3.5.2. 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. Parameters influencing potential evapotranspiration (wind speed, 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 cells. 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 matrix 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 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). WaNuLCAS derives 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.

3.5.3. 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. The WaNuLCAS model currently incorporates some of the processes, but aggregates them to a daily time step:

1) rainfall or irrigation (with additional run-on) and its allocation to infiltration and surface run-off (and/or pounding), on a seconds-to-minutes time scale,

2) infiltration into and drainage from the soil via a cascade of soil layers, and/or via bypass flow, on a minutes-to-hours time scale,
3) subsequent drainage and gradual approach to hydrostatic equilibrium on a hour-to-days time scale,
4) transfers of solutes between soil layers with mass flow,
5) evaporation from surface soil layers on a hour-to-day time scale, 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,

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

An option exist 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 infiltrate into the topsoil, can increase their overall resource capture vis-à-vis shallow rooted plants.

3.5.4. 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 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).

3.5.5. 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 rates 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 model 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 depend 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, above-ground biomass production and litterfall. In the model, the calculated above-ground tree biomass increment is first of all allocated to a buffer of carbohydrate reserves and is allocated from there to make (a) a canopy, consisting of leaves and small branches (<2 cm diameter), (b) a support structure, consisting of supporting branches and a trunk, and (c) replacement of leaves and branches transferred to litterfall.

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

Tree canopy shapes are approximated by a half ellipse on a stick (forming an umbrella), with as parameters (a) R, radius (half of the width); (b) 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; (c) 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); and (d) LAI-canopy (leaf area index within the canopy), which can vary between LAImin and LAImax.

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 discretisised on the basis of the zones it covers under a vertical projection, with even distribution within each zone.

3.5.6. UPTAKE AND COMPETITION

Uptake, U, of both water and nitrogen by the tree and the crop is driven by demand, D, 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 cell where the plant has roots.

For water the potential uptake is based on the matrix flux potential (De Willigen and Van Noordwijk 1987, 1991, 1994). If potential uptake (at plant level), PU, exceeds demand, actual uptake from each cell 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 above-ground biomass of 2 Mg ha-1, 1%N in new dry matter after that point; De Willigen and Van Noordwijk, 1987), a luxury uptake (stating that growth will not be reduced until N content falls below 80% of the above defined maximum uptake which is used as demand), a possibility for compensation of past uptake deficits and an option for N fixation (driven by the Ndfa parameter, indicating the part of the N demand which can be met from atmospheric fixation).

Competition is based on sharing the potential uptake rate for both (based on the combined root length densities) on the basis of relative root length multiplied by relative demand, D.

Water uptake from any cell is shared between all components having roots in a given cell, 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 cells in which a plant is rooted.

3.5.7. 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 cell a function of time or dependent on tree size or age.

3.5.8. 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).

3.5.9. 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 (a) plot size and tree spacing; (b) choice of tree species as reflected in their functional parameters of canopy shape and branch allocation, root distribution under given soil conditions); and (c) cropping cycle: crop types and planting dates.

Tactical options represented in the model are (a) tree pruning: predetermined dates or based on a prune-limit; (b) use of fertiliser and organic inputs and their distribution over the zones; and (c) crop residue removal.

At this stage only two types of plants are considered and thus it is implied 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.

3.5.10. EXAMPLE OF MODEL APPLICATION: 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 3.10).

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%.

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

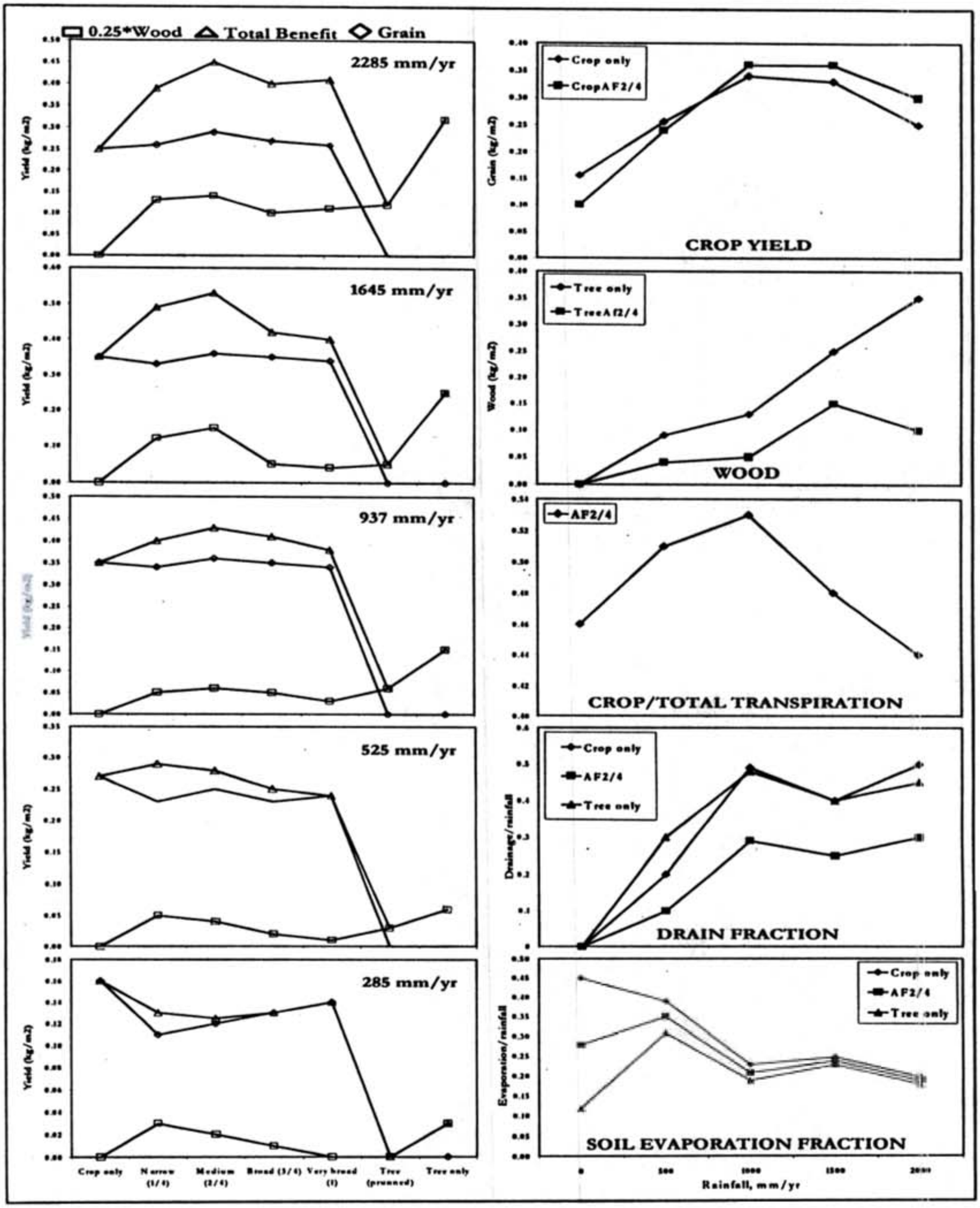

Figure 3.11. Calculations with the WaNuLCAS model of grain and wood production and water use for a range of annual rainfall conditions in an agroforestry system with isolated trees which are pruned when a crop is sown, resembling an early stage of a parkland system; production is accumulated over 2 years, involving 4 (at 2285 and 1645 mm/year) or 2 crops of 98 days duration, on a sandy soil with limited N mineralisation from soil organic matter.

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 3.11). The simulation involved a gradual shift from water to nitrogen as the major factor limiting crop production. At high rainfall the total N supply in the soil was effectively exhausted by the first crop in the pure crop control and the three following crop yields were low. Under these conditions the agroforestry system could increase crop yield (by up to 8%), by supplying at least some N for the later crops, thus compensating for the area without a crop and competition effects on crop growth. The medium tree canopy shape (2/4) gave the highest crop yield of all agroforestry systems in the three wettest climates. For the simulations at 450 and 240 mm rainfall, crop yields were reduced in agroforestry by 11 and 35% respectively, as competition for water dominated over positive effects on N supply; at 450 mm the four agroforestry systems gave equal grain yields, while at the 240 mm run, the narrow tree morphology was best. In contrast to grain yield, wood production was always higher in the pure tree system than in the agroforestry system. The narrow tree morphology produced more wood, as it invested less resources in a leaf + fine branch canopy. Total yield for the agroforestry system can be calculated if the value of wood can be expressed relative to that of grain. In Figure 3.11 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 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 effected by climate, as its N fixation was not limited by drought.

REFERENCES

Arah J and Hodnett M. 1997. Approximating soil hydrology in agroforestry models. *Agroforestry Forum* 8(2): 17-20

Cannell MGR, Mobbs DC and Lawson GJ. 1998. Complementarity of light and water use in tropical agroforests. II. Modelled theoretical tree production and potential crop yield in arid to humid climates. *Forest Ecology and Management* 102: 275-282

Dawson TE. 1993. Hydraulic lift and water use by plants: implications for water balance, performance and plant-plant interactions. *Oecologia* 95: 565-574

De Willigen P and Van Noordwijk M. 1987. Roots for plant production and nutrient use efficiency, Doctoral thesis Agricultural University Wageningen 282 pp

De Willigen P and Van Noordwijk M. 1991. Modelling nutrient uptake: from single roots to complete root systems. in: F.W.T. Penning de Vries, H.H. van Laar and M.J. Kropff (eds.) Simulation and Systems Analysis for Rice Production (SARP). Simulation Monographs, PUDOC, Wageningen. p. 277-295

De Willigen P and Van Noordwijk M. 1994. Diffusion and mass flow to a root with constant nutrient demand or behaving as a zero-sink. *Soil Sci.* 157: 162-175

Kropff MJ and Van Laar HH. 1993. Modelling crop - weed interactions. CAB International, Wallingford (UK)

Parton WJ, Ojima DS, Cole CV and Schimel DS. 1994. A general model for soil organic matter dynamics: sensitivity to litter chemistry, texture and management. In: Quantitative Modeling of Soil Forming Processes. Special Publication 39, Soil Science Society of America, Madison WI, USA, pp 147-167.

Smith DM, Jackson NA, Roberts JM and Ong CK. 1998. Reverse flow in tree roots and downward siphoning of water by *Grevillea robusta. Funct Ecol* (submitted - assuming this will move on to an 'in press' status soon)

Wösten JMH, Finke PA and Jansen MJW. 1995. Comparison of class and continuous pedotransfer functions to generate soil hydraulic characteristics. *Geoderma* 66: 27-237.

van Noordwijk, M. and Lusiana, B. 1998. WaNuLCAS 1.2 Manual. ICRAF-Southeast Asia, Bogor.

van Noordwijk, M. and Lusiana, B. 1999. WaNuLCAS, Backgrounds of a Model of Water, Nutrient and Light Capture in Agroforestry Systems. ICRAF-Southeast Asia, Bogor.