Land Use and Water Resources Research

Modelling the effects of leafing phenology on growth and water use by selected agroforestry tree species in semi-arid Kenya

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Abstract

The WaNuLCAS (**Wa**ter, **Nu**trient and **L**ight **C**apture in **A**groforestry **S**ystems) model was used to investigate the impact of tree leafing phenology on the growth and water use of selected agroforestry tree species in semi-arid Central Kenya. Three agroforestry species, grevillea (*Grevillea robusta*), alnus (*Alnus acuminata*) and paulownia (*Paulownia fortunei*), respectively providing evergreen, semi-deciduous and deciduous leafing phenologies, were intercropped with maize. It was hypothesised that the deciduous habit of alnus and paulownia would reduce demand for water relative to the evergreen grevillea under conditions of limited supplies. WaNuLCAS simulations showed that altering leafing phenology from evergreen through semi-deciduous to deciduous decreased water uptake and interception losses by the trees, but increased crop water uptake, drainage and soil evaporation rates for systems containing all three tree species. Drainage and soil evaporation were respectively 14 and 17% greater in the deciduous paulownia system than in the evergreen grevillea. Simulated water uptake and biomass accumulation by grevillea were more than double the corresponding values for paulownia, while crop water uptake in the grevillea and paulownia systems was reduced by 6% and 0.2% respectively relative to sole maize. The simulations imply that water use by paulownia is lower than for grevillea and suggest that leafing phenology is a key attribute affecting water use by trees. The significance of these observations for watershed management and stream flow are discussed.

Introduction

Increasing population pressure in Kenya and consequent shortages of arable land have induced considerable migration to semi-arid areas with low agricultural potential (Otengi *et al*., 1995). This has been accompanied by rapid clearance of natural forests to provide land for cultivation (Lott *et al*., 2000), supply timber products and meet basic community needs for commodities such as charcoal (KWS, 1999; Ayuk *et al*., 1999; Okello *et al*., 2001). This problem is particularly acute in the Naro Moru area west of Mount Kenya, where immigration has caused rapid changes in land use and increased demand for water (Njeru, 1995). Having originated from areas where water is a not limiting factor, immigrant farmers generally lack knowledge of water conservation techniques (Decurtins *et al*., 1998). Small-scale mixed farming is the predominant form of land use, with 70% of the plots being between 0.25 and 1.6 ha; in such dry environments, these plots are too small to support a family at a sustainable level (Njeru, 1995). Maize production in the area is water-limited (Liniger *et al*., 1998a), resulting in frequent crop failure (Decurtins *et al*., 1998). Another potential concern is the adoption of tree species such as grevillea by migrant small-scale farmers for use as boundary markers (Njeru and Liniger, 1994). Boundary plantings increase tree cover, fuel wood supplies and infiltration, protect against strong winds and reduce runoff (Young, 1997; Otengi *et al*., 2000). However, they also generate increased competition for water between trees and crops such as maize in areas where water resources are already insufficient to meet the needs for livestock and human consumption (Otengi *et al*., 2000). Moreover, irrigated and rain-fed crop production is rapidly expanding, with most of the irrigation supplies being obtained by illegal abstraction from rivers, leading to a serious decline in stream flow (Liniger *et al*., 1998a, b). Experience from South Africa shows that forest plantations characterised by evergreen canopies and deep root systems have a high potential for reducing stream flow in catchments, relative to the short, seasonally dormant indigenous vegetation which they typically replace (Dye and Bosch, 2000).

To test the hypothesis that the introduction of deciduous or semi-deciduous trees into agroforestry systems may reduce pressure on limited water supplies, the WaNuLCAS (**Wa**ter, **Nu**trient and **L**ight **C**apture in **A**groforestry **S**ystems) model (Van Noordwijk and Lusiana, 2000) was used to assess the influence of tree leafing phenology on crop performance and soil water balance. Modelling approaches are attractive because long-term studies of agroforestry systems in semi-arid environments are relatively rare due to the substantial financial, labour and time investments required (Ong *et al*., 2002). Three species with differing leafing phenologies were used; the evergreen grevillea, semi-deciduous alnus, and deciduous paulownia. Elucidation of the relationship of the leafing phenology of trees to the prevailing climatic conditions and growth periods of associated crops is essential for a full understanding of the functional aspects of agroforestry systems (Broadhead *et al*., 2003a). The present study tested the hypotheses that: (1) leafing phenology influences the water requirements of trees, the severity of competition for water between trees and crops, and hence crop growth and yield; and (2) the use of deciduous trees significantly reduces demand for water in water-limited environments. The objectives were to evaluate the effect of differing leafing phenologies (i.e. evergreen, semi-deciduous or deciduous) on soil water balance and tree and crop growth, using a newly developed tree leafing phenology routine in WaNuLCAS.

Site characteristics

The experimental work was carried out at Naro Moru in Nyeri District, 160 km north of Nairobi (latitude 0^{o} 05' S, longitude 37^{o} 00') and at an altitude of 2060 m above sea level. Naro Moru falls in the agro-climatic Zone IV, with a mean annual rainfall of 800 mm and mean annual maximum and minimum temperatures of 22.7 and 10.4 ^{o}C (Fig. 1). Evapotranspiration rates average 4.5 mm d^{-1} during the dry season (March and July-September) and 3.3 mm d^{-1} during the rainy season (Jaetzold and Schmidt, 1983; Berger, 1989). The natural vegetation mainly comprises grass and scattered acacia shrubs. The site was formerly virgin land which had been cropped with vegetables for two seasons before being adopted for the present study. The soils are moderately well drained verto-luvic Phaeozems. Profile pits showed that the soil was moderately deep (110 cm) near the stream which bisected the site, but became shallower (<50 cm) upslope on either side of the stream. The trial was planted on 2 June 2000 as a Randomised Complete Block Design (RCBD) containing four replicates of each treatment, namely grevillea+maize, alnus+maize, paulownia+maize and a sole maize control. Leafing phenology was characterised by determining leaf cover, leaf flushing and leaf fall, as described by Broadhead *et al*. (2003b).

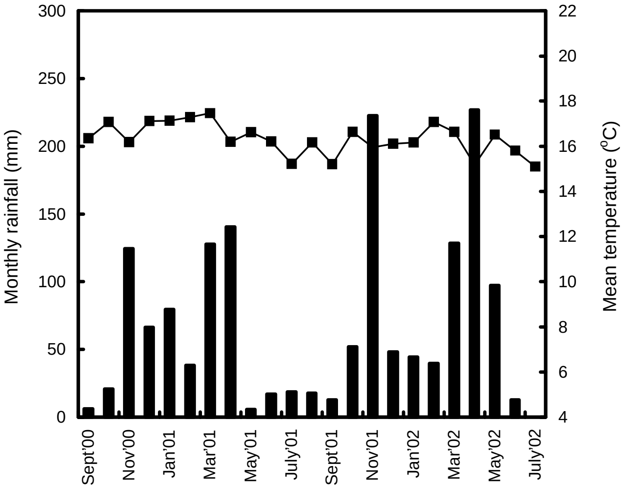


Figure 1 Timecourses of mean daily air temperature and monthly rainfall at Naro Moru, Kenya between September 2000 and July 2002.

WaNuLCAS

Model features

The WaNuLCAS model consists of two parts, namely the WaNulCAS.xls workbook for deriving model parameters and the WaNuLCAS.stm file for the dynamic simulation. The model is formulated in the STELLA (a flow chart-based modelling software) research-modelling environment and thus remains open to modification. WaNuLCAS places emphasis on below-ground interactions, where competition for water and nutrients (N and P) depends on the effective root length densities of the trees and crops and current demand by both components (Van Noordwijk and Lusiana, 2000). Simulations require prior definition of the soil profile, represented as a four-layer vertical profile, and the physical and chemical properties of each soil layer.

Agroforestry systems are defined in WaNuLCAS as four horizontally distributed spatial zones within which water, nitrogen and phosphorus balances and uptake by crop and/or weed species and up to three tree species may be examined (Fig. 2). The model typically assumes that trees occupy Zone 1, and Zones 2–4 are planted with a

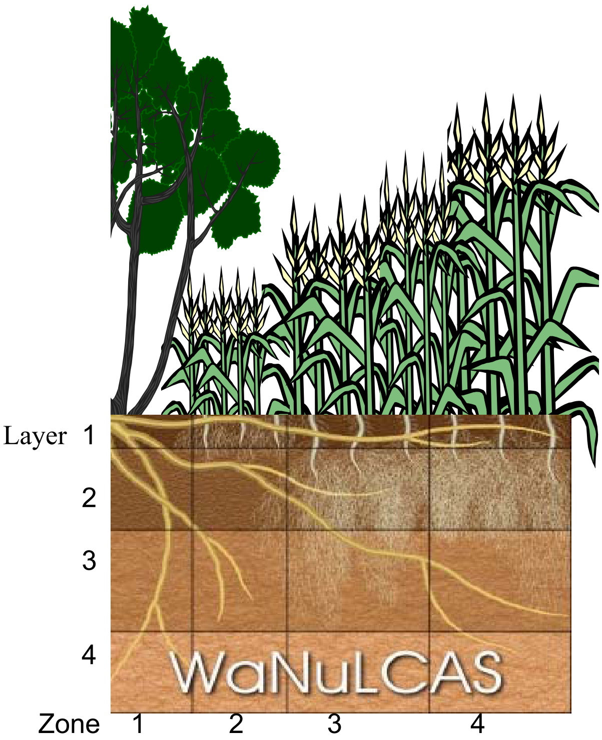


Figure 2 General layoutof the agroforestry zones and soil layers in WaNuLCAS.

single crop at any given time or within a defined sequence. Zones 2–3 include both tree and crop components and represent the area where the tree canopy and roots influence the crop to an extent which varies depending on distance from the tree row. The crop predominantly occupies Zone 4, with few or no tree roots being present. The soil profile is represented as four horizons (layers), the depth of which can be defined within the model, together with specified physical properties and initial water and nitrogen contents for each of the 16 compartments. The model incorporates standard management regimes, such as the choice of tree and crop species, spacing, tree-pruning and fertiliser rates. Specific parameters for each species examined in the present study were derived from specialised component models which take phenology into account.

Model inputs

Most inputs required to run WaNuLCAS are entered in the Excel file and then linked to the model in the WaNuLCAS.stm file. Inputs entered include: (1) climatic data, i.e. rainfall, soil temperature and potential evapotranspiration; (2) soil data i.e. nitrogen (N) and phosphorus (P) contents, % carbon (C), clay and silt contents, bulk density and soil texture for each soil layer; (3) management schedule, including planting and weeding dates, fertiliser input and pruning; and (4) crop and tree parameters such as the length of the vegetative cycle and water requirements.

Although individual users may not have measured all inputs required by the model, these are important in generating the soil and water parameters required to produce various outputs. Calculations of water infiltration into the soil profile require layer-specific estimates of 'field capacity' (soil water content one day after heavy rain). Similarly, calculations of potential water uptake rate for all soil layers are based on soil and rhizosphere water potentials and the corresponding matric flux potentials, determined as described by De Willigen *et al*. (2000). The model also uses the relationship between soil water potential and water content to derive the soil water content corresponding to specific root water potentials. As these relationships are often not measured for soils to which WaNuLCAS is applied, 'pedotransfer' functions are used (Arah and Hodnett, 1997). The values for soil physical properties are then derived via a pedotransfer function based on knowledge of soil texture, bulk density and organic matter content (Wösten *et al*., 1998). The pedotransfer function is included in the WaNuLCAS.xls file and, once the user has specified the clay, silt and organic matter contents and bulk density of the soil, all tables required by WaNuLCAS are automatically generated (Van Noordwijk and Lusiana, 2000).

Inputs entered into the STELLA file included information on rainfall and soil temperature expressed as monthly or daily mean values. The agroforestry zones and layers and leafing phenology component were also included.

Model outputs

Outputs include individual and overall biomass production by the trees and crops and the components of the water and nutrient balances for the entire system. The model provides an overview of the balance of inputs and outputs for nitrogen, phosphorus, carbon, water and financial returns. Although other parameters may be important for certain purposes, the present study focused on soil water balance and biomass production by the trees and crops. The water balance components include precipitation, rainfall interception by trees and crops, run-on and run-off, lateral flow, surface evaporation, uptake by the trees and crops and leaching/drainage. Output from WaNuLCAS is presented as tables or graphs which may be printed or saved in PowerPoint or other Microsoft software programs.

Experimental inputs

WaNuLCAS was used to model growth and water use in the grevillea+maize, alnus+maize, paulownia+maize and sole maize cropping systems. As WaNuLCAS could not simulate all three agroforestry treatments simultaneously, each treatment was simulated separately by switching off the other treatments by changing the date of planting to 100 years, which was beyond the five-year simulation period and therefore precluded simulation of that component. In the same way, switching off the tree component in the model allowed simulations for sole maize.

Climatic and soil parameters

Daily rainfall and mean temperature data for Naro Moru during the period between 2000 and 2002 were entered into separate WaNuLCAS.xls spreadsheets under the 'Weather' options. Soil characteristics entered included percentage N, P, organic carbon, clay and silt contents and bulk density. The pedotransfer function in WaNuLCAS then generated the tables required by the model.

Table 1. Data entry format showing crop management activities for Zones 2–4.

Crop type: Maize = 2	*Number of previous crops*	*Year of planting*[1]	*Day of planting*	*Fertiliserapplication*	
				DAP[2]	*CAN*[3]
2	0	1	286	-	316
2	1	2	85	85	136
2	2	2	286	286	316
2	3	3	85	85	136
2	4	3	286	286	316
2	5	4	85	85	136
2	6	4	286	286	316
2	7	5	85	85	136
2	8	5	286	286	316

[1] WaNuLCAS assumes the first year of simulation to be Year Zero (0) i.e. (2000); the crop calendar starts at Year 1 because the first crop was grown one year after planting the trees (October 2001).
[2] Di-Ammonium Phosphate (DAP) fertiliser was applied at the time of crop planting.
[3] Calcium Ammonium Nitrate fertiliser (CAN) was applied as a top dressing.

Table 2. Data entry format showing tree management activities for Zone 1.

Number of previous crops	Years after planting	Pruning[1] previous prunings	Number of	Day ofpruning (DOY)
0	1	x	0	0
1	2	✓	0	153
3	3	x	1	0
5	4	✓	1	153
7	5	x	2	0

[1] x and ✓ respectively denote no tree shoot pruning and shoot pruning events.

Calendar of events

Before running simulations, information concerning events occurring on specific calendar dates was entered, usually by specifying the Year and Day of Year (DOY) when they occurred. Other events were triggered internally; for example, crops were 'harvested' in the simulation based on the specifications for their vegetative and generative phases set up in the 'Crop Type' section of the WaNuLCAS.xls file. The crop was coded as 2, the designation for maize in the 'Crop Type' section of the model. Crop management information was entered to provide the dates when key activities such as crop planting and fertiliser applications occurred (Table 1). The dates when management activities such as tree planting and pruning took place were also entered (Table 2).

Table 3. Designated thickness of the soil layers and width of the agroforestry zones for simulations using WaNuLCAS for grevillea, alnus and paulownia.

Layer/ Zone	*Soil layer thickness (m)*	*Agroforestry zone width (m)*		
		grevillea	*alnus*	*paulownia*
1	0.10	0.7	0.7	0.7
2	0.20	1.5	1.5	1.6
3	0.30	3.5	3.5	3.4
4	0.40	2.3	2.3	2.3
Total[1]	1.00	8.0	8.0	8.0

[1] Total represents the sum of values for all soil layers and agroforestry Zones 1–4.

Agroforestry treatments and soil layers

The agroforestry treatments were regarded as an alley cropping system containing the 16 zones and layers shown in Figure 1. The zones defined for grevillea and alnus were comparable and differed only slightly from paulownia due to its wider canopy (Table 3). The soil layers represent the average depth of the individual horizons based on observations obtained using profile pits dug at the site.

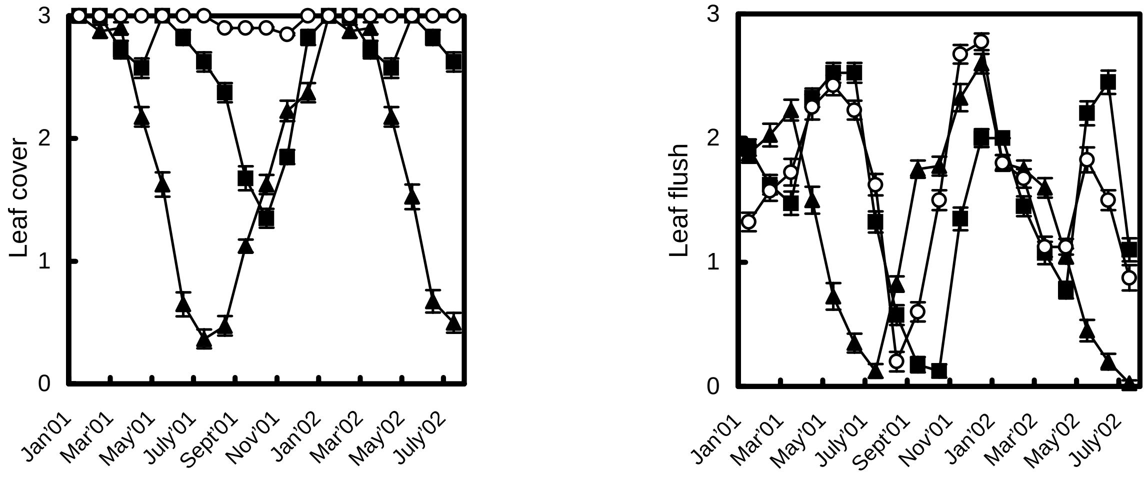
Leafing phenology

To simulate the effect of trees with differing leafing phenologies on tree and crop biomass production and soil water balance, the WaNuLCAS.stm files were modified to accommodate the inputs. Input parameters entered in tabular or graphical format included the time of year when leaf flushing and leaf fall commenced, while complete litter fall was defined as the day of the year (DOY) when leaf fall ceased (Table 4).

Table 4. Description of parameters used to characterise different leafing phenologies in the WaNuLCAS simulations.

No.	*Acronym*	*Definition*	*Default*	*Unit*	*WaNuLCAS Section*
1	T DOY 1 LfFlush	Defines when first cycle of leaf flushing starts	400	Day	Tree Growth
2	T DOY 1 SeaLitFall 1	Defines when first cycle of leaf fall starts	400	Day	Tree Growt
3	T DOY Comp1 LfFall	Defines when first complete leaf fall occurs	400	Day	Tree Growth
4	T DOY 2 LfFlush	Defines when second cycle of leaf flushing starts	400	Day	Tree Growth
5	T DOY SeaLit Fall 2 Start	Defines when second cycle of leaf fall starts	400	Day	Tree Growth
6	T DOY Comp2 LfFall	Defines when second complete leaf fall occurs	400	Day	Tree Growth

[1] The default value of 400 was set to fall outside the 365 day annual cycle within which phenological events must take place, and was used when specific events did not occur.



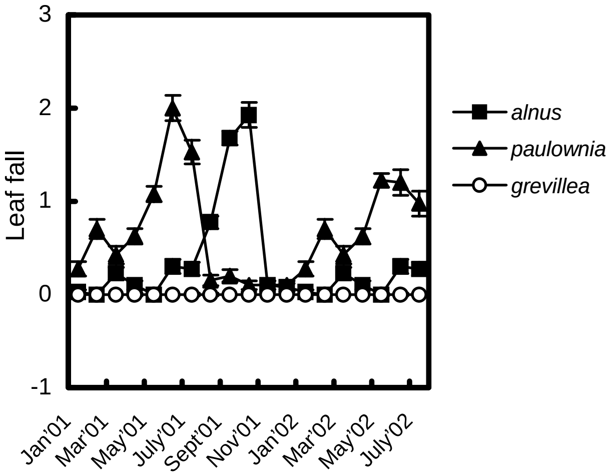


Figure 3 Timecourses of: leaf cover, leaf flush and leaf fall for grevillea, alnus and paulownia trees at Naro Moru between January 2001 and July 2002. Vertical bars show double standard errors of the mean.

Figure 3 shows the observed patterns of leaf cover, leaf flushing and leaf fall between January 2001 and July 2002, determined as described by Broadhead *et al*. (2003b). These were used to provide the leafing phenology inputs required for all three tree species. Leaf flushing in grevillea and alnus occurred twice annually during the long and short rains, necessitating the provision of the two cycles (1 and 2) shown in Table 4. An extra variable was provided in the

Table 5. Leafing phenology inputs (days) for grevillea, alnus and paulownia used in the WaNuLCAS simulations.

Phenology	*grevillea*	*alnus*	*paulownia*
T DOY 1 LfFlush	73	75	275
T DOY SeaLitFall 1 Start	400[1]	265	97
T DOY Comp I LfFall	400	280	170
T DOY 2 LfFlush	285	284	400
T DOY SeaLitFall 2 Start	400	400	400
T DOY Comp 2 LfFall	400	400	400

graphical option which allowed the proportion of leaves which fell to be entered for each species. This helped to distinguish between the semi-deciduous and deciduous leafing phenologies, with a value of 0.3 being set for the former and 1 for the latter. Table 5 shows the leafing phenology inputs for all tree species. The origins of the differing patterns of leaf fall, leaf flushing and leaf cover for the three tree species examined are discussed elsewhere (Muthuri, 2004).

Model simulations

The primary objective was to assess the effect of leafing phenology on soil water balance and tree and crop growth. Figure 4 summarises the scenarios simulated. Each tree species was subjected to all leafing phenology scenarios to compare the outputs for soil water balance, tree and crop biomass and trunk diameter.

Although the performance of each tree species was to be examined under it was not possible to achieve this within a single model run for individual species because the phenology input table in WaNuLCAS considers only a single scenario at any one time. An Excel table was therefore created within the model into which the daily information for trunk diameter and tree biomass generated during the simulations was copied; this was then used to provide the graphical outputs.

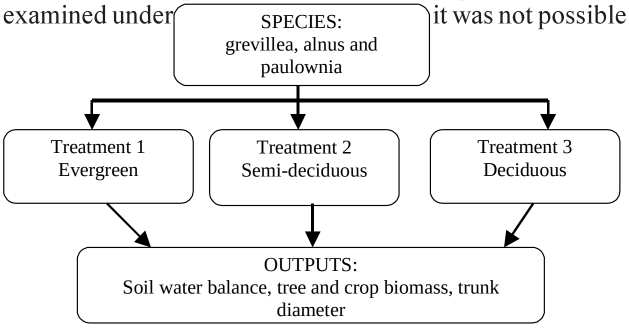


Figure 4 Flow diagram illustrating scenarios simulated.

Results

Water balance

Figure 5 shows the components of the water balance, i.e. soil evaporation, rainfall interception, drainage, runoff and water uptake by the trees and crops obtained from simulations using different tree leafing phenologies. The simulations indicate that a substantial proportion of the water balance was attributable to water uptake by the crop and trees, soil evaporation and drainage (averaging 27, 15, 36 and 10% respectively over the simulation period). The proportions attributable to interception losses and runoff were substantially smaller (5.5 and 3% respectively). Altering leafing phenology from evergreen, through semi-deciduous to deciduous decreased water uptake and interception losses for all tree species. Water uptake by the crop, drainage, evaporation and runoff all increased when a deciduous scenario was adopted, although runoff decreased in the alnus system when phenology was changed from semi-

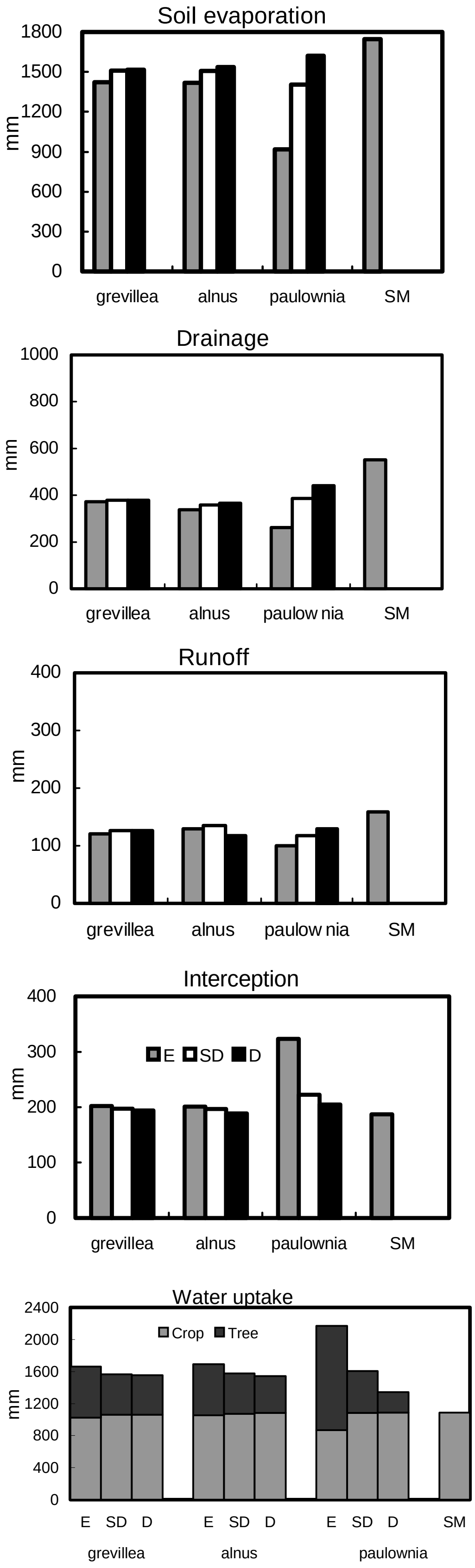


Figure 5. Simulated values for water balance components for sole maize (SM) and agroforestry systems containing grevillea, alnus or paulownia in a five year simulation involving evergreen (E), semi-deciduous (SD) and deciduous (D) leafing phenology scenarios.

deciduous to deciduous.

The variation in water balance components induced by altering leafing phenology was greatest in paulownia and smallest in alnus. Simulated total water uptake was nevertheless greater in all agroforestry systems than in sole maize, although estimated water uptake by the crop component of the agroforestry systems was close to that for sole maize, especially when the deciduous tree leafing phenology scenario was adopted. Simulated uptake by sole maize was 1090 mm. In the agroforestry treatments, the lowest and highest simulated crop water uptake values were obtained for the paulownia system using the evergreen and deciduous leafing phenology scenarios respectively. Conversely, the highest and lowest simulated tree water use values were obtained for the same treatments. The actual total precipitation during the five-year simulation period was 3914.5 mm, while the total for the simulated water balance components shown in Figure 5 was 3780 mm, or *c*.97% of the total precipitation; the balance may have been attributable to runoff and/or lateral flow. Thus the prediction of the overall water balance provided by WaNuLCAS is extremely good, although further refinement is clearly needed to improve the precision of the partitioning of water between the water balance components.

Basal stem diameter

Figure 6a shows the increments in basal stem diameter over the five-year simulation period, commencing on Julian Day 153 when the trees were planted. Observed basal diameters during the 27-month period after planting are also shown. Although no apparent difference was detected between the evergreen and semi-deciduous phenologies for grevillea and alnus during the initial stages of the simulation (*c*. 40 and 44 months respectively), the values were subsequently greatest under the evergreen scenario. By contrast, the differing trends for each treatment were clear from the outset in paulownia, suggesting there may have been a time lag before the full impact of leafing phenology on stem diameter became apparent. Simulated basal diameters in paulownia agreed more closely with the observed values than those for alnus and grevillea. As paulownia is actually deciduous, model predictions were close to the observed values.

Tree biomass production

The trends for above-ground biomass (Fig. 6b) were generally comparable to those for trunk diameter (Fig. 6a). As for basal stem diameter, the evergreen and semi-deciduous phenologies provided comparable values for above-ground biomass during the first 42 months of the simulation, but a clear ranking subsequently emerged, whereby the evergreen phenology provided the highest values, followed by the semi-deciduous phenology and finally the deciduous phenology in all species. However, some overlap between the semi-deciduous and deciduous phenologies was apparent for grevillea and alnus. Paulownia provided a sharp contrast to the other two species as biomass values were much lower under the deciduous scenario than under the evergreen or semi-deciduous phenologies.

Crop biomass

Figure 7 shows simulated and observed crop biomass at final harvest for the two seasons when field experiments were carried out. The simulations underestimated biomass, although the difference between simulated and observed values was smaller during the 2002 long cropping season. Changes in leafing phenology had little effect on simulated crop biomass during the 2001/2002 short cropping season, but the evergreen phenology consistently provided the lowest values for above-ground crop biomass during the 2002 long cropping season. The trends for simulated biomass production were consistent with those observed in the field experiment as biomass production was lower during the second season than during the first.

Discussion

WaNuLCAS proved sensitive to changes in leafing phenology, as shown by the results for biomass and water uptake. Less biomass was generally produced by all tree species when the leafing phenology option in the model was activated. The greatest changes in water balance were observed for paulownia, which showed a dramatic reduction in simulated water uptake as leafing phenology was altered from semi-deciduous to deciduous (Fig. 5). Although total water uptake was greater in the agroforestry systems than in sole maize, the quantity of water captured by sole maize was only 1.4% greater than the average apportioned to the crop under the deciduous and semi-deciduous scenarios, suggesting that the presence of trees does not necessarily reduce crop water use. An increased proportion of the available water was attributed to soil evaporation in sole maize; for instance, simulated soil evaporation was 1747 mm under sole maize compared to 1537 mm in the alnus system using the deciduous phenology scenario. Similar observations were obtained for runoff and drainage for all tree species and leafing phenologies, with the highest values being obtained for sole maize and the lowest using the evergreen leafing phenology. This is consistent with observations that agroforestry may improve water use efficiency by reducing the unproductive components of the water balance, i.e. run-off, soil evaporation and drainage (Ong *et al*., 1996; Rockstrom, 1997; Ong *et al*., 2002). However, increases in the drainage component were apparently beneficial in the present study as they would have facilitated recharge of the water table and replenishment of groundwater reserves, which may in turn increase stream flow.

Model simulations over a 20-year period using the CoupModel also revealed that soil evaporation and stream flow were lower in evergreen eucalyptus plantations than in existing natural vegetation in the Njoro area of Kenya (Alavi and Ong, 2004). Moreover, the change of land use in South Africa during the last century from the natural, seasonally dormant grassland or fynbos (sclerophyllous shrubland) to evergreen forest plantations has reduced stream flow over large parts of the country, to the detriment of downstream users (Bosch and Hewlett, 1982; Dye and Bosch, 2000). Therefore, although agroforestry offers considerable potential for exploiting residual water supplies in the soil profile and deeper reserves beyond the maximum rooting depth of annual crops (Howard *et al*., 1997; Lehmann

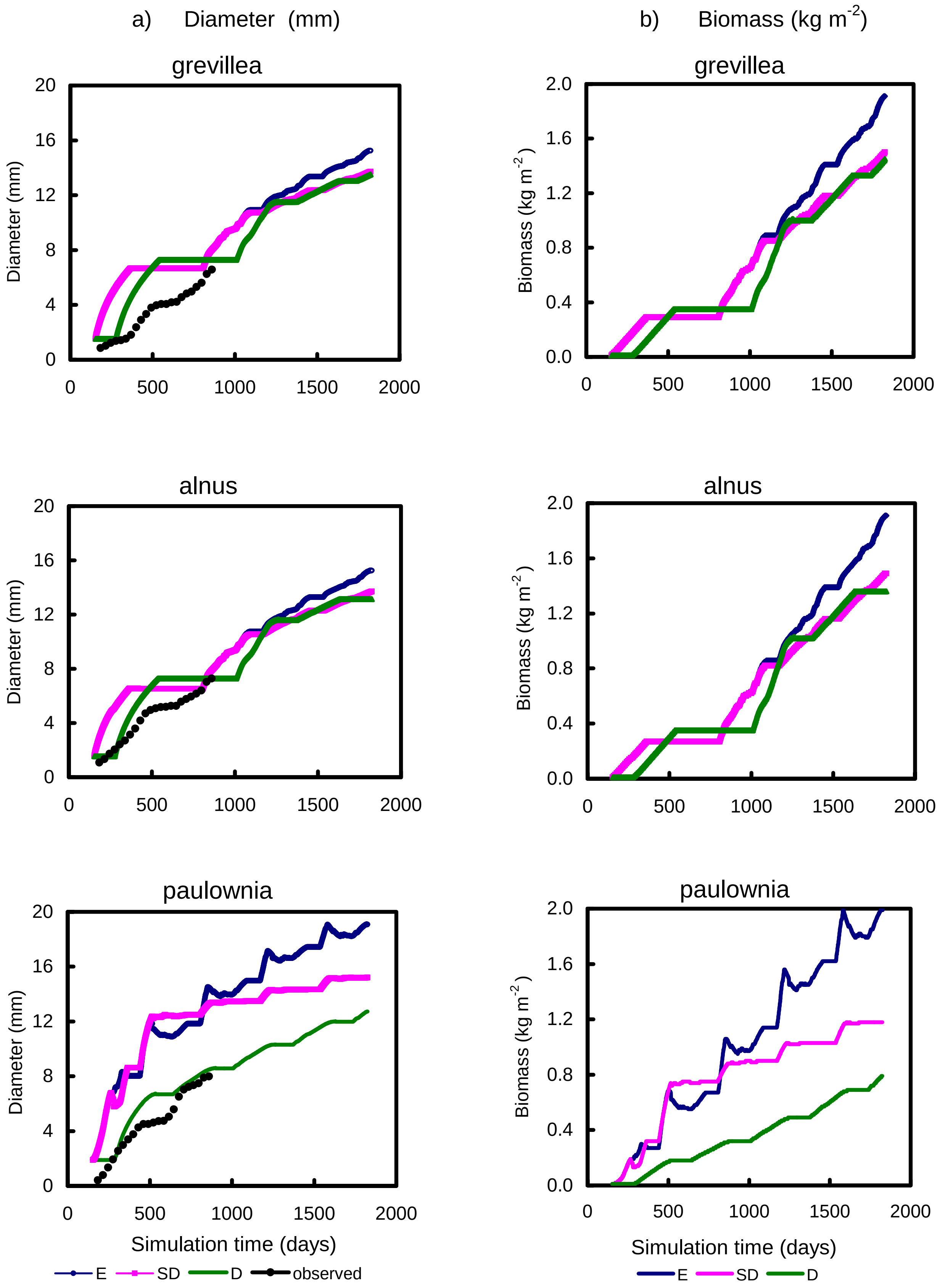


Figure 6 Simulated(a) basal stem diameter and (b) above-ground tree biomass values for agroforestry systems containing grevillea, alnus or paulownia in simulations involving evergreen (E), semi-deciduous (SD) and deciduous (D) leafing phenology scenarios. The observed stem basal diameter during the first 27 months of the study is also shown. The simulation period was five years commencing on Julian Day 153, when the trees were planted.

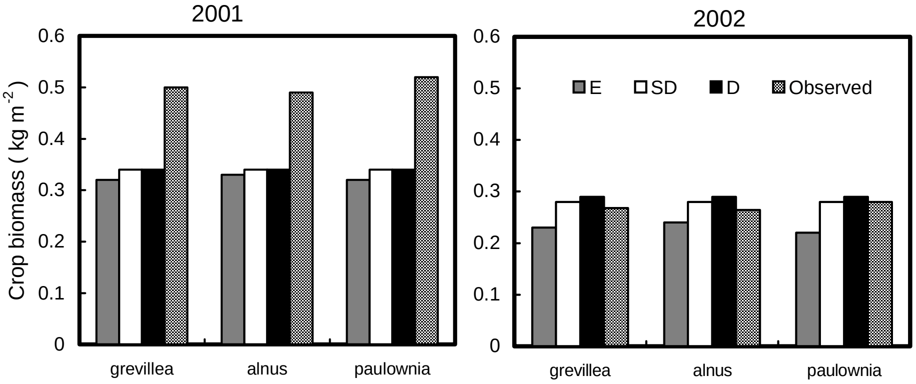


Figure 7 Simulated values for above-ground crop biomass at maturity in agroforestry systems containing grevillea, alnus or paulownia in simulations involving evergreen (E), semi-deciduous (S) or deciduous (D) leafing phenology scenarios during the 2001/2002 short and 2002 long cropping seasons. The observed above-ground biomass at maturity is also shown.

et al., 1998; Black and Ong, 2000; Lott *et al*., 2003), it is essential to achieve a satisfactory balance between recharge and exploitation of groundwater. Gas exchange measurements made under field conditions in the present study showed that there was no significant difference in instantaneous water use efficiency (WUE$_i$) between the three tree species examined (Muthuri, 2004), suggesting that differences in leafing phenology may be more important in determining the impact of agroforestry on soil water balance and stream flow. Model simulations also indicated that trees with deciduous or semi-deciduous leafing phenologies may provide a good compromise between the evergreen and sole maize systems because their water requirements are intermediate between these extremes. This view is in agreement with observations that leafing phenology may influence the partitioning of water as species exhibiting the smallest seasonal variation in leaf area have been shown to tap increasingly deep sources of soil water as the dry season progresses (Meinzer *et al*., 1999). Furthermore, competition for limited soil water during the dry season is reported to be influenced by species-dependent differences in leafing phenology (Meinzer *et al*., 2001).

Simulated water uptake by maize was greater than that for the tree component (Figs. 4 and 5). Previous studies of grevillea at Machakos, Kenya, using heat balance gauges (Lott *et al*., 2000; Lott *et al*., 2003) have shown that water use ranged from 2.6 mm d^{-1} during the dry season to 4.0 mm d^{-1} during the wet season. Over a five-year period, these values would translate into a greater cumulative water use than the simulated values obtained in the present study, for instance, 640 mm under the evergreen leafing phenology. WaNuLCAS therefore generally underestimated water use by the trees, especially grevillea and alnus, demonstrating that this aspect of the model simulations needs to be refined to improve accuracy. This may be achieved by reassessing the influence of the new leafing phenology function in the model on the main drivers of water use by the tree component, particularly transpirational demand, root length density and soil water content. The interaction between water uptake and other components within the model may also be crucial because more water was apportioned to soil evaporation than to water uptake by the trees.

Simulations of the increments in basal stem diameter and above-ground biomass production for the trees provided closely comparable trends. The effect of leafing phenology was greater in paulownia than in the other species, possibly because the simulations provided steep initial increases followed by an extended period without growth (Fig. 6). The outputs imply that the phenological aspects of the model require further refinement to overcome the anomalous initial period of rapid growth followed by an extended period without growth. This might involve further detailed studies of tree phenology and the coordination of increments in stem diameter with those for leaf area and biomass. The simulated above-ground biomass accumulation over five years by grevillea (1.9 kg m^{-2}) nevertheless compares favourably with the experimental value of 1.7 kg m^{-2} obtained over a 4.5 year period for a dispersed-planted agroforestry system containing grevillea at Machakos, Kenya (Lott *et al*., 2000).

Simulated crop biomass at maturity showed smaller differences between the various leafing phenology scenarios during the 2001/2 short rains (October–December) than during the 2002 long rains (April–June), perhaps because all tree species were in leaf between October 2001 and February 2002, matching the ‘evergreen’ phenology setting within WaNuLCAS during this season. However, the 2002 long cropping season coincided with a period when natural differences in leafing phenology between the tree species were more pronounced. These observations demonstrate that WaNuLCAS is sensitive to the various leafing phenology scenarios tested. However, the simulations underestimated crop biomass at Naro Moru, but overestimated this parameter at Thika, also in Kenya (Muthuri, 2004). Previous simulations for crops in Malawi showed that WaNuLCAS may either overestimate or underestimate maize biomass in some years (Chikusie-Chirwa, 2002). Planting date is a key factor in determining maize yields in Kenya (Mati, 2000). Although the crop management schedule defining planting and fertiliser application dates was specified within the WaNuLCAS simulations in the present study, the default settings for maize contained in the crop library section of the WaNuLCAS.xls file were used. The disparity between simulated and observed biomass values may therefore be partly attributable to differences in the duration of specific growth stages (i.e. generative and vegetative) between the maize variety used in the field trials and the default settings in the model. This is possible because maize varieties differ in the duration of crop growth, which may in turn affect biomass accumulation. The differences between simulated and observed values were much smaller during the 2002 long rains, when the simulated crop biomass obtained using the evergreen phenology for grevillea (0.35 kg m^{-2}) was comparable to the values obtained using WaNuLCAS of 0.40 kg m^{-2} for Central Kenya (Muchiri *et al*., 2002) and 0.41 kg m^{-2} for Thika District, Kenya (Muthuri, 2004).

Conclusions

Information for the Ewaso Ng'iro river, part of which flows through the Naro Moru area, indicates that average stream flow during the dry season, including tributaries from the Aberdare Mountains, has decreased from 9 $m^3 s^{-1}$ in the 1960s to 1.2 $m^3 s^{-1}$ in the 1980s. This dramatic decline has been caused by a combination of illegal water abstraction for irrigation, which increased ten-fold over the same period, changes in land use, and removal of vegetation cover (Liniger *et al*., 1998b). This observation emphasises the need to develop land use systems which have less severe effects on stream flow, as well as management tools capable of predicting the impact of future human activities. The present study sought to address this challenge by demonstrating the ability of the WaNuLCAS model to simulate the influence of tree leafing phenology on soil water balance and tree and crop performance. The five-year simulations reported here indicate that tree leafing phenology affects the simulated values for tree and crop growth and water use. Simulations over longer periods of at least 10 years, to reflect the normal rotation cycle for the tree species examined, would be invaluable in elucidating the longer-term implications of incorporating trees into cropping systems in the Naro Moru area and elsewhere. Simulations involving the vegetable crops which are popular in the Naro Moru area should also be carried out. Simulations involving comparisons of the tree species examined in the present study with other popular fast-growing species such as eucalyptus are also highly desirable. Plot-level studies such as those reported here should be extended to encompass the entire watershed (catchment). The phenology module in WaNuLCAS clearly needs to be refined to improve the precision of model outputs, particularly regarding water use by the tree and crop components. Once this has been achieved, WaNuLCAS will offer a powerful tool for evaluating the impact of specific land use systems and tree/crop combinations on soil water balance and streamflow, thereby providing a means to improve water resource management in areas such as Naro Moru where agricultural activity is increasing rapidly and water supplies are limited.

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