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Tree species and pruning regime affect crop yield on bench terraces in SW Uganda

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Abstract

Integration of trees on farms may exert complementary or competitive effects on crop yield. This four year study examined novel systems in which *Alnus acuminata* (alnus), *Calliandra calothyrsus* (calliandra), *Sesbania sesban* (sesbania) or a mixture of all three were grown on the degraded upper part of bench terraces in Uganda; beans or maize were grown on the more fertile lower terrace during the short and long rains. Three pruning treatments (shoot, root or shoot+root pruning) were applied to the tree rows adjacent to the crops; shoot prunings were applied as green manure to the woodlot from which they came. Pruning increased survival in calliandra and reduced survival in sesbania; alnus was unaffected. Pruning reduced tree height and stem diameter in alnus, but did not affect calliandra or sesbania. Maize yield adjacent to unpruned calliandra, alnus and sesbania or a mixture of all three was reduced by 48, 17, 6 and 24 % relative to sole maize. Shoot pruning initially sustained crop performance but shoot+root pruning became necessary when tree age exceeded two years; shoot+root pruning increased maize yield by 88, 40, 11 and 31 % in the calliandra, alnus, sesbania and tree mixture systems relative to unpruned trees. Bean yield adjacent to unpruned calliandra, alnus, sesbania and the tree mixture was 44, 31, 33 and 22 % lower than in sole crops and pruning had no significant effect on crop yield. The results suggest that sesbania fallows may be used on the upper terrace without reducing crop yield on the lower terrace, whereas pruning of alnus is needed to sustain yield. Calliandra woodlots appear to be unsuitable as crop yield was reduced even after pruning.

Introduction

Increasing populations in the African highlands have caused traditional shifting cultivation to be abandoned in favour of intensive farming (Ong et al. 2006, 2007). However, this process has not been accompanied by increased mechanisation or fertiliser use (Swinkels et al. 1997), causing serious degradation of natural resources and a decline in *per capita* food production (Sanchez et al. 1997). As average land holdings decrease, farmers cannot afford to allocate separate areas to grow crops and trees. In such cases, agroforestry may provide a viable alternative to sustain productivity on smallholder farms while supplying a range of tree products. This is particularly important in south-western Uganda, where crop yield is <35 % of potential production and there is an estimated 40 % shortfall in wood supply (Siriri and Bekunda 2004); similar problems occur throughout the semi-arid and sub-humid tropics. The present study examined novel systems in which the degraded upper third of terraces on steep hillsides was planted with trees, while the lower terrace was used for crop production.

Incorporation of trees on cropland may enhance productivity by increasing nutrient input through nitrogen fixation (Sanginga et al. 1995; Sun et al. 2008), spatial and/or temporal complementarity in resource capture by trees and crops (Ong et al. 2006, 2007), increased infiltration and storage of water (Wallace 1996; Sun et al. 2008), maintenance of, or increases in, soil organic matter (Schroeder 1995; Sun et al. 2008), reduced nutrient losses by erosion and leaching (Sun et al. 2008) and improved soil physical properties and biological activity (Yamoah et al. 1986). Agroforestry technologies promoted in East Africa include improved fallows containing *Sesbania sesban* and rotational woodlots of *Calliandra calothyrsus* or *Alnus acuminata* (Siriri and Raussen 2003). These aim to improve soil fertility and provide valuable tree products by planting trees on the upper section of bench terraces which have become degraded following repeated scouring during heavy rain and regular down-slope cultivation (Agus et al. 1997). Planting trees on the upper terrace is a recommended rehabilitation practice (Raussen et al. 1999; Siriri and

Raussen 2003) which allows cropping to continue on the more fertile lower terrace. Contour planting of trees has also proved successful in limiting runoff and erosion and improving fertility on hillslopes under a wide range of climatic conditions in China (Sun et al. 2008).

However, agroforestry does not always provide a solution, as negative interactions may occur due to competition with adjacent crops (Ong et al. 2006, 2007; Sun et al. 2008). Some reports suggest there is little competition on bench terraces due to spatial or temporal separation of the trees and crops (Cooper et al. 1996), although farmers have reported that trees may compete with adjacent crops (Wajja-Musukwe et al. 1997; Sun et al. 2008). This is important as crop production on the lower terrace is vital for food security during the first 2-3 years after planting while farmers await the benefits of trees grown on the upper terrace. Effective strategies are needed to minimise adverse tree-crop interactions on terraced land.

Schroth (1999) suggested two options to enhance complementarity: (i) selection of trees with characteristics which minimise competition; and (ii) management to limit their competitive impact. Characteristics which limit competition do not always coincide with the intended use of trees by farmers, for example, when timber production or revenue generation from the sale of greenhouse gas credits (TIST 2008) are key objectives. When farmers' needs and ecological compatibility conflict, understanding and appropriate manipulation of the underlying processes are essential. Root and/or shoot pruning may be used to control the competitive impact of trees (Ong et al. 2002, 2006, 2007; Bayala et al. 2008). In semi-arid Kenya, Jackson et al. (2000) showed that severe shoot pruning reduced water use by trees, improving recharge of the crop rooting zone, while Jones et al. (1998) found that shoot pruning of *Prosopis juliflora* in semi-arid Nigeria reduced below-ground competition with sorghum. Chandrashekara (2007) recommended shoot pruning regimes and frequencies for 10 important tree species in humid Kerala, India to limit competition with understorey crops. The present study examined the role of root and/or shoot pruning as management tools to reduce the competitiveness of trees on terraces in sub-humid Uganda. The objectives were to determine (i) the impact and spatial extent of competition between trees on the upper terrace and adjacent crops, and (ii) the effectiveness of root and/or shoot pruning in controlling deleterious effects on crop yield.

Materials and methods

Kabale District, SW Uganda, experiences bimodal rainfall of *c*. 1000 mm yr^{-1}, which is generally greater and more evenly distributed during the long (September-February) than the short rains (April-June). Most land is steeply terraced to control runoff and erosion; these are 15-20 m wide with a rise of *c*. 1.5 m between terraces. Agriculture involves small-scale arable farming, with sorghum, maize, beans, peas and sweet and Irish potatoes as the main crops. This study took place at Kigezi High School (1^o 15’ S, 29^o 55’ E, altitude 1850 m), where the mean slope of terraces is *c*. 8 %. The soils are haplic ferralitic sandy clay loams developed from phyllite parent material. Topsoil analysis (0-15 cm) showed that mean pH was 6.5 and clay content decreased from 37.4 to 27.1 % between the upper and lower terrace ($p<0.05$; Siriri and Raussen, 2003). Organic matter was very low but increased from 1.11 to 1.31 g kg^{-1} between upper and lower terrace, suggesting that N supplies were limiting, though this was not specifically determined. Bicarbonate EDTA extractable phosphorus and exchangeable potassium concentrations were 27-36 mg kg^{-1} and 0.48-0.54 mol_c kg^{-1} respectively; P values decreased between the upper and lower terrace.

A split-plot design with three replicates was used (Fig. 1). Trees were planted in three rows at a density equivalent to 10000 trees ha^{-1} on the upper third of the terrace (6 m wide). Treatments comprised four tree-based systems (sole stands of *Alnus acuminata* Kunth (alnus), *Calliandra calothyrsus* Meissner (calliandra), *Sesbania sesban* (L.) Merr. var. sesban (sesbania) and a mixture of all three species) plus sole crop control plots. These tree species were chosen due to their ability to produce 24-27 t ha^{-1} of fuelwood and *c*. 30 t ha^{-1} of above-ground biomass under the prevailing conditions and their N-fixing capability (Siriri and Raussen 2003). The experimental design was unbalanced because the main plots containing sole crop controls could only accommodate three of the four pruning sub-treatments (Fig. 1), but was as nearly balanced as possible given the prevailing site constraints. Main treatment plots (tree species) on the upper terrace (6 m wide x 26 m long) were randomly allocated in each block. Sub-treatments comprising four management regimes (no pruning, root pruning, shoot pruning and root+shoot pruning) were imposed on the tree row adjacent to the main cropping area on the lower terrace. The other tree rows were not pruned to maximise woody biomass production and reflect the objectives of subsistence farmers. Sub-treatment plots (6 m wide x 5 m long) were randomly allocated in each main treatment. Sole crops were grown continuously on the lower terrace (12 m wide).

Alnus and calliandra were planted in September 2000 using potted seedlings and sesbania was planted in March 2001 using bare-rooted seedlings. The phased planting ensured that all species could be harvested simultaneously as sesbania, a shrubby species, matures sooner than calliandra and alnus, which are both trees. A single row of each species was planted in the tree mixture. Based on previous studies (Siriri and Raussen 2003), the least competitive species, sesbania, was situated adjacent to the crops, calliandra was planted in the central row, and alnus, believed to be the most competitive, was grown furthest from the crops. Main and sub-plots were separated by 4 and 2 m wide walkways to provide access and minimise interference (Fig. 1).

A relatively mild pruning regime was chosen as a compromise between effective control of competition and maximum production of woody biomass and green manure for soil improvement. Pruning was implemented simultaneously for all tree species when calliandra and alnus were 12 months old and sesbania was six months old to avoid compromising the growth of young trees. Shoot pruning involved removing all branches from the lower third of the crown of trees adjacent to the cropping areas on the lower terrace and the sole crop plots on the upper terrace, and was repeated before each cropping season; prunings were returned to the plots from which they came. Root pruning was carried out to a depth of 30 cm when the trees were young and 50 cm when they were over three years old. The former represents a

Table 1 shows land-use systems on the upper and lower terrace for eight cropping seasons between March 2000 and March 2004. In the first year, crops were grown among the trees following traditional practice to maximise output and shorten cropping time lost during tree fallows. As the tree canopies began to close, cropping ceased among the trees but continued on the lower terrace. Cropping followed the normal rotation in Kabale in which beans (*Phaseolus vulgaris cv*. K132) and maize (*Zea mays* L. *cv*. H622) were grown during the short and long cropping seasons. Beans and maize were planted at spacings of 50 x 10 cm and 75 x 30 cm; yields were calculated on a net plot area basis. No inorganic or organic fertilisers were applied.

Tree performance was assessed from observations of survival, height, basal diameter and diameter at breast height (DBH) for all trees in each replicate of all sub-treatments; these observations began in April 2001 and were repeated 24 and 36 months after tree establishment. Crop performance on the lower terrace was assessed in terms of oven-dry grain yield for material harvested from a net plot area (3 x 6 m), leaving a 1 m guard area at the boundary between adjoining pruning sub-treatment plots and at the interface with the trees; row-by-row measurements examined the effect of distance from the trees. Net plot area for sole crop plots on the upper terrace was 3 x 4 m. Freshly harvested grain was dried to constant weight at 80 ^{o}C.

Results were analysed using Genstat (Genstat 5 Release 6.1). As conventional analysis of variance was inappropriate due to the unbalanced experimental design and variability within blocks established by an initial cover crop of beans, the residual maximum likelihood approach (REML) was chosen as this provides reliable estimates of treatment effects in unbalanced designs containing more than one source of error. In Genstat, REML uses linear modelling to analyse variance components and predict means. REML was used to test for significant differences ($p<0.05$) in crop yield between treatments. Standard errors of the difference between means (SED) and standard errors of the mean (SEM) are presented.

Mean values for specific treatments provided by REML may vary depending on how treatments are structured in the analysis, providing an explanation for the differing mean crop yields shown in Tables 2 and 3. Table 2 compares crop yield adjacent to unpruned trees with sole crop plots; as only the unpruned treatment of all tree-based systems was included in the analysis, the main treatment had one level of sub-treatment. The treatment structure (or fixed model) was covariate+main treatment, while the block structure (or random model) was Block/treatment. Table 3 compares crop yields for all pruning treatments and tree species. In this analysis, species and pruning regime represented the main and sub-treatments. The treatment structure (or fixed model) used was covariate+main treatment* sub-treatment; in both cases, the covariate was yield from the cover crop. When the influence of distance from the trees was examined, an additional ‘distance’ factor was incorporated, creating a split-split plot factor within the analysis. Block structure was Block/species/distance while treatment structure was species*distance.

Results

Mean daily maximum and minimum air temperatures during the study period were 24.2 and 11.7 ^{o}C (Fig. 2); maximum values were higher and minimum values lower during the dry seasons (March and July-August) than during the rainy seasons (April-June and September-February). Daily saturation vapour pressure deficit (SD) at 1500 h ranged between 0.76 and 1.79 kPa and was generally greatest during the long dry season; SD at 0800 h was invariably <0.2 kPa.

Tree survival for calliandra and alnus exceeded 90 % and was greater than for the sesbania and mixed tree systems 24 and 36 months after planting ($p<0.001$; Fig. 3a). Survival of sesbania was 81 % at 24 months and 77 % at 36 months; the mixed system was intermediate between the calliandra and alnus systems and sole sesbania. Despite its poorer survival, tree height was greatest in sesbania at 24 and 36 months and lowest in calliandra ($p<0.05$; Fig. 3b); values for alnus and the mixed tree system were intermediate between these treatments.

Figure 4 shows tree height, diameter at breast height (DBH) and survival in the unpruned and shoot+root pruned treatments for the tree row adjacent to the cropping area in the alnus, sesbania and calliandra systems. Although shoot+root pruning was expected to have the greatest impact on tree performance as the most severe management regime, this treatment increased survival in alnus and calliandra 24 months after planting ($p<0.05$; Fig. 4e) but had no effect on sesbania. After 36 months, survival was unaffected by shoot+root pruning in alnus but was increased in calliandra and decreased in sesbania relative to unpruned trees ($p<0.01$; Fig. 4f). Mean tree height at 24 months was greatest in sesbania ($p<0.01$), but decreased slightly between 24 and 36 months (Fig. 4a, b) due to dieback and death of some trees, whereas height in alnus increased ($p<0.001$); calliandra was shortest at both sampling dates. Pruning reduced height in alnus at both sampling dates ($p<0.05$) but had no detectable effect on calliandra or sesbania. Similarly, DBH did not differ significantly between species at 24 months (Fig. 4c) but was greater in unpruned than in shoot+ root pruned alnus at 36 months ($p<0.05$; Fig. 4d).

Crops grown among young trees on the upper terrace during the first two seasons after planting the trees showed differing responses. Maize yield at maturity during the 2000/1 long rains did not differ significantly between sole crop and agroforestry systems, although values were invariably slightly lower in the latter. However, the yield of sole beans during the 2001 short rains was approximately twice that in the agroforestry systems even though planting densities were identical ($p<0.001$; results not shown).

Table 2 shows crop yields on the lower terrace adjacent to unpruned trees grown on the upper terrace for six seasons excluding the 2003 short rains when poor rains caused crop failure. Maize yield on the lower terrace was not affected by the presence of trees during the 2000/1 long rains, whereas bean yield was reduced by 39, 37, 24 and 18 % relative to the sole crop in the sesbania, calliandra, alnus and mixed tree systems during the 2001 short rains ($p<0.05$). Maize yield during the 2001/2 long rains was reduced by >50 % in the calliandra treatment, but by only 2 and 12 % in the sesbania and alnus systems. Similar trends occurred in the 2002 short and 2002/3 long cropping seasons and yield losses increased with time in the calliandra and alnus treatments. By contrast, maize yield was greatest in the sesbania system during the 2002/3 and 2003/4 long rains, when the trees were over two years old. The impact of the mixed tree system was comparable to alnus in all seasons.

Row-by-row analysis of crop yield was used to assess spatial variation in crop performance on the lower terrace adjacent to unpruned trees at distances up to 6 m for maize and 4 m for beans (Fig. 5). Sampling distances differed because waterlogging of the lower terrace associated with its concave profile adversely affected the growth of beans, but not maize. Yield increased with distance from the trees in all treatments and seasons ($p<0.001$) and sole crop yield also generally increased between the upper and lower terrace. Crop yield was reduced within 3 m of alnus and calliandra in all seasons ($p<0.001$) but was similar to or exceeded that of sole crops at all distances from sesbania during the 2002/3 and 2003/4 long rains (Fig. 5d, e). The tree species*distance interaction was significant during the first 18 months after tree establishment (2001 short and 2001/2 long rains) but not during the 2002 short and 2002/3 long rains as the trees grew larger, but again became significant during the 2003/4 long rains, when the trees were three years old.

Pruning alnus and calliandra generally increased maize yield ($p<0.05$-0.001; Table 3) although there was no consistent difference between pruning treatments. Root+shoot pruning became increasingly effective as the trees aged ($p<0.05$). Maize benefitted more from root pruning than shoot pruning of alnus at 18 months, but the reverse applied at 30 months. Pruning sesbania did not improve crop yield except for maize in the root+shoot pruning treatment of sole sesbania and the mixed tree system during the 2003/4 long rains. Pruning provided no significant benefit for beans in either of the seasons examined.

Discussion

Monthly rainfall was greatest during the first half of the long rains (September-November) in all four years (Fig. 2). Daily maximum SD did not exceed 1.8 kPa, reflecting the humid environment of tropical highland areas such as Kabale. Seasonal trends for daily maximum air temperature showed less variation than those for minimum temperature; maximum values were greatest and minimum values lowest during the dry seasons due to the greater radiative exchange associated with limited cloud cover.

Tree survival was lower in sesbania than in alnus or calliandra 24 and 36 months after planting, but height was greatest in sesbania (Fig. 3). Unlike alnus and calliandra, which are trees, sesbania is a short-lived deciduous shrub (Katende et al. 1995). Although some reports suggest 12-18 months is sufficient to reach maturity (Kwesiga and Coe 1994), there is no universal recommendation for its optimal growth period as this depends on planting pattern and density and farmers' objectives. The growth period used here may have exceeded the optimum for sesbania in improved fallows, increasing mortality. The increased survival of calliandra after pruning (Fig. 4) reflects responses seen in previous studies in which pruning young trees enhanced survival and biomass production, whereas older trees showed increased mortality due to their lower re-growth capacity (ICRAF 1994). Although shoot pruning of alnus has been linked to increases in stem diameter and advocated as a strategy for improving timber production in Kabale (Sande 2002), root+shoot pruning reduced tree height and DBH in the present study (Fig. 4), and hence woody biomass production. In humid Kerala, Chandrashekara (2007) reported that shoot pruning may increase annual branch and foliage production without affecting DBH, even under more severe pruning regimes than applied here. This contrast may reflect differences in tree age, soil depth and fertility and pruning frequency.

The absence of significant yield reductions when maize was intercropped with trees on the upper terrace during the 2000/1 long rains suggests that crops may be integrated with trees during establishment of agroforestry systems, particularly when tall species such as maize, which compete effectively for above-ground resources, are used. The observation that the more rapid initial growth of alnus relative to calliandra tended to depress crop yield ($p<0.01$) contrasts with reports that alnus is less competitive than other tree species (ICRAF 1995). Bean yield in the agroforestry systems was approximately half that of sole crops ($p<0.001$) during the 2001 short rains when the tree canopies began to close, shading understorey crops. Crop performance may also have been affected by competition for water (Lott et al. 2000) as rainfall was lower than in the 2000/1 long rains (Fig. 2).

Maize yield on the lower terrace was unaffected by unpruned trees on the upper terrace during the 2000/1 long rains (Table 2) as the trees were still too young (*c*. 6 months) to influence associated crops. Lott et al (2000) reported a similar lack of effect during establishment of systems containing *Grevillea robusta* and maize in semi-arid Kenya, although the competitive influence of trees increased as they grew larger and was closely correlated with rainfall. Sesbania was most competitive during the 2001 short rains (Table 2) but subsequently lost leaves, reducing competition with associated crops; maize yield in the sesbania system was similar to or greater than in sole maize during the 2001/2, 2002/3 and 2003/4 seasons. Bean yield was also greatest in the sesbania treatment during the 2002 short rains.

Seasonal variation in climatic conditions influenced the impact of trees, particularly during the 2002 short rains, when crop yield was lower in all tree-based systems than in sole crops ($p<0.05$; Table 2). Siriri and Raussen (2003) noted that the differing effects of various tree species on crop performance was less obvious in low rainfall seasons, suggesting that water use differs little between tree species when water supplies are limited as their optimal requirements are not being met, whereas inter-specific variation in the regulation of transpiration becomes important when water is freely available.

The marked increase in crop yield with distance from unpruned trees in all seasons (Fig. 5) illustrates their potentially detrimental impact, although it should be noted that this trend resulted not only from the decreasing competitive influence of the trees, but also from increasing fertility across the terrace (Raussen et al. 1999; Siriri and Raussen 2003). The latter is evident from the increase in sole crop yield with distance from the notional tree line for all except the 2001 short rains. A possible explanation for the observation that the tree species*distance interaction was significant during the first 18 months after tree establishment (2001 short and 2001/2 long rains), but disappeared during the 2002 short and 2002/3 long rains is that the root systems of all tree species increased in size with time, extending their influence over an increasing proportion of the lower terrace and eliminating the species differences initially observed. The reappearance of a significant species*distance interaction during the 2003/4 long rains, when the trees were three years old, may reflect their contrasting growth characteristics. While sesbania was shedding leaves and showed stem dieback, unpruned calliandra and alnus trees were extending their canopies and shading adjacent crops; the roots of unpruned trees may also have extended further into cropping area, increasing the intensity of below-ground competition.

Figure 5 suggests that calliandra requires careful management as almost complete crop failure occurred within 4 m of the trees during the 2002/3 and 2003/4 long rains. Crop yield adjacent to unpruned trees generally decreased with time, probably due to increased competition and declining soil fertility caused by continuous cropping on the lower terrace without addition of inorganic fertiliser or green manure, supporting previous reports of the unsustainability of traditional continuous cropping systems (Siriri and Raussen 2003). However, it should be noted that suitably managed rotational woodlots on the degraded upper terrace benches may provide valuable services for subsistence farmers, including provision of timber, poles, fuelwood, fodder and mulch without seriously compromising food production, as the upper terrace provides only 5-10 % of total yield when the entire terrace is planted with maize or beans. When woodlots on the upper terrace are harvested, cropping may resume until improvements in soil conditions produced by the trees are exhausted, when the cycle recommences (Siriri and Raussen 2003).

Root, shoot or root+shoot pruning of alnus and calliandra generally increased crop yield on the lower terrace relative to unpruned treatments for maize but not for beans (Table 3); the beneficial influence of pruning generally ranked in the order alnus>calliandra>tree mixture>sesbania. The yield advantage of pruning calliandra and alnus increased as the trees grew larger and competition increased. The results suggest that shoot pruning provides an effective management strategy to limit the competitive impact of alnus on associated crops but root+shoot pruning is required for calliandra. The limited yield improvement provided by pruning sesbania is unlikely to be attractive as the labour input required would negate any economic benefit.

The modest crop yield responses observed may reflect the conservative tree shoot pruning regime adopted relative to those advocated by Chandrashekara (2007) in Kerala, i.e. removal of 50-90 % of the canopy; the present pruning regimes were designed to minimise labour requirements and avoid compromising production of fuelwood and green manure for soil improvement. As only the lower third of the canopy was removed from the tree row adjacent to sole crops, this may have been insufficient to eliminate competition for light. Jackson et al. (2000) noted that a similar pruning regime produced no significant improvement in maize yield in systems containing *Grevillea robusta* in Western Kenya. Moreover, the trees were pruned prior to the cropping season, compared to four times annually recommended for systems containing *Senna spectabilis* and maize in Eastern

Kenya (Namirembe *et al*., 2009); nevertheless, the results show that relatively mild shoot pruning of alnus and calliandra may increase maize yield, while root pruning induced significant responses even when a shallow pruning depth was used to ensure this could be achieved using the hoes readily available to subsistence farmers for land preparation and maintenance.

Interactions between tree species, pruning regimes and effects on associated crops have been reported previously in the semi-arid and sub-humid tropics. Thus, Jones et al. (1998) found that removal of half of the crown of *Prosopis juliflora* trees grown at 5 m spacings in semi-arid Nigeria reduced their competitive impact on sorghum and increased grain yield at all distances from the trees, whereas pruning of *Acacia nilotica* had little effect; crown pruning not only decreased competition for above-ground resources, but also reduced root length density in *P. juliflora* and competition for below-ground resources. The reductions in root length density in *P. juliflora* were accompanied by corresponding increases in sorghum, tipping the balance of below-ground competition in favour of the crop component. Root pruning of *G. robusta* and *A. acuminata* in semi-arid Kenya to a depth of 0.6 m at a distance of 0.5 m from the tree rows decreased rooting density in the surface soil horizons and greatly reduced water use for nine months after pruning (Ong et al. 2007). The reduction in sap flow was most pronounced when transpiration was greatest, especially in the more rapidly transpiring grevillea; daily transpiration rates nine months after pruning were reduced by 25-35 % in root-pruned trees of both species. However, Wajja-Muskwe et al. (2008) reported that root pruning five years after planting various tree species, including *A. acuminata*, on deep soils in humid Uganda improved crop yield by 10 % within 0-7 m of the tree rows but reduced yield on the unpruned side of the tree rows, with the result that there was no overall benefit. Thus, whilst root pruning at the interface between trees and crops on terraces was effective in the present study, the application of one-sided pruning in other systems may simply redirect competitive interactions.

Conclusions

Previous research suggests that shoot pruning reduces above-ground competition and may limit competition by inducing root mortality and redirecting the partitioning of assimilates in favour of shoot regrowth during crop establishment. The present study shows that short-lived sesbania fallows may be grown on the upper section of terraces with little impact on crop yield on the lower terrace, although pruning of alnus and calliandra was essential to sustain crop yield. Root+shoot pruning was generally effective in controlling competition, whereas the relatively light shoot pruning imposed was ineffective for calliandra. As expected, the tree mixture had intermediate effects on crop yield. The relatively mild pruning regimes used did not entirely eliminate competition between trees and crops, and beans were more sensitive than maize. The contrasting responses of these species may reflect differing growth conditions during the short and long rains as the lower rainfall and its poorer distribution in the former may have restricted the ability of beans to respond to reduced competition induced by pruning. As the impact of pruning on tree/crop interactions differs between species, careful selection and management are vital to determine the success of agroforestry systems, particularly when water supplies are limiting.

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Table 1. Land-use systems used on the upper and lower terrace sections during eight consecutive cropping seasons at Kabale, Uganda.

Terrace position	**Land use system and cropping season**							
	2000 short rains	**2000/1 long rains**	**2001 short rains**	**2001/2 long rains**	**2002 short rains**	**2002/3 long rains**	**2003 short rains**	**2003/4 long rains**
Upper	*Beans	Trees+maize	Trees+beans	Trees	Trees	Trees	Trees	Trees
Lower	*Beans	Maize	Beans	Maize	Beans	Maize	Beans (failed)	Maize

↑ Alnus & calliandra planted

↑ Sesbania planted

*Initial crop to characterise site variability; results were used as a covariate for statistical analysis of data for all subsequent seasons

Table 2. Impact of unpruned trees grown on the degraded upper terrace bench on crop yield at maturity on the more fertile lower terrace at Kabale, Uganda.

	Cropping season					
	2000/1 long rains	**2001 short rains**	**2001/2 long rains**	**2002 short rains**	**2002/3 long rains**	**2003/4 long rains**
Treatment	Maize yield [kg ha^{-1}]	Bean yield [kg ha^{-1}]	Maize yield [kg ha^{-1}]	Bean yield [kg ha^{-1}]	Maize yield [kg ha^{-1}]	Maize yield [kg ha^{-1}]
Alnus	3029	947	2178	308	866	1570
Calliandra	2926	781	1202	239	199	455
Sesbania	ND[a]	757	2418	453	1359	2717
Tree mixture	3131	1015	1978	399	876	1081
Sole crop	3369	1238	2468	579	1300	2105
SED[b]	400^{ns}	140^{***}	347^{***}	128^{*}	378^{**}	760^{**}

[a] ND - No data available as Sesbania was planted in March 2001 (*cf*. Materials and Methods).

[b] SED - standard error of the difference for comparing treatment means; *, ** and *** denote significance at $p<0.05$, 0.01 and 0.001 respectively; ns, not significant).

Table 3. Effect of root, shoot or root+shoot pruning of trees grown on the degraded upper terrace bench on the yield of maize and bean crops grown on the more fertile lower terrace during five cropping seasons at Kabale, Uganda.

	Cropping season				
	2001 short rains	**2001/2 long rains**	**2002 short rains**	**2002/3 long rains**	**2003/4 long rains**
Tree management	Bean yield [kg ha^{-1}]	Maize yield [kg ha^{-1}]	Bean yield [kg ha^{-1}]	Maize yield [kg ha^{-1}]	Maize yield [kg ha^{-1}]
			Alnus acuminata		
Unpruned	984	2191	301	738	1237
Root pruned	812	2246	382	780	1354
Shoot pruned	941	1652	468	1524	1740
Root+shoot pruned	1045	2789	560	1030	2013
SED[a]	124^{ns}	510^{*}	157^{ns}	416^{*}	302^{*}
			Calliandra calothyrsus		
Unpruned	791	1502	296	123	739
Root pruned	832	2699	239	460	620
Shoot pruned	900	1662	360	418	318
Root+shoot pruned	763	2497	346	868	1078
SED[a]	94^{ns}	535^{***}	62^{ns}	225^{**}	192^{***}
			Sesbania sesban		
Unpruned	704	2206	404	1220	2773
Root pruned	783	1862	515	1279	2068
Shoot pruned	849	2039	491	1178	2929
Root+shoot pruned	809	2233	560	1349	3313
SED[a]	158^{ns}	299^{ns}	97^{ns}	231^{ns}	458^{*}
			Tree mixture		
Unpruned	981	1553	347	841	1039
Root pruned	935	1936	476	1231	2033
Shoot pruned	1034	1970	342	644	1047
Root+shoot pruned	1039	1717	482	668	2110
SED[a]	91^{ns}	628^{ns}	152^{ns}	203^{ns}	481^{*}

[a] SED - standard error of the difference for comparing treatment means; *, ** and *** indicate significance at $p<0.05$, 0.01 and 0.01 respectively; ns, not significant.

List of legends

Fig 1 Experimental design: main treatments on upper terrace were sole stands of alnus (Al), calliandra (Call), sesbania (Ss), a mixture of all three tree species and a sole crop control treatment (C). Sub-treatments were shoot pruning (s), root pruning (r), root+shoot pruning (rs) or no pruning (np). Unshaded areas show sole crop control plots (C)

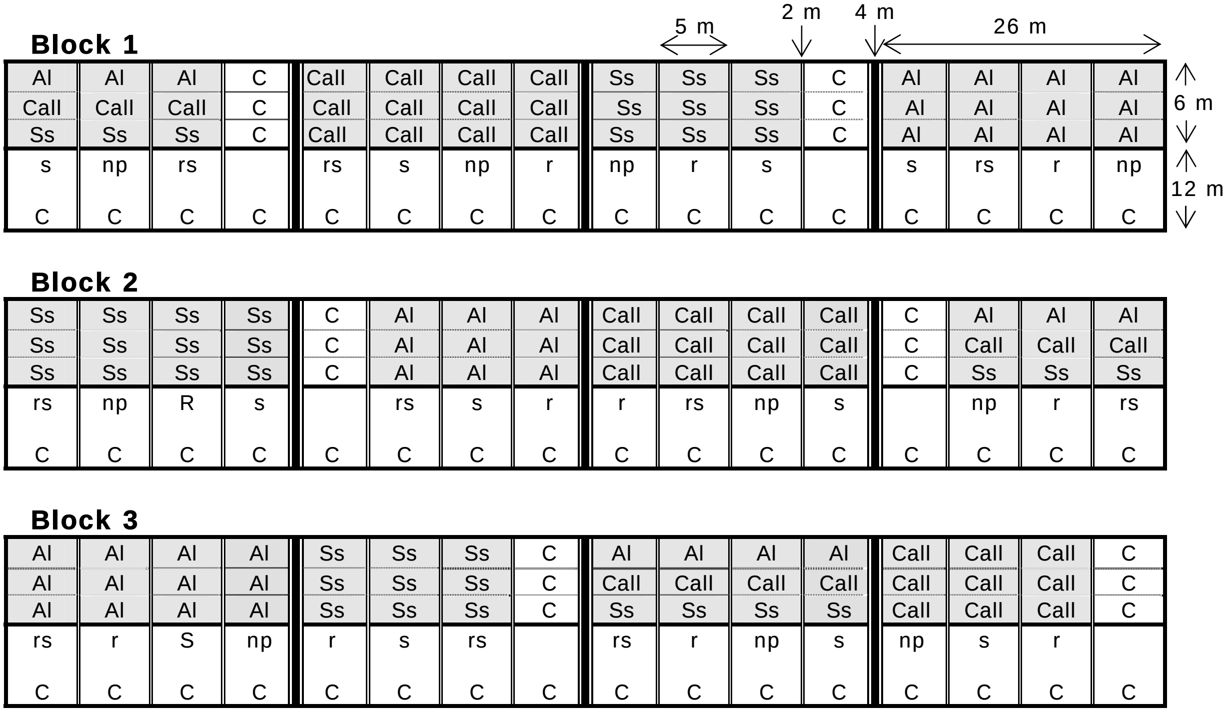
Fig 2 Saturation vapour pressure deficit (SD) at 0800 and 1500 h, maximum and minimum air temperatures and total monthly rainfall during the study period at Kabale, Uganda. Data provided by the Meteorological Department, Kabale District Government

Fig 3 Timecourses of (a) mean tree survival and (b) mean tree height for all trees within the main treatment plots at Kabale, Uganda. Double standard errors of the mean are shown

Fig 4 Effect of root+shoot pruning on mean tree height (a & b), stem diameter at breast height (DBH, c & d) and survival (e & f) for the tree row closest to the cropping area at 24 (a, c, e) and 36 months (b, d, f) after planting at Kabale, Uganda. Single standard errors of the mean are shown

Fig 5 Influence of unpruned trees on yield at maturity of maize and beans at various distances from the trees during the 2001 and 2002 short rains (beans) and 2002/2, 2002/3 and 2003/4 long rains (maize) at Kabale, Uganda. SED denotes standard error of the difference for the species*distance from tree interaction for crop yield

Siriri et al Figure 1



Block 1

Al	Al	Al	C	Call	Call	Call	Call	Ss	Ss	Ss	C	Al	Al	Al	Al
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Ss	Ss	Ss	C	Call	Call	Call	Call	Ss	Ss	Ss	C	Al	Al	Al	Al
s C	np C	rs C	C	rs C	s C	np C	r C	np C	r C	s C	C	s C	rs C	r C	np C

Block 2

Ss	Ss	Ss	Ss	C	Al	Al	Al	Call	Call	Call	Call	C	Al	Al	Al
Ss	Ss	Ss	Ss	C	Al	Al	Al	Call	Call	Call	Call	C	Call	Call	Call
Ss	Ss	Ss	Ss	C	Al	Al	Al	Call	Call	Call	Call	C	Ss	Ss	Ss
rs C	np C	R C	s C	C	rs C	s C	r C	r C	rs C	np C	s C	C	np C	r C	rs C

Block 3

Al	Al	Al	Al	Ss	Ss	Ss	C	Al	Al	Al	Al	Call	Call	Call	C
Al	Al	Al	Al	Ss	Ss	Ss	C	Call	Call	Call	Call	Call	Call	Call	C
Al	Al	Al	Al	Ss	Ss	Ss	C	Ss	Ss	Ss	Ss	Call	Call	Call	C
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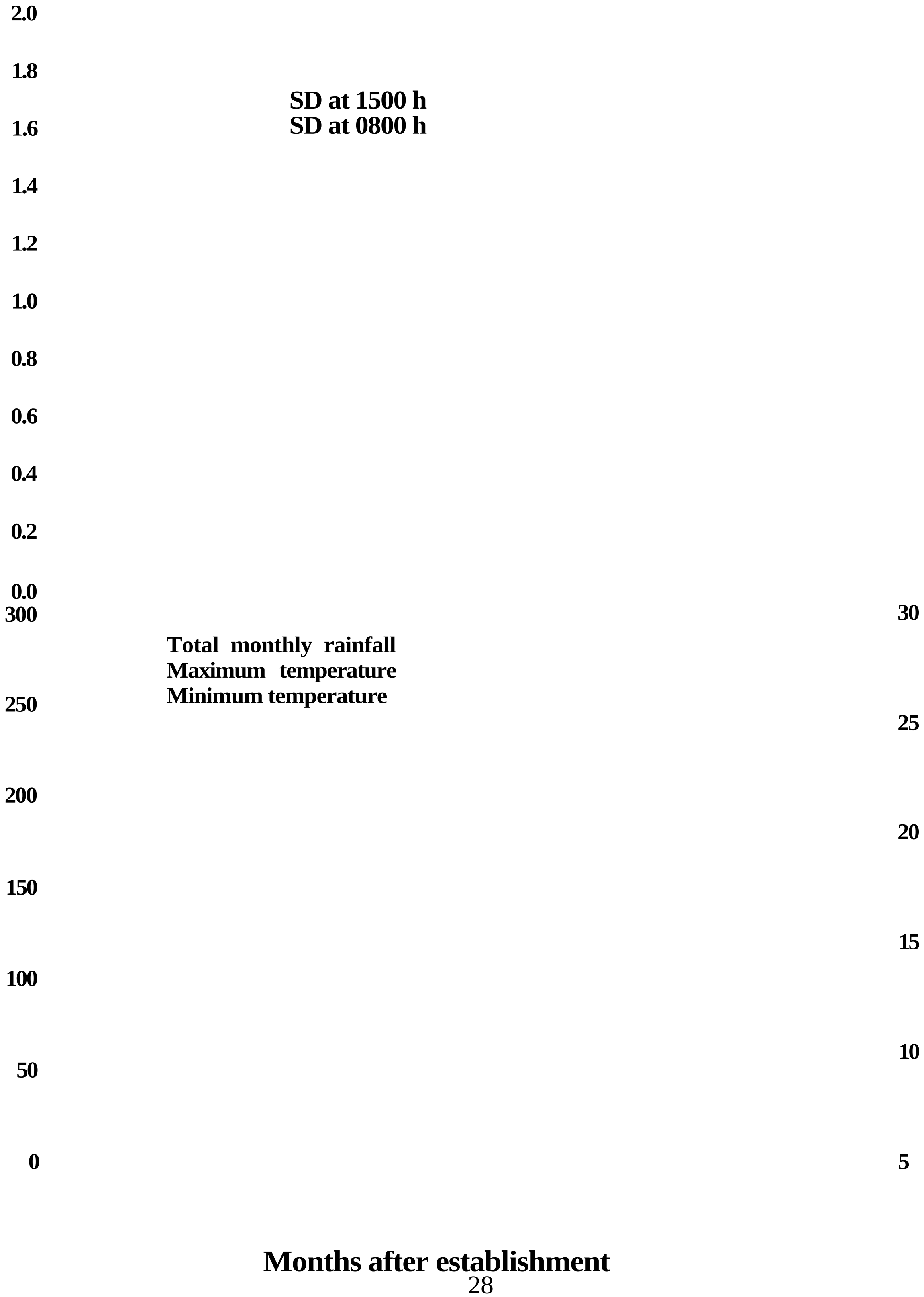
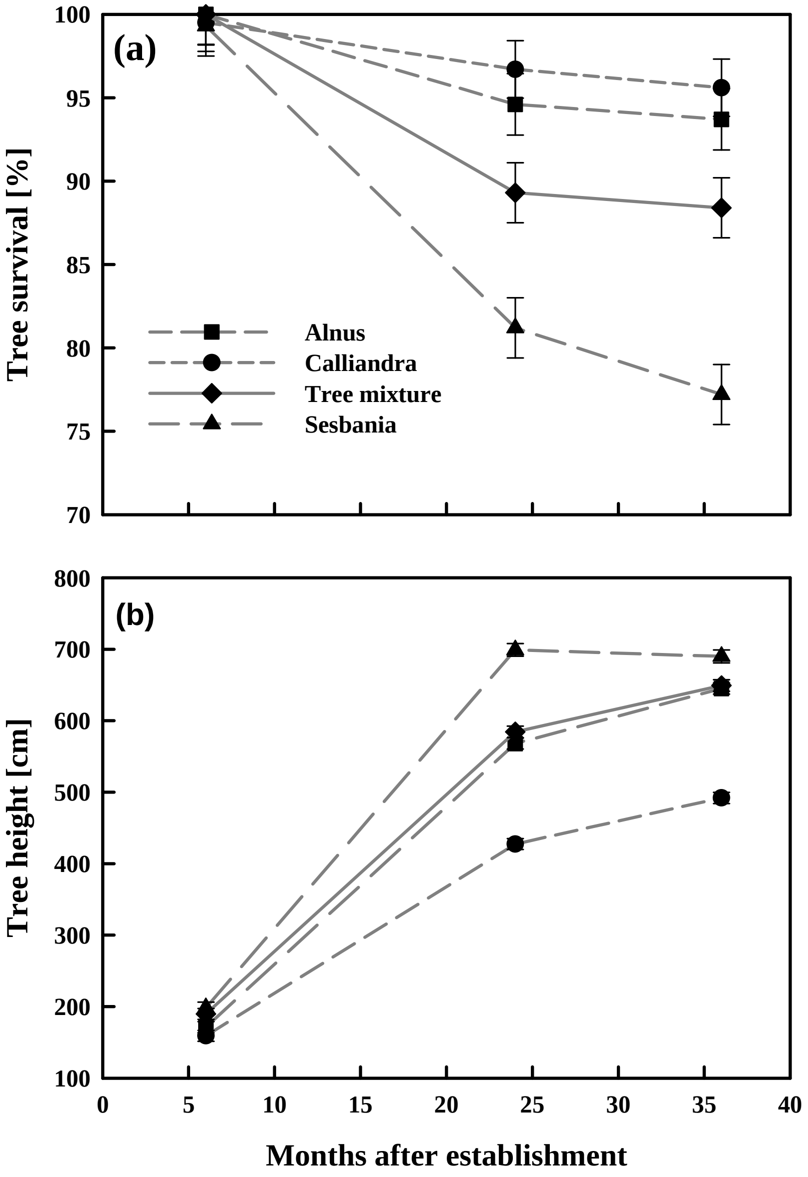
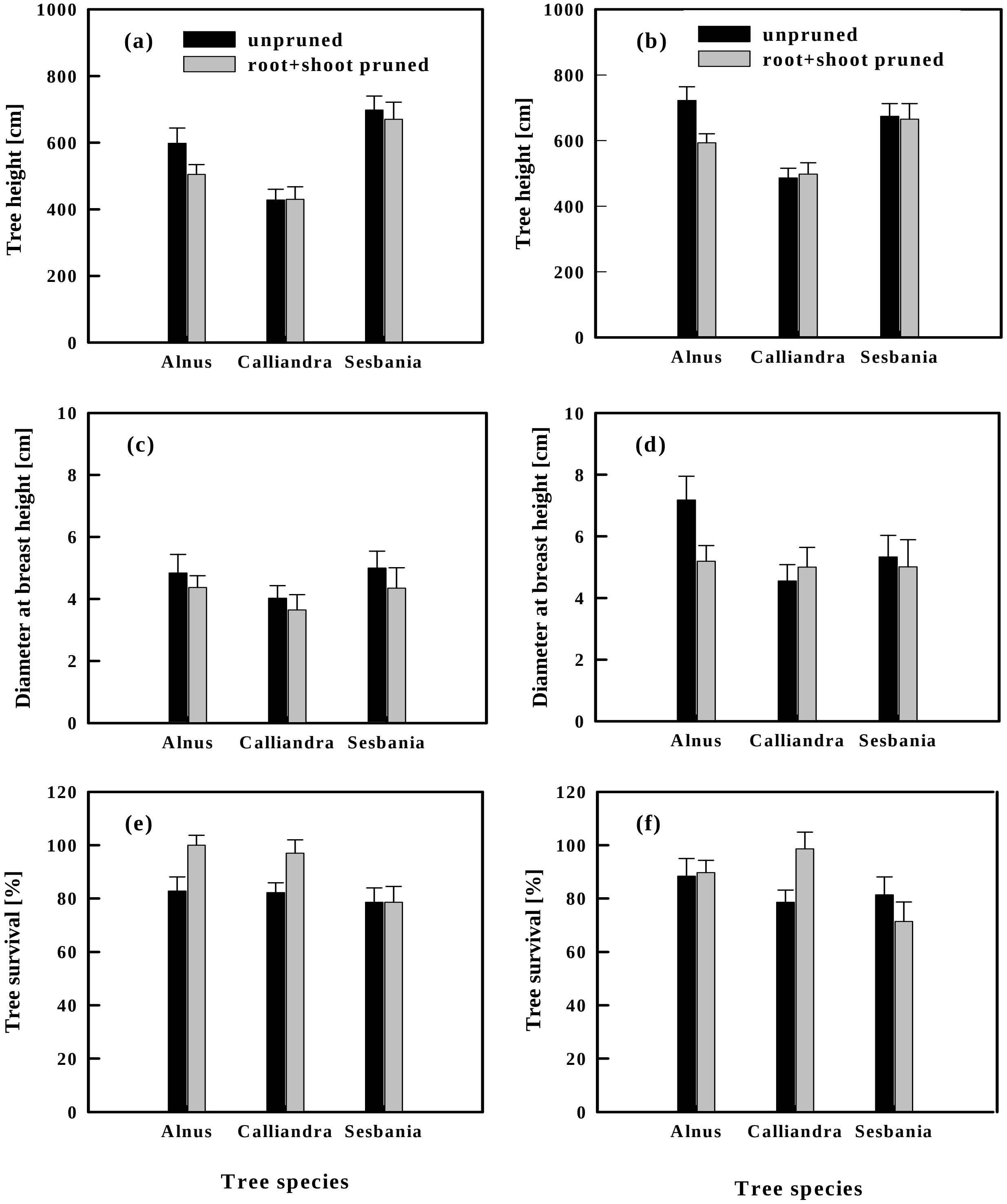
Siriri et al Figure 2



Siriri et al Figure 3



Siriri et al Figure 4



Siriri et al Figure 5