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Tree–crop interactions: manipulation of water use and root function

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Abstract

This paper describes recent research findings on tree–crop interactions in the semiarid tropics focusing on the potential of agroforestry systems to improve the efficiency with which land and water are currently used; the trade-offs between crop productivity and environmental function, and strategies to manipulate tree root function. There is strong evidence that agroforestry has potential for improving water use efficiency by reducing the unproductive components of the water balance, i.e. run-off, soil evaporation and drainage. Examples from India and Kenya show that simultaneous agroforestry systems could double rainfall utilisation compared to annual cropping systems, largely due to temporal complementarity. Where soil loss through erosion is a serious problem, contour hedgerows can provide a viable alternative to conventional soil conservation measures. However, even though soil losses can be dramatically reduced, whether beneficial effects on crops will develop is often unpredictable and usually insufficient to attract widespread adoption of contour hedges. Strategies to reduce the trade-offs between crop and tree interactions or environmental function include the use of high value trees or trees which provide direct benefits to farmers.

Recent reviews on root research indicate that there appears to be limited scope for spatial differentiation in rooting between trees and crops (i.e. spatial complementarity) in water-limited environments, unless ground-water is accessible to tree roots. Instead, it is argued that it is more worthwhile to manage below-ground competition by shoot and root-pruning. Pruning of lateral roots could redirect root function and be a powerful tool for improving spatial complementarity, provided that there are adequate resources at depth. However, the downward displacement of functional tree roots following root-pruning must not be allowed to affect their safety net role in the interception of nutrients leaching from the zone of crop rooting and the long-term hydrological

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implications must not be ignored when attempting to meet demand for trees and their products.

Keywords: Agroforestry; Water use; Root architecture and function; Sap flow; Productivity; Semiarid

1. Introduction

The benefit of deep-rooted vegetation for maintaining ecosystem functioning is a major attraction for using agroforestry for sustainable land and water management in areas where high energy input large scale agriculture is impractical (Kidd and Pimental, 1992). As in Australia, removal of native perennial vegetation and its replacement by shallow-rooted annual crops and pastures in many tropical countries has led to a profound change in the pattern of energy capture by vegetation and to hydrological imbalances. In the Sahel, removal of vegetation with deep roots has led to increased drainage from 10–20 to 200–300 mm per year and leaching of nitrate to the water table (Edmunds, 1991; Deans et al., 1995). On the sandy soils of Niger, unfertilised millet fields utilise only 6–16% of the total rainfall in a watershed and the remainder is lost as run-off, drainage or through soil evaporation (Rockstrom, 1997).

In this paper we review recent evidence of how agroforestry may be able to improve the efficiency with which existing land and water are currently used, with the ultimate aim of achieving sustainability of production and resource use. Because much of the future increase in food and wood production in the tropics, necessary for the needs of increasing populations, will have to be achieved from land and water resources already in use, agroforestry is one of the promising options (Young, 2000). We use examples from the semiarid tropics, where average land holdings are rapidly declining (1–2 ha compared to 1000–2000 ha in Australia) but, unlike Australia where tree rows are 100–200 m apart (White et al., 2002), it is necessary to integrate trees and crops more closely without compromising the already low crop yields. In particular, we focus on recent attempts to manipulate root functions in order to improve spatial complementarity in below-ground resource use and to promote a closer integration of trees and crops.

2. Efficient use of rainfall

Can agroforestry increase productivity through more effective use of rainfall? Cannell et al. (1996) argued that agroforestry may increase productivity provided the trees capture resources which are under-utilised by crops. In annual systems where the land lies bare for extended periods, the residual water remaining in the soil after harvest, and off-season rainfall, are often unused, particularly in areas of unimodal rainfall. For instance, at Hyderabad, India (annual rainfall 800 mm) substantial amounts of water remain available below 50 cm depth after harvesting sorghum (*Sorghum bicolour*) and pigeonpea (*Cajanus cajan*) (Ong et al., 1992) and about 20% of the annual rainfall occurs outside the normal cropping season which could be used by perennial species. The scope for improving water use is, therefore, considerable, because a maximum of 40% of the annual rainfall is utilised by the most effective cropping systems and the remainder of the water is lost as run-off (26%) or deep drainage (33%) (Ong et al., 1992). The hypothesis that agroforestry may increase productivity by capturing a larger proportion of the annual rainfall (Ong et al., 1992) was supported by the Hyderabad studies, which demonstrated that improvements in annual rainfall utilisation by up to 80% were possible in perennial pigeonpea/groundnut agroforestry systems, primarily because the use of off-season rainfall was increased (Marshall, 1995). These observations demonstrate the potential of agroforestry for temporal complementarity in areas where significant rainfall occurs outside the normal cropping seasons. However, the short-term nature of these experiments, often involving only 1 or 2 years of measurements, makes it impossible to assess the long-term implications.

More recently, Ong and his colleagues described a long-term study at Machakos, Kenya, of the water use and productivity of *Grevillea robusta*-based agroforestry systems on hill-slopes (Ong et al., 2000). *G. robusta* is considered by farmers in the highlands of East Africa to be an outstanding agroforestry tree. It is believed to be deep rooting and to possess few lateral roots, which suggests good potential for below-ground complementarity (Lott et al., 1996; Howard et al., 1997). Water use by individual trees and crops was measured using constant temperature sap flow gauges and scaled to stand transpiration based on linear relationships between sap flow and leaf area across varying environmental conditions and tree ages. Stand transpiration rates ranged from 2.6 to 4.0 mm per day, calculated over four consecutive years (Lott et al., 2000). Throughout the measurement period, the sole tree and agroforestry stands had similar water use, reaching a maximum rainfall utilisation of about 66.2 and 62.2%. About 25% of the tree transpiration occurred during the dry season indicating that trees were able to utilise off-season rainfall (amounting to 16% of the total rainfall) and residual soil water outside the cropping period. In drought seasons, the agroforestry system utilised 85% of the seasonal rainfall, which is about twice the water consumption of a sole maize crop. The results of Lott et al. (2000) confirmed the previous findings in India that agroforestry systems greatly increased the utilisation of rainfall compared to annual cropping systems.

Initially, the *G. robusta*/maize agroforestry system was more productive than either the sole trees or crops giving a land equivalent ratio (LER) greater than 1.0, indicating that either a larger proportion of the available resources was captured, or that the captured resources were used more efficiently for dry matter production (Ong et al., 2000). This situation occurs when there is niche differentiation between the tree and crop or green area duration is extended, and provides evidence of complementarity. Nevertheless, the LER for each component never approached unity, demonstrating that there was always competition for the same resource pool, irrespective of crop species or tree size. Such LER values are consistent with alley cropping studies in India and Kenya in which resource capture was dominated by the tree component because of the relatively high tree planting density. Ong and Leakey (1999) commented that agroforestry research has typically focused on fast-growing tree species planted at high density with the result that trees capture most of the available resources. In addition, the potential microclimatic benefits for under-storey crops were negated by reductions in soil moisture resulting from increased interception losses and water use by trees. Sap flow measurements on a wide range of tree species showed that when seasonal rainfall was below average, maize yields were linearly and negatively correlated with the quantity of water transpired by the trees, including *G. robusta* (Anon, 1997). Crop failure occurred when tree transpiration exceeded 100 mm.

3. Trade-offs between crop productivity, tree products, and environmental functions

Although early process-orientated research in agroforestry concentrated on 'resource capture' (Ong and Black, 1994; Sinoquet and Cruz, 1995), the majority of tree–crop interaction studies in tropical countries have focused on how the inclusion of trees can improve crop productivity rather than environmental functions.

Agronomic reviews of tropical agroforestry systems concluded that yield increases are rare in alley cropping in the semiarid tropics because fertility improvement by mulching does not offset the large competitive effect of trees on crops for water and nutrients (Sanchez, 1995; Rao et al., 1998), unlike the generally positive influence of scattered trees on crops (Ong and Leakey, 1999). Major disappointments with alley cropping in the semiarid tropics and elsewhere have led to a greater emphasis on sequential agroforestry systems, such as improved fallows, which segregate trees and crops in order to remove the undesirable competitive effects of the trees (Cooper and Buresh, 1999).

The most notable exception is contour planting of trees on hill-slopes. These are highly effective in reducing soil erosion and have provided more encouraging results than alley cropping on flatter lands (Young, 1997). Garrity (1996) suggested that contour hedgerows should be able to capture the run-off and soil which would otherwise be lost from hillside cultivation, thereby compensating for the extra resources required for tree growth. The key is to design contour hedgerows which are efficient in erosion control without compromising crop productivity.

It is only recently that agroforestry researchers have examined the interactions between crop yield and hydrological (Lefroy and Stirzaker, 1999) or environmental functions (Wallace et al., 2000). To reduce the trade-offs between crop productivity and environmental functions in the semiarid tropics it is crucial to select appropriate trees and to design tree spacing to minimise competition. For example, Kiepe (1995) used a slow-growing tree, *Senna siamea*, to form contour hedgerows in Machakos, Kenya. The trees reduced soil erosion from 58 to 1.4 t ha^{-1} over 3 years and did not reduce crop yield. In addition, Kiepe (1995) observed that when sloping land was transformed into a series of terraces, soil physical properties were greatly improved. However, subsequent studies by Kinama et al. (2000) on the same contour hedgerows provided contradictory results. Although substantial amounts of water and soil were saved by the hedgerows, the hedge reduced crop yield by 35%, but this was largely caused by a sequence of below average rainfalls (Fig. 1). In the semiarid tropics, the competitive effects of hedgerows on crops generally exceed the benefits gained by preventing the small and infrequent amount of run-off commonly found. Nevertheless, cultivation of crops on hill-slopes induces unacceptable soil losses which must be prevented. Ditches or terraces are often used for this purpose in the Machakos area (Tiffen et al., 1994). Initial enthusiasm for contour hedgerows to provide the same soil conservation function in semiarid areas was dampened by the slow and sporadic adoption of contour hedgerows even in humid and

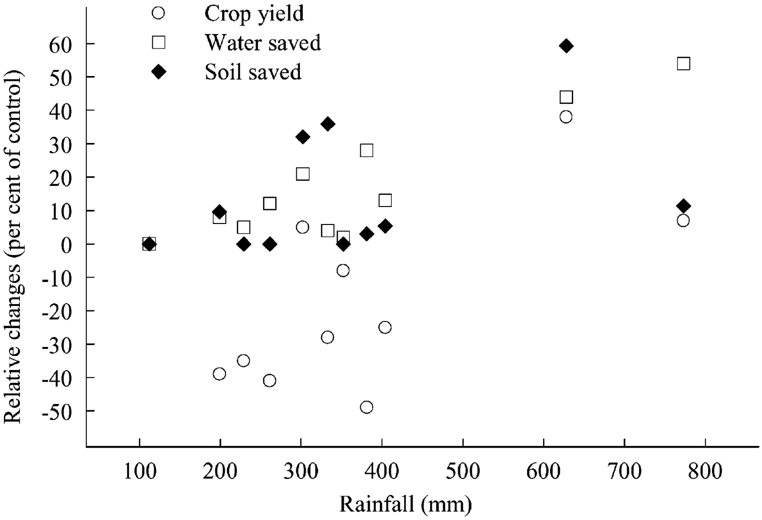

Fig. 1. Changes in crop yield, water use and soil erosion in response to varying seasonal rainfall at Machakos Kenya, after establishing *S. siamea* contour hedges. Presented values are relative to those obtained in control plots lacking contour hedges (adapted from Kiepe (1995) and Kinama et al. (2000))

sub-humid regions where soil erosion control is even more dramatic, but where the beneficial effects on crop yield are unpredictable and insufficient to attract widespread adoption. In a cost–benefit analysis study, Nelson et al. (1997) showed that the slow return to investment in contour hedgerows may explain why farmers are reluctant to adopt the technology. Instead, farmers are keen to adopt low-cost technologies such as natural vegetative strips for erosion control in the humid tropics, where such control is essential for long-term productivity of hill-slopes (Garrity et al., 1999). *Panicum maximum* grass strips are widely adopted in the Machakos area despite greater trade-offs between erosion control and crop productivity. They are twice as competitive as *S. siamea* hedgerows where rainfall is less than 280 mm (Kinama et al., 2000). However, farmers in the area are more interested in the direct benefit from the grass which provides fodder for dairy production. In central Kenya, farmers use highly competitive species such as Napier grass (*Pennisetum purpureum*) and *Calliandra calothyrsus* trees for soil conservation on hill-slopes, where they produce 3–5 t ha^{-1} per year of high quality fodder (Angima, 2000). So farmers accept erosion control when they can combine it with a clear return on their investment.

Ong and Leakey (1999) suggested that instead of focusing primarily on soil conservation in such situations, attention should be focused on the utilisation of trees that provide direct and more immediate benefits to farmers while minimising losses of crop yield. Indeed, many farmers are already practising or beginning to experiment with such systems. In the traditional farmed parklands of West Africa, dense shading by shea butter trees (*Vitellaria paradoxa*) and nere (*Parkia biglobosa*) often reduces millet yield by 50–80% (Kater et al., 1992). Nevertheless, the trees are highly valued by farmers because economic yields from marketable tree products, compensate for the loss of crop

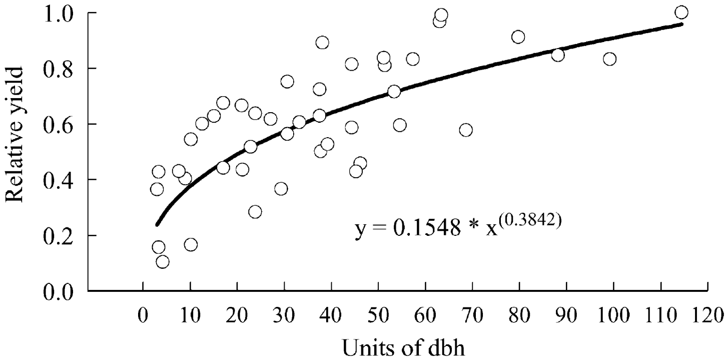

Fig. 2. Effects of distance from individual *M. volkensii* trees measured as units of dbh (distance from tree (m) divided by dbh (m)) on relative yield of maize.

yield. In semiarid Kenya, farmers have recently developed an intensive parkland system using the fast-growing indigenous species *Melia volkensii* (Meliaceae) which is reputed to be highly compatible with crops and can provide high value timber in 5–10 years (Stewart and Blomley, 1994; Tedd, 1997). However, recent observations in farmers' fields confirmed results from controlled experiments at Machakos where even crown-pruned *M. volkensii* trees were found to be highly competitive with crops. Fig. 2 illustrates the effects of pruned *M. volkensii* trees on crop growth in transects starting at the base of each tree on farms in Kenya. Actual distances were divided by diameter at breast height (dbh) to remove the effect of tree size and yield data are expressed as fractions of the maximum yield in each transect. Data from transects were only recorded where it was certain that they could extend far enough from the tree that an estimate of the 'control yield' could be included. The following fitted equation had r^2 of 57%.

$$Y = 0.1548X^{0.3842}$$

In use, the equation indicates that 12 large (0.35 m dbh) trees ha^{-1} would reduce crop yield by 12.5%, but yield reduction could increase to 40% if the trees were unpruned.

To determine whether growing *M. volkensii* trees in croplands is cost effective or not, we compared the value of timber products gained with that of the crop value lost due to competition over an 11-year-rotation at Kitui district, Kenya. The balance sheet does not take into account costs for seed, cultivation, tree planting stock or labour into account, which would increase the surplus of cash from the tree products because in recent years, crop failure occurs 50% of the time (Table 1). The estimates show that at the end of the rotation, the accumulated income from tree products exceeds the accumulated value of crop yield lost through competition by US$ 10 or 42% during average years and US$ 22 or 180% with the assumption of 50% crop failure (in this district of Kenya, in the last 8 years, 6 of the 16 cropping seasons have failed). Factors which encourage farmers to plant *M. volkensii* trees include good financial returns in a relatively short time, strong demand for the product, high value timber and the ability to produce a range of products continuously. Survey results indicated that durable high quality timber could be produced in 10 years while firewood, fodder and poles can be produced at each pruning, lopping or

Table 1
Estimated value (US$) of tree products and potential income lost due to tree–crop competition during an 11-year-rotation of a single *M. volkensii* tree growing in a maize field at Kitui district in Kenya[a]

Product	Two crops per annum	Crop failure (50%)
Accumulated value of crop lost	23.6	11.8
Stem value at harvest	14.4	14.4
Fodder value	8.4	8.4
Firewood value	10.7	10.7
Difference between value of tree products and value of crop yield forgone	+10.0	+21.8

[a] Data presented assume good crop yields of 1 t ha^{-1} of maize twice per annum and also assume 50% crop failure.

thinning occasion. In some districts, *M. volkensii* can produce poles in less than 3 years, timber in less than 5 years from coppiced stems and once planted, *M. volkensii* can grow faster in fields than it does in the wild (Stewart and Blomley, 1994; Tedd, 1997). These findings on the value of *M. volkensii* products may help explain why most farmers claim that *M. volkensii* trees 'do not' compete with crops. Some experienced farmers have increased tree planting density in their cropland and seem willing to sacrifice some of their crops in exchange for anticipated benefits from the trees. Despite such encouraging innovations the planting of *M. volkensii* and other trees is still restricted to a few districts in Kenya and the majority of dry-land farmers are still reluctant to plant trees because of increased risk of crop failure due to competition from trees during drought.

Long-term studies with *Leucaena leucocephala* hedgerows in Machakos (Mathuva et al., 1998) suggested that maize yield in alleys between rows of trees did not compensate for the crop yield lost in the areas occupied by trees and they found that it was more profitable to use the tree prunings for fodder than for green manure. Subsequent studies at Machakos, showed that there was little complementarity in the use of light and water between *L. leucocephala* and maize (Howard et al., 1995; Govindrajan et al., 1996). Such findings are not confined to alley cropping systems. For example, Ong et al. (2000) reported that while below-ground resources remained abundant, grain yield of understorey crops was not significantly affected by the presence of *G. robusta* trees on hillslopes during the first four seasons. However, as the trees increased in size, below-ground resources became progressively depleted, and tree growth became dependent on current rainfall. Concurrently, the risk of crop failure increased from once every six seasons to five every six seasons (Ong et al., 2000). This is particularly worrying because *G. robusta* is considered the most outstanding tree for agroforestry in East Africa and is the preferred species for boundary planting by farmers who relocated from the highly populated highlands to the drier, less populated lowlands. These studies show that the nature and extent of the interactions between trees and crops change greatly as agroforestry systems mature and that the intensity of the interactions depends on the prevailing environmental conditions, particularly seasonal rainfall. However, long-term studies of agroforestry systems in semiarid environments are rare because of the substantial financial, labour and time investment involved.

4. Below-ground complementarity

Considerable progress has been made in recent years regarding the concepts and techniques for studies of competitivity and below-ground interactions (Cannell et al., 1996; van Noordwijk et al., 1996; Schroth, 1999). In terms of new techniques, the development of simple methods for quantifying root length based on fractal principles (Spek and van Noordwijk, 1994) and deriving competitivity indices from the proportional relationships between first order lateral and tap roots and trunk diameter without the need for extensive excavation (van Noordwijk and Purnomosidhi, 1995), the relatively low cost heat-pulse technique for measuring root function (Khan and Ong, 1996), and the use of isotopic ratios of water utilised by plants (Burgess et al., 2000) are the most exciting. How useful are these methods for unravelling below-ground interactions in dry-lands? Can they be used to screen the large number of tree species potentially suitable for dry-land agroforestry? Can these methods replace the traditional and tedious method of root excavation with the attendant difficulties of distinguishing between the co-existing roots of the tree and crop components?

Recent reviews of tree–crop interactions for below-ground resources in rain-fed systems (Ong et al., 1999; Odhiambo et al., 1999) concluded the following.

1. Traditional methods of root excavation have highlighted the overlapping distribution of tree and crop roots within the crop rooting zone and the apparent lack of significant spatial complementarity even for species which farmers regard as highly compatible for simultaneous agroforestry systems (Smith et al., 1997; Odhiambo et al., 1999; Schroth, 1999).
2. The co-existence of tree and crop roots in the upper soil layers in agroforestry systems corresponds to the situation in savanna systems with tree–grass interactions (Scholes and Walker, 1993).
3. Root length density of tree roots within the crop rooting zone may be important in determining the intensity of competition between trees and crops (Odhiambo et al., 1999).
4. Less labour intensive approaches, such as competition index (CI) were poor indicators of competition, partly because the index ignores the influence of tree size. However, this problem may be overcome by making adjustments to the calculations (Ong et al., 1999).
5. CI cannot detect the substantial variation in fine root length observed between seasons and neither can it account for variations in transpiration demand or changes in fine root amounts as a consequence of shoot pruning (Ong et al., 1999; Ozier-Lafontaine et al., 1999).
6. Root and crown functions are the driving forces determining the severity of tree–crop interactions. Sap flow studies have highlighted the capacity of tree roots to alternate activities such as water uptake from one part of the root system to another, in response to changes in soil profile moisture content (Burgess et al., 1998; Smith et al., 1998; Ong et al., 1999).
7. Isotopic studies have highlighted the importance of understanding the extent of exploration by tree roots as well as site hydrology. They also show how the competitivity

of an individual tree species can vary between sites with different hydrological characteristics (Smith et al., 1998).

8. Despite recent attention to root research, progress in selecting suitable species for intercropping in dry-lands has been surprisingly slow. It appears that the twin goals of fast-growing trees (preferred by farmers and researchers), and low competitivity, are mutually exclusive when nutrients and water are confined to the topsoil (van Noordwijk et al., 1996).

5. Management options

5.1. Short-term studies

If competition is to be minimised, tree planting must be combined with appropriate management practices such as crown and root-pruning. The relative importance of above- and below-ground competition is crucial in determining the best management strategy, as is the timing of pruning. However, experience with alley cropping has shown that few farmers are willing to incur the high labour costs required for regular pruning, simply to reduce competition from fast-growing trees. Nevertheless, a survey of farmers' tree-growing practices in central Kenya revealed a surprising range of local pruning practices. These techniques are not only less labour demanding and more effective in lowering competition than traditional crown-pruning methods, but at the same time, they improve the quality of the timber produced, which is important for income generation on small farms. *G. robusta* trees are pollarded or completely defoliated once every 2 or 3 years, usually during the dry season when labour demand is minimal and there is no risk of damaging associated crops. In contrast, *M. volkensii* trees are pruned from the outset to improve the quality of the timber and also to reduce competition with crops. Crown-pruning not only reduces transpiration and, hence, competition, it also leads to tree root dieback (Jones et al., 1998; Schroth, 1999). Unfortunately, crown-pruning may also lead to the development of more superficial root systems than normal (Hairiah et al., 1992), which would be an undesirable outcome.

Singh et al. (1989) demonstrated that root barriers to 0.5 m depth are extremely effective in reducing competition between 4-year-old *L. leucocephala* hedgerows and associated crops in Hyderabad, India. However, the beneficial effects lasted only one season because tree roots re-invaded the crop rooting zone from beneath the root barriers. Surprisingly, at the same site, and using *L. leucocephala,* Korwar and Radder (1994) were less successful in reducing tree–crop competition by root-pruning than by coppicing. However, this resulted from the fact that because of interception losses, there was insufficient re-wetting of the soil profile following root-pruning. Similarly, Schroth and Zech (1995) failed to observe any beneficial effects of root barriers in an alley cropping study with *Gliricidia sepium* and sorghum in West Africa. In contrast, studies in the post-rainy season in Bangladesh (Hocking, 1998, Hocking and Islam, 1998) revealed that below-ground competition from a wide range of tree species (mainly fruit trees) was virtually eliminated by pruning the lateral roots off the trees. Likewise, in our current (unpublished) studies in Uganda, root-pruning to 0.5 m depth which was imposed in the eighth and ninth seasons after establishment of alley cropping systems, confirmed that competition from roots was responsible for most of the reduction in crop yield. Competition by *Maesopsis emini*, the fastest growing of the 12 tree species compared, was completely eliminated by root-pruning. In order to understand these effects, we are examining the long-term effects of tree root-pruning on competition with crops and the functioning of tree root systems in addition to involving farmers in their assessments of the costs and benefits of this approach. It was also encouraging to find that in Indiana, USA, Jose et al. (2000) reported that root-pruning is not only beneficial for maize growth in alley cropping with black walnut (*Juglans nigra*) and red oak (*Quercus rubra*) but that agroforestry is much more attractive economically than traditional agriculture or forestry (Benjamin et al., 2000).

5.2. Recent sap flow results from root-pruning studies in Uganda

In order to understand the impacts of root-pruning on root system function, we have made measurements of sap flow in roots and trunks before and after lateral root-pruning. There was a significant ($P < 0.001$) reduction in sap flow through the trunk of *G. robusta* trees following severing of about half of the lateral roots, but 5 days later, sap flow had recovered and was the same as in the stems of trees that had not been root-pruned (Fig. 3). Interestingly, not all tree species responded to root-pruning in the above manner. Fig. 4 presents similar data for *M. emini* growing on the same site. With *M. emini,* the same extent of root-pruning had no significant effect on sap flow through the tree stem (see also Woodall and Ward, 2002). In the prevailing environmental conditions at Kifu (annual bimodal rainfall of 1200 mm per year) it was not the unsevered lateral roots that

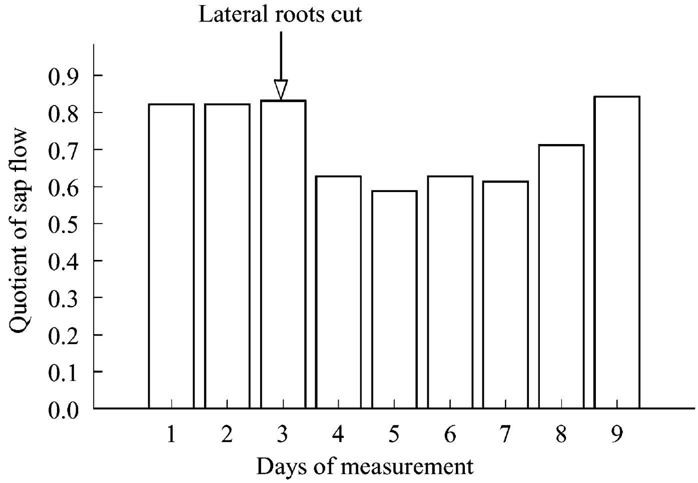

Fig. 3. Effects of root-pruning on mean daily sap flow in the stems of *G. robusta* trees at Kifu, Uganda. Data are sap flow in stems of root-pruned trees divided by the sap flow in stems of unpruned trees. On pruned trees, half of the lateral roots within 30 cm of the soil surface were pruned-off close to the root collar on day 3.

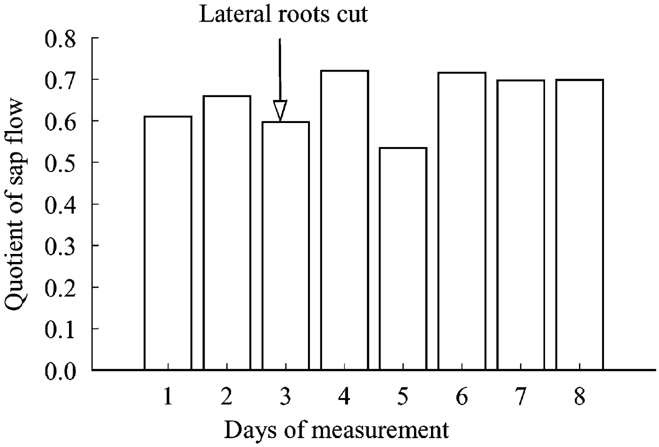

Fig. 4. Effects of root-pruning on mean daily sap flow in the stems of *M. emini* trees at Kifu, Uganda. Data are sap flow in stems of root-pruned trees divided by the sap flow in stems of unpruned trees. On pruned trees, half of the lateral roots within 30 cm of the soil surface were pruned close to the root collar on day 3.

compensated for the reduction in water absorbing surface area after root-pruning, because sap flow through the unsevered lateral roots did not change (Fig. 5). Consequently, it seems that roots that were located more deeply, increased their rates of sap flow to satisfy transpirational demand from the atmosphere.

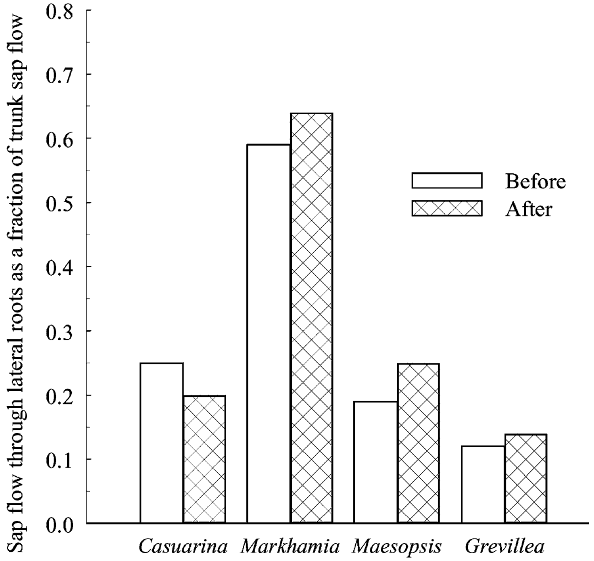

Fig. 5. Sap flow through intact shallow lateral roots of four tree species at Kifu, Uganda as percent of sap flow in the stem before and after severing about 50% of the lateral roots.

5.3. Farmers perceptions and the need for long-term studies

Long-term studies of the effects of root-pruning are needed because such information is crucial for promotion of the technology to farmers. While many farmers appreciate the benefits of reduced tree–crop competition following crown-pruning, ideas of below-ground competition are completely new to most of them. The experience in Bangladesh indicated that root-pruning is feasible when land is at a premium (average of only 0.8 ha per household), crop yields and earnings are quite low and there is a need to grow more trees for household needs as well as for income generation (Hocking, 1998). While crown-pruning yields immediate products (firewood and fodder) and offers longer term gains in crop yield, benefits from root-pruning are delayed and, thus, farmers need convincing that the effort is worthwhile. In Africa, many farmers consider root-pruning too difficult and impractical to execute. Fortunately, the techniques themselves can be quickly and easily demonstrated in the field and experience has shown that farmers can readily change their minds regarding the practicality of incorporating root-pruning into their cultivation cycles. Our early results from root-pruning show dramatic improvement of crop growth. Consequently, pruning offers farmers the chance to increase yields of both crops and tree products using tools that they already own and it seems conceivable that after root-pruning, they could even increase the number of trees that they grow without jeopardising crop productivity. Such effects will help reduce poverty in rural areas, especially where these approaches are combined with selecting trees for the improved value of their products. However, the need to monitor tree and crop growth as root-pruned trees develop over 10 years or so, a typical dry-land tree rotation, is essential. Such studies will allow farmers to see whether the benefits to crop growth persist as the trees grow large. Scientifically, the most pressing questions that require addressing in long-term studies are as follows.

1. Does forcing trees to extract most of their water from beneath the crop rooting zone influence soil water recharge at depth, and what are the implications for the long-term water balance?
2. Is the growth of the tree and its stability in the wind significantly influenced by root-pruning?
3. Does the loss of fine roots and mycorrhizas diminish the capacity of the tree roots to intercept and recycle plant nutrients that leach from near the soil surface?
4. What are the implications of severing surface roots on N_2 fixation and mycorrhizal activity?

6. Conclusions

It is disappointing that so few tree species with limited competitive effects on crop plants have been identified to date. However, it is possible to integrate competitive tree species into crop lands, but such trees require management, e.g. pruning, to reduce their competitiveness. Where fruits are the target output from the trees, there is limited scope for crown-pruning without jeopardising fruit production, but for some other trees, e.g. *G. robusta* and *M. volkensii*, firewood is a target product and in consequence, crown-pruning is part of the management strategy. For fruit trees, root-pruning seems a much better option for reducing tree water use in the zone occupied by crop roots and, hence, competition with crops, but farmers need convincing that the technique works and is easy to apply. With root-pruning, it seems advisable to begin pruning when the trees are young. That will avoid the need to sever large roots and will also diminish the risk of prejudicing the stability of large trees. Early intervention may result in a permanent alteration to root system architecture and could limit the frequency with which pruning needs to be conducted. It was encouraging that in western Uganda, farmers readily adopted the technology after being shown why it was necessary, how it might work, and the technique was demonstrated in the field.

However, there are points that require quantification before root-pruning can be seriously promoted as a satisfactory method of integrating large numbers of potentially competitive trees into agroforestry. That root-pruned trees are compelled to extract water largely from beneath the crop rooting zone will probably not diminish the amount of water that they transpire. Consequently, studies involving the long-term water balance at sites where trees have been root-pruned should not be ignored. The results of Ong et al. (2000) where competition was limited while trees were young (small) and resources were plentiful, should be borne in mind when considering the expansion of tree planting in crop lands. Similarly, because most of the plant nutrients, mycorrhizas and nitrogen fixing nodules tend to occupy surface horizons, the effects of tree root-pruning on nutrient leaching and nitrogen fixation should be addressed as a matter of urgency.

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