et al., 1998). The next challenge will be to include phosphorus as a second nutrient into the scheme. There are still serious questions, however, how to represent the interactions with organic P pools, and the Century model may have to be modified in this respect (Gijsman et al., 1996). In its current state the model is available for testing and we welcome any suggestions for co-operation on this.

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