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Trees improve water storage and reduce soil evaporation in agroforestry systems on bench terraces in SW Uganda

D. Siriri · J. Wilson · R. Coe · M. M. Tenywa ·
M. A. Bekunda · C. K. Ong · C. R. Black

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Abstract The success of agroforestry in semi-arid areas depends on efficient use of available water and effective strategies to limit tree/crop competition and maximise productivity. On hillsides, planting improved tree fallows on the degraded upper section of bench terraces is a recommended practice to improve soil fertility while cropping continues on the lower terrace to maintain food production. This study examined the influence of tree fallows on soil water content (θ_w) and evaporation (E_s). *Alnus acuminata* Kunth (alnus), *Calliandra calothyrsus* Meissner (calliandra), *Sesbania sesban* L. (sesbania), a mixture of all three species, or sole crops (beans (*Phaseolus vulgaris* L.) or maize (*Zea mays* L.)) were grown on the upper terrace. The same sole crops were grown on the lower terrace. Four management regimes (unpruned, root, shoot and root + shoot pruned) were applied to the tree rows adjacent to the cropping area. Neutron probe and microlysimeter approaches were used to determine θ_w and E_s when the trees were *c*. 3.5 years old. Sesbania and alnus increased θ_w by 9–18 % in the cropping area on the lower terrace but calliandra reduced θ_w by 3–15 %. After heavy rain, E_s comprised 29–38 % of precipitation in the tree-based treatments and 53 % under sole crops. Absolute values declined as rainfall decreased, but E_s as a proportion of rainfall increased to 39–45 % in the tree-based treatments and 62 % for sole crops. Root + shoot pruning of alnus and the tree mixture increased θ_w in the cropping area but had no significant effect in the other tree-based treatments. The results suggest that sesbania and alnus can be planted on smallholdings without compromising water supply to adjacent crops, whereas calliandra decreased water availability despite reducing E_s. These results provide a mechanistic understanding of reported effects on crop yield in the same site.

Keywords *Alnus acuminata* Kunth · *Calliandra calothyrsus* Meissner · Improved fallows · Root and shoot pruning · *Sesbania sesban* L. · Soil water storage

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D. Siriri
UNOPS Millennium Villages Project, Plot 8, Muti Drive,
P.O. Box 448, Mbarara, Uganda

J. Wilson
Centre for Ecology & Hydrology, Bush Estate, Penicuik
EH26 0QB, UK

R. Coe · C. K. Ong
World Agroforestry Centre, P.O. Box 30677,
Nairobi, Kenya

M. M. Tenywa · M. A. Bekunda
Soil Science Department, Makerere University,
P.O. Box 7062, Kampala, Uganda

C. R. Black (✉)
Plant & Crop Science Division, University of
Nottingham, Sutton Bonington Campus,
Loughborough LE12 5RD, UK
e-mail: Colin.Black@nottingham.ac.uk

Introduction

Water supplies for agriculture are seriously threatened by global climate change (Gregory and Ingram 2000; Fischer et al. 2005). As two thirds of the World's population is expected to experience water shortages by 2050 (Rosenzweig et al. 2004), it is vital to improve the efficiency with which available water is used for food production. Increasing populations in the African highlands have forced a move from traditional shifting cultivation to more intensive farming, although this has not been accompanied by mechanisation or application of fertiliser or irrigation (Swinkels et al. 1997; Ong et al. 2006, 2007), resulting in depletion of natural resources and declining per capita food production (Sanchez et al. 1997). The small size of land-holdings means that farmers cannot allocate separate areas for trees and crops. Agroforestry may be a viable option to sustain productivity while providing essential tree products and ecological services in areas such as SW Uganda where crop yields are <35 % of potential production and the shortfall of wood supply is *c*. 40 % (Siriri and Bekunda 2004; Siriri et al. 2010). Similar problems occur throughout the semi-arid and sub-humid tropics.

Traditional cropping systems often cannot fully utilise available rainfall due to losses by evaporation from the soil surface (E_s), runoff and drainage (Ong et al. 1996, 2006, 2007). As E_s comprises 20–40 % of rainfall in East and West Africa (Wallace et al. 1999; Jackson and Wallace 1999; Wallace and Gregory 2002), this has major implications for crop production. Key factors affecting E_s are soil moisture content, ground cover and microclimate (Wallace and Gregory 2002; Lin 2010). Strategies that manipulate these factors may be used to reduce E_s and increase the proportion of rainfall available to crops (Lin 2010). Development of land use systems that use scarce resources efficiently is vital to improve food security as future climate change scenarios predict reduced or more erratic rainfall in sub-Saharan Africa (Wallace and Gregory 2002).

Integration of trees on cropland may improve productivity by: providing spatial and/or temporal complementarity of resource capture by trees and crops (Ong et al. 2006, 2007); increasing soil organic matter content, infiltration and water storage (Wallace 1996; Sun et al. 2008); improving soil physical properties and biological activity (Yamoah et al. 1986); and enhancing nutrient supplies through nitrogen fixation and reduced leaching and soil erosion (Sun et al. 2008). Agroforestry systems promoted in East Africa include improved fallows containing *Sesbania sesban* and rotational woodlots of *Calliandra calothyrsus* or *Alnus acuminata* (Siriri and Raussen 2003; Siriri et al. 2010). Planting trees on the degraded upper part of bench terraces subject to repeated down-slope cultivation and scouring by heavy rain is a recommended practice to improve fertility and provide valuable tree products while cropping continues on the more fertile middle and lower terrace (Raussen et al. 1999; Siriri and Raussen 2003; Siriri et al. 2010). Planting trees on contours reduces runoff and erosion and improves soil fertility under a wide range of climatic conditions (Sun et al. 2008). However, agroforestry does not always provide a solution, as competition with crops is common (Ong et al. 2006, 2007; Sun et al. 2008; Siriri et al. 2010).

Bench terraces create a matrix of conditions for crops as their concave shape limits productivity on the upper terrace due to limited soil depth, water retention and fertility, and causes waterlogging on the lower terrace after heavy rainfall. Crop yield on the upper terrace is much lower than on the more fertile middle and lower sections, and may contribute only 5 % of the total yield (Siriri et al. 2010). Some studies suggest that spatial or temporal separation of trees and crops may be used to limit competition (Cooper et al. 1996), but farmers report that detrimental interactions may still occur (Wajja-Musukwe et al. 2008; Sun et al. 2008). This is important as continued crop production on the middle and lower terrace is vital for food security as farmers await the benefits of trees grown on the upper terrace (Siriri et al. 2010). Effective strategies to limit competition and enforce complementarity are vital.

Schroth (1999) suggested two options, selection of trees with characteristics that encourage complementarity and management interventions that limit competition. However, characteristics that reduce competition by trees are not always consistent with their intended use by farmers, including timber production or revenue generation from greenhouse gas credits (TIST 2008). When farmers' needs and ecological compatibility conflict, understanding and manipulation of the underlying processes are essential. Shoot and/or root pruning of trees may be used to control competition (Ong et al. 2006, 2007; Bayala et al. 2008; Siriri et al. 2010). Jones et al. (1998) reported that shoot pruning of *Prosopis juliflora* limited below-ground competition with sorghum, while Jackson et al. (2000) showed that this practice reduced water use by trees and improved recharge of the crop rooting zone. Chandrashekara (2007) recommended shoot pruning regimes and frequencies for 10 important tree species in Kerala, India to limit competition with understorey crops, while Wajja-Musukwe et al. (2008) showed that root pruning one side of tree rows in sub-humid Uganda had little effect on tree growth but reduced competition with adjacent crops; however, competition was increased on the unpruned side of the tree row. Previous studies in Uganda have shown that unpruned sesbania fallows on the upper terrace had little impact on crop yield on the lower terrace, but that shoot and/or root pruning of alnus and, especially, calliandra was needed to maintain crop yield (Siriri et al. 2010).

Although inclusion of trees in farming systems may alter microclimate in ways that reduce soil evaporation and offset rainfall losses due to canopy interception (Ong et al. 2006, 2007; Lott et al. 2009; Lin 2010; Siriri et al. 2010), Lott et al. (2009) concluded that competition for water negated the potential benefits of microclimatic amelioration for understorey maize. The influence of microclimatic amelioration associated with the closely spaced, fast growing trees used in improved fallows and rotational woodlots on E_s and θ_w is unknown. As the use of such systems by smallholder farmers is increasing in semi-arid and sub-humid areas, studies of effects on E_s and θ_w are essential to understand how these systems influence water use efficiency, crop yield and food security. This study aimed to: (1) determine the influence on E_s and θ_w of planting improved tree fallows on the degraded upper section of bench terraces while cropping continued on the middle and lower terrace; and (2) examine the effectiveness of root and shoot pruning in improving compatibility between trees and crops.

Materials and methods

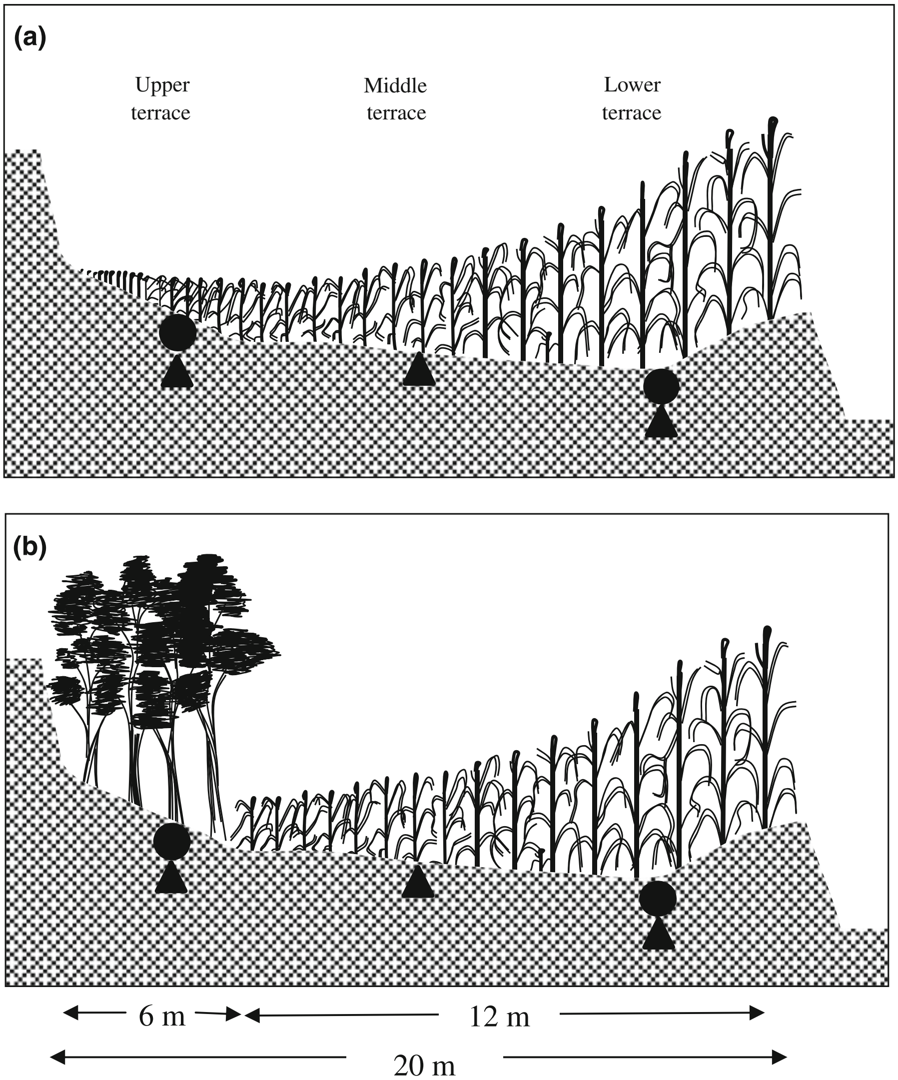
Experimental design

The study was conducted at Kigezi High School, Kabale District, SW Uganda (1°15′S, 29°55′E, 1,850 m asl). The bimodal rainfall (*c*. 1,000 mm year^{-1}) is greater and more evenly distributed during the long cropping season (September–February) than during the short cropping season (April–June). Most land is terraced to control runoff and erosion; terraces are typically 20 m wide, with a rise of *c*. 1.5 m between them, and are used for smallholder production of sorghum (*Sorghum bicolor* L.), maize (*Zea mays* L.), beans (*Phaseolus vulgaris* L.), peas (*Pisum sativum* L.), sweet potato (*Ipomea batatas* L.) and Irish potatoes (*Solanum tuberosum* L.; Fig. 1a). The soil was a haplic ferralitic sandy clay loam developed from phyllite parent material. Topsoil pH (0–15 cm) was 6.5, and clay content decreased from 37.4 to 27.1 % between the upper and lower terrace due to erosive transfer during heavy rain and repeated downhill cultivation using hoes; soil organic matter increased from 1.11 to 1.31 g kg^{-1}. Mean bicarbonate EDTA extractable phosphorus and exchangeable potassium concentrations were respectively 27–36 mg kg^{-1} and 0.48–0.54 mol$_c$ kg^{-1} (Siriri and Raussen 2003).

Trees were grown on the upper third of the terrace for 4 years, while cropping continued on the middle and lower parts of the terrace (Fig. 1b). Sole stands of *Alnus acuminata* Kunth (alnus), *Calliandra calothyrsus* Meissner (calliandra), *Sesbania sesban* (L.) Merr. var. sesban (sesbania), a mixture of all three, and a sole crop control treatment were grown on the upper terrace (6 m wide). Alnus and calliandra were planted in September 2000 and sesbania in March 2001 to ensure all tree species were all ready for harvest at the same time (Siriri et al. 2010). These species were chosen for their N-fixing capacity and ability to produce 24–27 t ha^{-1} of fuelwood and 30 t ha^{-1} of above-ground biomass under local climatic conditions (Siriri and Raussen 2003), and were planted in three rows at a density equivalent to 10,000 trees ha^{-1}. A single row of each species was grown in the tree mixture; sesbania, the least competitive species, was located next to the cropping area, calliandra in the central row and alnus, believed to be the most competitive (Siriri and Raussen 2003; Siriri et al. 2010), was planted furthest from the cropping area.

An unbalanced split plot design containing three blocks was used (Siriri et al. 2010). Main treatment plots on the upper terrace (trees or sole crop; 26 m long × 6 m wide) were randomly allocated in each block. Four tree management sub-treatments (unpruned, root pruned, shoot pruned and root + shoot pruned) were randomly allocated within each main treatment

Fig. 1 Schematic diagram showing variation in crop performance on bench terraces on hillslopes in SW Uganda: **a** sole crop and **b** trees grown on the upper terrace with crops on the middle and lower terrace. *Circle* location of measurements of soil evaporation and below-canopy solar radiation; *filled triangle* location of volumetric soil water content measurements



using 5 × 6 m sub-plots. Main and sub-treatment plots were respectively separated by 4 and 2 m wide paths to minimise interference. Sole crops of maize (*Zea mays* L. *cv*. H622) or beans (*Phaseolus vulgaris* L. *cv*. K132) were grown on the middle and lower terrace (each 6 m wide; Fig. 1b) during the long and short cropping seasons respectively. Beans were planted at a 50 × 10 cm spacing and maize at 75 × 30 cm. A sole crop treatment was grown on the upper terrace for comparison with the tree-based treatments.

The tree management regimes were a compromise between effective control of competition and maximum production of woody biomass and green manure. Shoot pruning involved removing all branches from the lower third of the canopy of the tree row adjacent to the down-slope cropping area before each cropping season. Prunings were returned as green manure to the plots from which they came. Root pruning was achieved by digging and infilling trenches 0.5 m from the outer tree row to sever roots growing into the cropping area before each rainy season; these were 30 cm deep when the trees were young and 50 cm deep when they were over 3 years old. The former represents the depth achievable using hand hoes during normal field operations (Siriri et al. 2010); deeper pruning would have compromised tree establishment and growth.

Climatic conditions

Solar radiation, air temperature and atmospheric saturation deficit (SD) above the tree and crop canopies were recorded by an automatic weather station (BWS200, Campbell Scientific, Shepshed, UK). Rainfall (ARG100 tipping bucket raingauge), wind speed (RM Young Young Rain Sentry), wet and dry bulb air temperatures and atmospheric saturation deficit (CS215) and solar radiation (CS300 silicon pyranometer) were automatically measured and recorded.

Soil water evaporation (E_s)

Microlysimeters were used to determine the substantial spatial variation in E_s introduced by the integration of trees on bench terraces due to their simplicity and reliability. Microlysimeters comprise rigid enclosures containing small soil volumes (1–3 kg) which are placed in closely fitting pits in the soil and weighed daily. Lysimeters of the type described by Daamen et al. (1993) and modified as suggested by Jackson and Wallace (1999) were used. These comprised UPVC cylinders 160 mm in diameter and 100 mm deep. Their walls were perforated with 10 mm diameter holes to allow roots to explore the enclosed soil (Villalobos and Fereres 1990) and the lower end was chamfered to provide a cutting edge to ease installation. Before each set of measurements, the lysimeter cylinders were pushed into the soil and left for 4 days, during which vertical drainage was unimpeded. Undisturbed soil cores were removed by excavating the lysimeters to a depth of 20–30 mm below the base; excess soil was removed before sealing the base and the perforations in the lysimeter walls using waterproof tape to prevent exchange of water. Lysimeters were prepared between 0700 and 0800 h after overnight rain, or when precipitation ceased if rain fell during the day before being installed in pits (165 mm diameter × 90 mm deep) *c.* 1 m from where the soil cores were collected. The casing protruded 10 mm above the soil to prevent entry of runoff or extraneous soil.

Two lysimeters were installed in all replicates of the unpruned and root + shoot pruned sub-treatments of the four tree-based treatments and the sole crop on the upper terrace, and also in the cropping area on the lower terrace (Fig. 1), giving a total of 36 lysimeters. These were weighed twice daily (0700–0800 and 1700–1800 h) using a balance (0.1 g resolution, equivalent to 0.01 mm of water) powered by a generator. Soil in the lysimeters was replaced after each rainfall event. In the absence of rain, lysimeters were used for up to 7 days, as recommended by Daamen et al. (1993). Measurements were made between 14 March and 10 July 2004 during Periods i–iv shown in Fig. 2a to determine E_s under both rainy and dry conditions. As E_s from moist soil depends primarily on microclimatic conditions, total shortwave radiation was measured 0.5 m above the soil for all lysimeter locations (SKS1110 pyranometer, Skye Instruments, Llandrindod Wells, UK); incident solar radiation was obtained from the weather station.

Volumetric soil moisture content (θ_w)

Neutron probes have been used to determine θ_w for a wide range of soil types and land use systems. Their underlying theory, use and calibration are described by Bell (1987). Access tubes were installed in the upper, middle and lower terrace (Fig. 1) in the unpruned and root + shoot pruning sub-treatments of all four tree-based treatments and the sole crop control on the upper terrace (total of 81 tubes). The unpruned treatment represents current local practice and was expected to create the greatest competition for water with neighbouring crops, whereas the shoot + root pruning treatment was anticipated to be most effective in reducing competition. Three access tubes installed outside the experimental area on each of the upper, middle and lower terrace sections were used to calibrate the neutron probe (Wallingford Model IHII) against paired gravimetric measurements of θ_w obtained using soil cores across the full range of θ_w (Hillel 1998). Separate calibrations were constructed for the 0–30 cm and deeper soil horizons for each terrace position to account for the differing soil characteristics of topsoil and subsoil.

The base of the aluminium access tubes (5 cm diameter × 2 mm wall thickness) was sealed to prevent entry of ground water, while the top projected 5 cm above the soil and was covered by a metal cap to exclude rain and soil. Tubes were installed vertically after removing soil cores using an auger. Mean tube depth was 116.9, 139.7 and 174.6 cm on the upper, middle and lower terrace, reflecting the systematic variation in soil depth, and hence maximum rooting depth. Measurements were made at 15 cm intervals between 15 and 60 cm and at 20 cm intervals to the

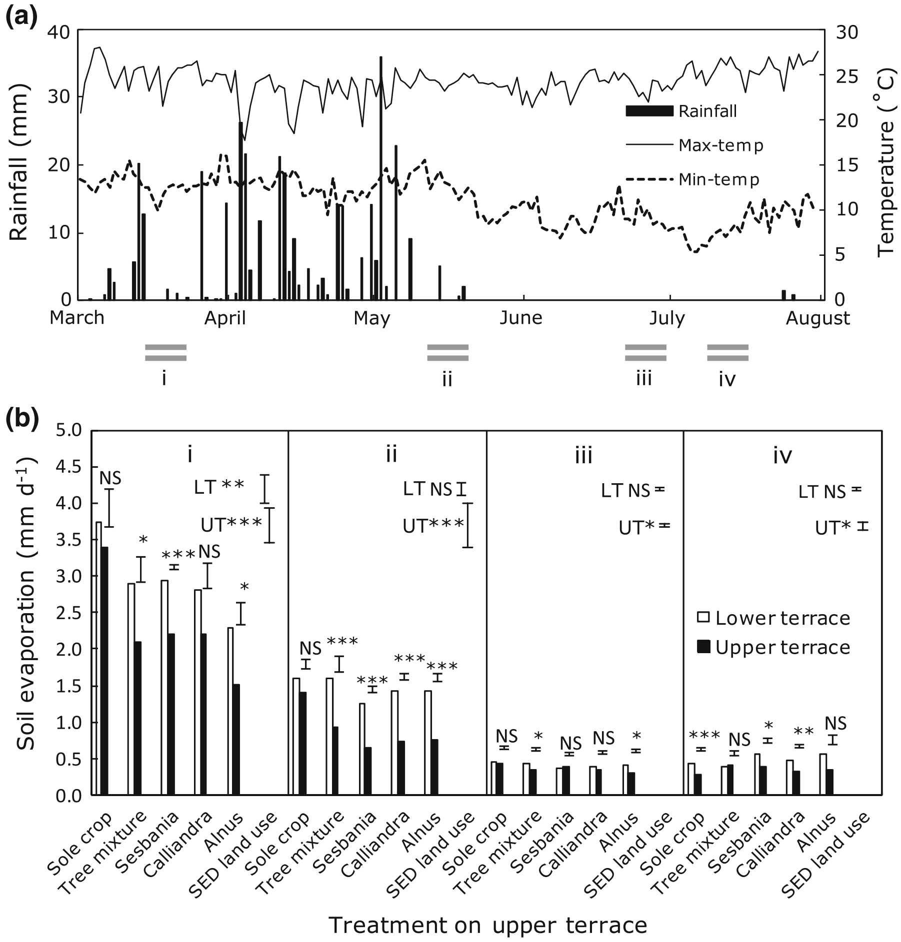


Fig. 2 **a** Daily rainfall, maximum and minimum air temperature and **b** mean daily soil evaporation (E_s) during the 2004 short rains and subsequent dry season. *Horizontal tramlines* in **a** show periods when E_s was measured and correspond to *panels i*, *ii*, *iii* and *iv* in (**b**). *Error bars* above each pair of treatment histograms show standard errors of the difference between treatment means (SED) for comparing the upper and lower terrace for specific land use treatments. The *error bars* for "SED land use" show SEDs for comparing E_s between land use treatments on the upper (UT) and lower (LT) terrace sections. *, ** and *** denote $P < 0.05$, $P < 0.01$ and $P < 0.001$; *NS* no significant effect

maximum depth of individual tubes. As neutron probe measurements at depths <15 cm may underestimate moisture content due to the loss of emitted radiation from the soil surface (Bell 1987), no consideration is given to the values obtained for the surface soil horizon in the "Discussion" section. θ_w was measured at approximately weekly intervals between 29 November 2003 and 21 January 2004 and 13–26 March 2004 to give a total of 11 measurement dates.

Statistical analysis

The experimental design required split-plot analysis of variance as its unbalanced nature meant that the equivalent model had to be fitted using the residual maximum likelihood approach (REML), with estimated values and standard errors of the difference for treatment effects being taken from the fitted model (Siriri et al. 2010). Local variation in the performance of a cover crop of beans grown before the main experiment began was used as a covariate to remove any confounding influence on actual variation between treatments. Species and pruning regime represented the main and sub-treatments and the treatment structure was covariate + main treatment × sub-treatment; the covariate was yield from the cover crop. All analyses were carried out using Genstat 8 (Release 8.1) software. Standard errors of the difference between means (SED) and standard errors of the mean (SEM) are shown; significance was assumed at $P \leq 0.05$.

Results

Climatic conditions

Daily maximum temperature was generally lower and minimum temperature much higher during the 2004 short rains (March–May) than during the dry season (June–August; Fig. 2a) due to the greater radiative exchange associated with limited cloud cover during the latter period. Mean daily maximum and minimum temperatures were respectively 24.2 and 11.7 °C. SD at 1500 h rarely reached 1.5 kPa during the rainy season, but often exceeded 2 kPa during the later stages of the dry season (data not shown). SD at 0800 h was generally <0.2 kPa during the rainy season and rarely reached 0.5 kPa, even in the dry season. The relatively low air temperature and SD values reflect the humid environment of tropical highland areas such as Kabale. Rainfall was well distributed during the rainy season, with seven events >20 mm (Fig. 2a). Little rain fell during the dry season.

Solar radiation

Figure 3a shows the mean diurnal timecourses for total short wave radiation measured above the tree canopy and 0.5 m above the soil on the upper terrace for the sole crop and all unpruned tree treatments in March 2004, when alnus and calliandra were 41 months old and sesbania was 35 months old. Mean below-canopy values for the tree-based systems ranged from 45 % of the above-canopy value (alnus) to 59 % (sesbania), and were much lower than in the sole bean crop (74 %; $P < 0.001$). Cumulative shortwave radiation under the tree canopies over the same period was between 29 % (sesbania) and 56 % (alnus) lower than in sole crops on the upper terrace ($P < 0.001$; Fig. 3b). There were no significant treatment differences in the cropping zone on the lower terrace, although values were 12–25 % lower in the tree-based treatments than when sole bean crops were grown on the upper terrace. The influence of terrace position was significant ($P < 0.01$) as cumulative radiation under the sole bean crop on the upper terrace was approximately double that in the alnus, calliandra and tree mixture treatments and significantly greater than that of the sole crop on the lower terrace. Although no significant treatment effects were detected on the lower terrace, cumulative shortwave radiation under the sole crop was lower than on the upper terrace, whereas the reverse applied for alnus, calliandra and the tree mixture, reflecting treatment differences in canopy structure and shading intensity.

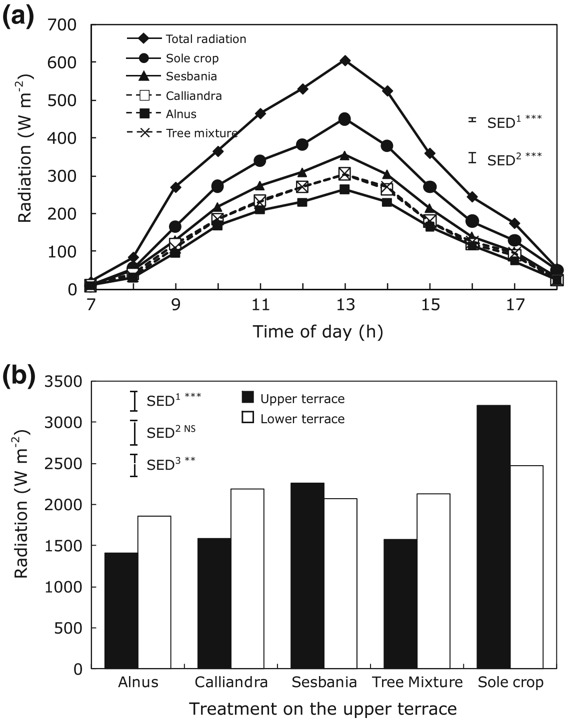


Fig. 3 **a** Mean diurnal timecourses for above- and below-canopy short wave radiation in the unpruned tree treatments and sole bean crop during March 2004 and **b** cumulative below-canopy short wave radiation. In **a** SED^1 and SED^2 respectively show standard errors of the difference between treatment means and the treatment × time interaction; in **b** SED^1, SED^2 and SED^3 show values for comparing treatment means for the upper terrace, lower terrace and values for both terrace positions. *, ** and *** denote $P < 0.05$, $P < 0.01$ and $P < 0.001$; *NS* no significant effect

Soil evaporation (E_s)

Measurements during a period when rainfall and the diurnal temperature range varied greatly showed that E_s differed between land use treatments on the upper terrace and also in the cropping area on the lower terrace, particularly after high rainfall (Fig. 2a, b). During Period 1 (15–24 March 2004; Fig. 2bi), E_s was greatest in the sole crop and lowest in the alnus treatment for both terrace positions ($P < 0.001$). When mean values for the upper and lower terrace are considered, 53 % of rainfall received by the sole crop was lost as E_s, compared to 29–40 % in the tree-based treatments ($P < 0.001$). Absolute E_s values were lower during Period 2 (14–21 May 2004; Fig. 2bii) but, when expressed as a proportion of rainfall, E_s increased to 62 % in the sole crop and

39–53 % in the tree-based treatments. Values on the upper terrace were higher for the sole crop than in all other treatments ($P < 0.001$). Almost no rainfall occurred during Periods 3 and 4 (23–30 June 2004 and 7–14 July 2004; Fig. 2a), resulting in a further decline in E_s (Fig. 2biii, iv). Soil evaporation was similar during both periods and did not differ between land use treatments.

The extent of the differences in E_s between terrace positions varied between treatments. During Period 1, E_s was greater in the cropping area on the lower terrace than on the upper terrace in the alnus, sesbania and tree mixture treatments ($P < 0.01$). A similar, but non-significant, trend was apparent for the calliandra and the sole crop treatments. During Period 2, the presence of trees on the upper terrace reduced E_s by *c*. 50 % relative to the lower terrace ($P < 0.001$), but the difference between terrace positions was again not significant for the sole crop. During Period 3, E_s was again lower on the upper terrace in the alnus and tree mixture treatments ($P < 0.05$). During Period 4, E_s was lower on the upper terrace in the calliandra, sesbania and sole crop treatments ($P < 0.01$, $P < 0.05$ and $P < 0.001$), but did not differ significantly for the alnus and tree mixture treatments, in contrast to Period 3.

Volumetric water content (θ_w)

Rainfall during the 7–9 day period preceding each measurement date varied between 0 and 102 mm, whereas mean daily temperature and relative humidity showed much smaller variation, ranging from 17.1 to 19.4 °C and 68 to 84 % (Table 1). Table 2 illustrates the increase in soil depth between the upper and lower terrace, which is typical of bench terraces in SW Uganda. On the upper terrace, θ_w tended to be greater under sesbania than in the sole crop treatment for all soil depths, although this was significant only for the 30–45 cm horizon ($P < 0.05$). None of the other tree-based treatments showed a significant difference relative to the sole crop for any horizon. On the middle terrace, θ_w was greater in the 60–80 and 80–100 horizons of the sesbania treatment than in the sole crop ($P < 0.001$). Values for calliandra and the tree mixture did not differ from the sole crop except in the 80–100 horizon, where θ_w was greater in the calliandra and lower in the tree mixture treatment than in the sole crop ($P < 0.05$). On the lower terrace, θ_w was greater in the alnus treatment than in the sole crop for all depths between 15 and 60 cm ($P < 0.01$–$P < 0.001$). Values for the other tree-based systems did not differ significantly from the sole crop.

Table 1 Total rainfall, mean air temperature (T_a) and mean relative humidity (*RH*) at 1200 h during the week preceding neutron probe measurements

Measurement date	Climatic variable		
	Rainfall (mm)	T_a (°C)	*RH* (%)
29 November 2003	19	18.5	83
4 December 2003	102	17.4	84
12 December 2003	21	17.1	84
20 December 2003	6	18.0	74
31 December 2003	0	17.7	68
7 January 2004	41	17.7	82
15 January 2004	11	18.8	75
21 January 2004	39	18.7	84
13 March 2004	14	19.4	77
19 March 2004	38	18.2	81
26 March 2004	2	19.1	78

The extent of the increase in mean θ_w for the entire soil profile varied between treatments depending on terrace position (Table 2). Mean θ_w was greatest in the alnus and sesbania treatments on the upper terrace ($P < 0.001$), and in the sesbania treatment on the middle terrace ($P < 0.001$), followed sequentially by the alnus, sole crop, calliandra and tree mixture treatments. On the lower terrace, θ_w was again greatest for alnus ($P < 0.001$), but did not differ between the other treatments. Values for all terrace positions were 7–15 % greater for alnus than for the sole crop, and 14–18 % greater on the upper and middle terrace for sesbania ($P < 0.001$). Values for calliandra and the tree mixture were 3–15 % lower than in the sole crop.

Mean θ_w values increased with depth ($P < 0.01$–$P < 0.001$) and were greater after ‘high’ rainfall (>20 mm; five events; Fig. 4b, d, f) than after ‘low’ rainfall (<20 mm; six events; Fig. 4a, c, e; $P < 0.01$). The influence of land use treatment was also greater after high rainfall for all terrace positions ($P < 0.001$). Values for θ_w in the surface 60 cm of the profile were generally greatest for alnus and sesbania on the upper and middle terrace, and for alnus on the lower terrace when rainfall was >20 mm ($P < 0.001$; Fig. 4b, d, f), but not when rainfall was <20 mm (Fig. 4a, c, e). The results suggest that sesbania and, especially, alnus

Table 2 Profiles of volumetric soil water content (θ_w) and profile mean values for the upper, middle and lower terrace; values are means for all 11 sampling dates for the unpruned tree treatments and sole bean crop on the upper terrace

Treatment on upper terrace	Volumetric water content (cm^3 cm^{-3})							
	Soil depth (cm)							
	0–15	15–30	30–45	45–60	60–80	80–100	100–120	Profile mean
Upper terrace								
Alnus	14.6	22.9	23.9	28.0	30.8			24.4
Calliandra	11.5	20.2	22.0	25.7	27.7			20.2
Sesbania	16.7	23.0	25.8	28.4	28.1			24.2
Tree mixture	11.4	20.6	19.9	22.2	22.3			18.3
Sole beans	12.8	20.4	21.4	25.2	26.4			21.0
SED	1.9*	2.0^{NS}	2.1*	2.6^{NS}	4.5^{NS}			1.0***
Middle terrace								
Alnus	17.2	25.2	25.9	25.8	24.5	29.7		25.0
Calliandra	12.4	19.8	20.8	20.8	25.7	40.7		19.7
Sesbania	15.3	23.7	25.8	26.3	32.3	40.4		27.3
Tree mixture	12.6	21.0	22.3	22.8	24.2	25.5		21.0
Sole beans	13.7	22.7	23.3	23.5	23.7	34.1		23.6
SED	1.5**	1.9^{NS}	2.2^{NS}	1.6^{NS}	2.2***	2.8***		0.9***
Lower terrace								
Alnus	22.0	30.1	30.0	32.2	30.5	31.0	39.3	30.6
Calliandra	17.3	22.1	22.9	23.9	31.7	28.7	37.4	26.8
Sesbania	15.8	24.1	24.2	27.1	27.9	29.3	37.6	26.5
Tree mixture	17.1	22.6	23.6	24.5	27.7	30.8	36.6	25.5
Sole beans	19.3	23.6	24.7	26.0	27.8	33.1	38.2	27.6
SED	1.8^{NS}	2.3**	2.2**	2.4***	3.6^{NS}	2.4^{NS}	2.7^{NS}	1.1***

NS No significant effect

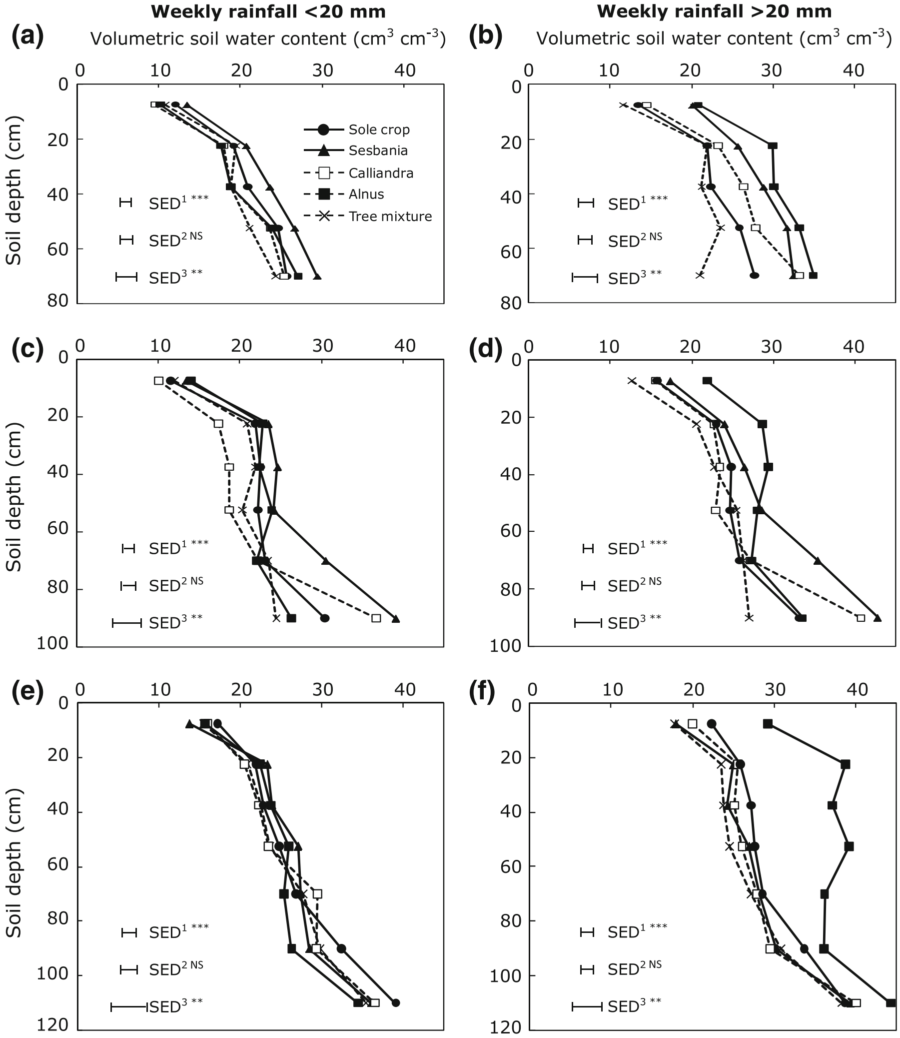
*, ** and *** denote $P < 0.05$, $P < 0.01$, $P < 0.001$

facilitate soil rewetting during periods of high rainfall; θ_w tended to be lowest in the tree mixture and calliandra treatments.

Mean θ_w values for the entire soil profile are summarised in Fig. 4g for all main treatments, terrace positions and sampling dates within each rainfall category. The significant treatment × rainfall interaction on the upper terrace ($P < 0.05$) indicates that the influence of rainfall varied among treatments; thus, θ_w was lower in the alnus treatment than in the sesbania treatment when rainfall was <20 mm ($P < 0.001$), but was similar when rainfall was >20 mm. Soil water content was between 14 % (tree mixture) and 53 % (alnus) greater in the tree-based treatments when rainfall >20 mm, compared to 9 % in the sole crop.

No significant treatment × rainfall interaction was detected on the middle terrace, where mean θ_w was greatest in the sesbania treatment after low rainfall ($P < 0.001$; Fig. 4g), but did not differ between the other tree-based treatments. When rainfall was >20 mm, θ_w was greatest in the sesbania and alnus treatments ($P < 0.001$), in which values were 12–36 % greater than after low rainfall. There was again a significant treatment x rainfall interaction on the lower terrace ($P < 0.05$), where mean profile θ_w differed little between treatments when rainfall was <20 mm but was much greater in the alnus treatment when rainfall was >20 mm ($P < 0.001$). Mean θ_w in the tree-based treatments was between 6 % (tree mixture) and 50 % greater (alnus) after high rainfall compared to 10 % in the sole crop treatment.

Fig. 4 Profiles of volumetric soil water content (θ_w) in the unpruned tree treatments and sole bean crop for the upper (**a**, **b**), middle (**c**, **d**) and lower (**e**, **f**) terrace following periods of low (**a**, **c**, **e**) or high (**b**, **d**, **f**) rainfall (<20 mm and >20 mm respectively). **g** Mean θ_w values for the entire profile. In **a**–**f**, SED^1, SED^2 and SED^3 respectively show values for comparing land use systems, soil depths and the land use system × treatment interaction. *, ** and *** denote $P < 0.05$, $P < 0.01$ and $P < 0.001$; *NS* no significant effect



(g)

	Weekly rainfall <20 mm			Weekly rainfall >20 mm		
Treatment	**Upper**	**Middle**	**Lower**	**Upper**	**Middle**	**Lower**
Sole crop	20.5	21.9	26.5	22.3	24.6	29.1
Alnus	19.5	21.9	24.9	29.8	28.2	37.3
Calliandra	19.1	20.6	25.4	25.1	25.5	27.8
Sesbania	22.7	25.9	25.7	27.7	29.1	27.4
Tree mixture	18.9	20.5	25.1	19.9	22.5	26.6
SED	1.2***	1.2***	1.5**	1.4***	1.1***	1.3***

The effect of root + shoot pruning the trees on the upper terrace on mean profile θ_w within the cropping area on the lower terrace was greatest for the tree mixture (Table 3), in which θ_w was increased by *c.* 43 % at distances of 2 and 6 m from the tree line compared to unpruned trees ($P < 0.001$). Pruning of alnus increased θ_w by 14 % 2 m from the tree line ($P < 0.05$), but had no effect at 6 m; pruning of calliandra and sesbania had no detectable effect at either distance.

Discussion

Tree growth and potential competitive impact

Mean tree height and diameter at breast height (dbh) 36 months (alnus, calliandra) or 30 months after planting (sesbania) were respectively 7.1 m and 7.2 cm, 6.8 m and 5.3 cm, and 5.1 and 4.4 cm for unpruned alnus, sesbania and calliandra trees (Siriri

Table 3 Effect of root and shoot pruning of the tree row adjacent to the cropping area on volumetric soil water content (θ_w) 2 m and 6 m from the tree line

Treatment on upper terrace	Volumetric water content (cm^3 cm^{-3})					
	2 m from tree row			6 m from tree row		
	Root + shoot pruned	Unpruned	SED	Root + shoot pruned	Unpruned	SED
Alnus	25.3 ± 0.7	22.1 ± 0.9	1.2*	31.0 ± 1.0	29.9 ± 1.3	1.8^{NS}
Calliandra	18.6 ± 0.9	19.8 ± 0.6	1.2^{NS}	26.8 ± 1.1	26.2 ± 1.1	1.6^{NS}
Sesbania	26.7 ± 0.9	29.4 ± 1.3	1.6^{NS}	27.2 ± 0.7	29.0 ± 1.0	1.2^{NS}
Tree mixture	26.6 ± 1.1	18.5 ± 0.8	1.5***	31.7 ± 0.9	22.3 ± 1.0	1.2***

Single standard errors of the mean (SEM) and standard errors of the difference between treatment means (SED) are shown

*, ** and *** denote $P < 0.05$, $P < 0.01$ and $P < 0.001$

NS No significant effect

et al. 2010). Tree height and dbh were significantly reduced by root + shoot pruning only in alnus, by 15 and 29 % respectively. The trees were therefore sufficiently well established to compete strongly with adjacent crops for above- and below-ground resources unless subjected to appropriate management practices such as root and/or shoot pruning. The presence of unpruned trees is likely to have influenced soil water balance in the adjacent cropping area both directly by abstracting soil moisture and indirectly through microclimatic modifications.

Soil evaporation (E_s)

Trees influence E_s through effects on microclimate and soil water content (Ong et al. 1996, 2006, 2007; Otengi et al. 2007; Lin 2010). The microclimatic factors most likely to be modified are solar radiation receipts at ground level and wind speed (Wallace 1996; Otengi et al. 2007). However, aerodynamic factors such as wind speed are less important in the relatively closed canopies provided by well-established improved tree fallows and rotational woodlots (Ritchie 1972; Wallace and Gregory 2002), with the result that solar radiation is the major factor governing first stage evaporation following rainfall. In the present study, irradiance measured 0.5 m above the soil was reduced by 29–56 % in the tree-based treatments relative to the sole crop treatment on the upper terrace, and by 12–25 % in the cropping zone on the lower terrace (Fig. 3). The results for the upper terrace are consistent with Jackson and Wallace (1999), who found that net radiation, the primary driver of soil surface evaporation, was reduced by ≤65 % in a linear agroforestry system at Machakos in semi-arid Kenya, where incident radiation is generally greater than in the humid African highlands examined here. The variation between tree-based systems reflects their differing canopy structures; thus, the denser canopy of alnus reduced below-canopy irradiance to a much greater extent than the more open canopy of sesbania (Fig. 3).

These differences were reflected by effects on E_s (Fig. 2b), particularly after periods of high rainfall when this process depends primarily on the energy balance at the soil surface, whereas E_s during periods of low rainfall (Fig. 2, Periods 2–4) is determined mainly by soil hydraulic properties (Hillel 1998). The ability of tree-based systems to retain soil moisture is potentially important in affecting E_s; thus, the increase in E_s as a proportion of rainfall between Periods 1 and 2 was greatest for alnus (from 29 to 45 %), possibly because slower depletion of soil moisture during Period 1 following relatively high rainfall increased water supplies to maintain soil evaporation during the drier Period 2. Raussen et al. (1999) reported that soil hydraulic conductivity under alnus woodlots was more than twice that of continuous cropping systems, thereby enhancing infiltration of rainfall.

The mean reduction in E_s in the tree-based treatments relative to sole crops during the rainy season (Periods 1 and 2), ranging between 20 % (tree mixture) and 36 % (alnus), was much greater than during the dry season (Periods 3 and 4) when E_s was similar in all treatments (Fig. 2b). The reductions in E_s in the tree-based systems during the rainy season are greater than reported for a linear agroforestry system containing *Grevillea robusta* in Kenya, where the mean decrease relative to sole maize was 16 % (Jackson and Wallace

1999). This contrast may have occurred because differences in planting arrangement (linear vs. block planting) influenced the intensity and extent of shading. A study of a mulched contour hedgerow system containing maize and cowpea (*Vigna unguiculata* L.) in semi-arid Kenya showed a reduction in E_s of <9 % relative to bare soil (Kinama et al. 2005). Expressed as a percentage of rainfall, E_s was nevertheless high under unmulched maize/senna (*Senna spectabilis* (DC.) H.S. Irwin and R.C. Barneby) and grass strip/maize intercrops (60 and 65 % respectively), suggesting that the improved fallow/rotational woodlot systems examined here were more effective in reducing E_s than linear agroforestry systems. Moreover, spatial variation in E_s in the present study appeared to be greater than in linear agroforestry systems as the microclimatic changes induced by growing trees on the upper terrace reduced E_s by up to 30 % on the cropped lower terrace at distances of up to 6 m from the tree line during Period 1 (Fig. 2b). The similarity of the E_s values obtained when sole crops were planted on both the upper and lower terrace suggests that variation in leaf area index associated with the fertility gradient was too small to affect soil evaporation, implying that the significant reduction in E_s on the lower terrace in the tree-based treatments resulted from microclimatic modifications caused by the presence of trees on the upper terrace. The linear agroforestry system described by Jackson and Wallace (1999) represents an intermediate scenario as the trees strongly influenced E_s at a distance of 0.3 m from the tree line, but not at 2.5 m.

Volumetric soil moisture content (θ_w)

Factors influencing the capacity of tree-based systems to store water include infiltration, soil water evaporation, abstraction by trees and crops, organic matter content and textural characteristics (Ong et al. 2006, 2007). However, the limited literature regarding the importance of these factors for the species examined here precludes comparison with previous studies of soil water storage and microclimate in agroforestry systems, as most have focussed on deep-rooted tree species (Jackson et al. 2000; Lott et al. 2003; Radersma and Ong 2004; Lott et al. 2009) and have rarely examined the short-lived shrubs that are often used in fallows and rotational woodlots. The presence of alnus and sesbania increased θ_w relative to the sole crop control treatment on the upper terrace, but a similar effect was not found for the calliandra and tree mixture treatments (Table 2). This observation reflects the trend for E_s, which was lowest for alnus (Fig. 2b), perhaps because its dense canopy and more intense litterfall reduced both E_s and runoff. The dense undergrowth in the sesbania treatment may have induced similar effects, increasing mean profile values for θ_w. Similar trends were apparent on the middle terrace (Table 2), where mean profile θ_w was greatest in the alnus and sesbania treatments, although there was no evidence of the further increase in θ_w between the middle and lower terrace that had been anticipated in view of the greater soil depth at the latter location (Fig. 1; Table 2). This observation suggests that the ability of trees grown on the upper terrace to modify soil hydrological properties in ways that improve water storage on the upper and middle terrace does not extend to the lower terrace.

The observed beneficial influence of sesbania contrasts with reports that θ_w in the topsoil was lower in improved fallows containing sesbania than under sole maize (Hartemink et al. 1996). This effect was attributed to aggressive water abstraction by sesbania, whereas water conservation by sesbania in the present study appeared to outweigh losses resulting from abstraction by roots. However, although E_s was lower in the calliandra treatment than under sole crops (Fig. 2b), mean profile θ_w values were similar in both treatments following periods of both high and low rainfall (Fig. 4g), suggesting that greater lateral extension of its roots into the cropping area compared to the other tree species examined created a more extensive spatial hydrological influence. Siriri et al. (2010) noted that calliandra depressed crop yield for distances of up to several metres from the tree line, supporting evidence that the roots of this species are highly versatile and may extend over considerable lateral and vertical distances (Hairiah et al. 1992). Inclusion of calliandra in the tree mixture may have been responsible for the significant reduction in θ_w relative to the sole crop control treatment, supporting the supposition that, although E_s was reduced (Fig. 2b), the water saved was absorbed by its extensive root system. Nevertheless, calliandra is widely used for fodder by farmers in Kabale despite its competitiveness with crops (Nyeko et al. 2004).

When rainfall was <20 mm during the week preceding measurements, mean profile θ_w was greater in the tree-based treatments than in the sole crop control only for sesbania (Fig. 4g), perhaps because transpiration was lower than in the other tree species, or because its bushy growth habit reduced E_s. When rainfall was >20 mm, mean θ_w was greatest in the sesbania and, especially, the alnus treatments, perhaps because the mulching effect of the greater litter deposition increased infiltration. A further possibility is that the misty conditions encountered in the morning during the rainy season due to the low air temperature and high humidity allowed trees to trap additional moisture in the form of dew on their canopy, in a manner analogous to cloud forests; some species may be more effective than others in channelling this source of moisture to the soil due to differences in crown architecture.

The observation that root + shoot pruning of alnus and the tree mixture increased θ_w on the lower terrace, but had no detectable effect in the calliandra and sesbania treatments (Table 3) reflects the finding that pruning the latter two species did not improve crop performance, although for different reasons (Siriri et al. 2010). The lack of any crop yield response to root + shoot pruning sesbania during five cropping seasons when beans or maize were grown substantiates the absence of any adverse effect of unpruned trees on θ_w in the adjacent cropping area; indeed, the presence of unpruned sesbania on the upper terrace increased values for θ_w in the cropping area, whereas unpruned calliandra trees competed strongly for water and reduced θ_w on the lower terrace and the yield of bean and maize crops by *c*. 40 % over six cropping seasons during which rainfall varied greatly (Siriri et al. 2010). The pruning intensity used here may have been insufficient to control competition effectively; thus, a more extreme management regime than annual root pruning to 30 cm depth when the trees were young and 50 cm when they reached 3 years of age may be required for calliandra.

Conclusions

Previous studies of the effectiveness of root and/or shoot pruning in controlling competition by tree fallows grown on the upper section of bench terraces in Uganda showed that unpruned sesbania had little impact on crop yield on the lower terrace, whereas pruning of alnus and, especially, calliandra was vital to maintain crop yield (Siriri et al. 2010). The present study has revealed that some tree species have beneficial effects on E_s and θ_w in the adjacent cropping area and that the effects of pruning on crop yield were associated with reductions in E_s and increases in θ_w. The presence of sesbania or alnus on the upper terrace increased θ_w on both the upper and lower terrace, whereas calliandra tended to reduce θ_w for all terrace positions; the presence of trees greatly reduced E_s compared to sole crops following periods of high rainfall. Root + shoot pruning of the tree mixture and alnus increased θ_w in the cropping area compared to unpruned trees, but had no significant effect in the other tree-based treatments. Sesbania and alnus may be incorporated into smallholdings without compromising water supplies to adjacent crops, but the extensive lateral rooting of calliandra deprived adjacent crops of water even though E_s was reduced.

The use of tree fallows on the upper section of bench terraces is recommended for soil fertility improvement and production of valuable tree products on steep hillslopes in East Africa, and such approaches may be more widely applicable throughout the semi-arid and sub-humid tropics. The key is to identify appropriate species and management practices that enhance crop yield on the lower terrace while enabling tree products to be harvested from the upper terrace.

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