

Contrasting effects of roots and mulch from three agroforestry tree species on yields of alley cropped maize

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Abstract

In agroforestry associations, tree roots may influence crop yields both favorably, especially through mulch production and the improvement of soil fertility through root effects, and unfavorably through above- and below-ground competition. A field experiment was conducted on a shallow sandy Plinthic/Ferric Acrisol in the sub-humid savanna of central Togo in order to compare the competitiveness of *Gliricidia sepium*, *Calliandra calothyrsus* and *Senna siamea* hedges when grown in association with maize. The effect of hedge distance on maize yields was tested by measuring yield gradients in unilaterally open alleys. In 6.4-m-wide alleys, maize yields were lower than in the sole cropping control because of the reduction in cropped surface and a yield depression near the *Calliandra* hedges. With increasing hedge distance, yields per row increased over the control yields in alley cropping with *Gliricidia*, but not with *Senna* and *Calliandra*. Root barriers between hedges and crops increased maize yields in the *Calliandra* plots, indicating a high competitiveness of the root system of this species. In the *Senna* and (non-significantly) *Gliricidia* plots, maize yields at the interface were reduced rather than increased by the root barriers. For this, the reduction of the crop rooting volume and of favorable hedge root effects on soil conditions are discussed as possible reasons. Tree species with highly competitive root systems, like *Calliandra* at this site, should be used in fallow improvement systems rather than in agroforestry associations.

Keywords: Alley cropping; *Calliandra calothyrsus*; Competition; *Gliricidia sepium*; Maize; *Senna siamea*

1. Introduction

The association of trees with agricultural crops has several potential advantages. Beside the production of nutrient-rich biomass, the presence of the perennial root systems in the cultivated plots may be one of the most significant. Tree roots may improve the soil structure and create macro-pores, thus increasing water infiltration, reducing surface runoff and erosion and improving soil penetration by crop roots (Van Noordwijk et al., 1991; Sanginga et al., 1992; Schroth and Zech,

1995). They may take up nutrients from the soil solution when no crops are present or their root systems are not yet fully developed, thus reducing leaching losses, as indicated by lower nutrient leaching under perennial than under annual crops (Seyfried and Rao, 1991; Kühne, 1993). With their continuous turnover, tree roots contribute to the organic matter supply of the soil and the maintenance of biological activity (Yamoah et al., 1986b; Szott et al., 1991a). Although the importance of these processes certainly depends on specific site and management conditions, they form a considerable part of the justification of agroforestry research and extension.

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The disadvantage of active tree roots in cropping systems, however, is potential competition with the crops. Several workers have stressed the similarity of root distribution in the soil profile between trees and annual crops, indicating a considerable overlapping of the soil resources they use (Jonsson et al., 1988; Dhyani et al., 1990; Ruhigwa et al., 1992). Yield responses of annual crops to the reduction of tree root competition by root trenching or root barriers in agroforestry associations have been reported (Singh et al., 1989; Ong et al., 1991; Rao et al., 1991; Schroth et al., 1995). Together with shoot competition for light, root competition for water and nutrients is often held responsible for observed yield depressions at the tree–crop interface of agroforestry associations (Lal, 1991; Szott et al., 1991b; Salazar et al., 1993).

To avoid negative interactions in agroforestry systems, tree species should be identified which provide the desirable functions of tree roots in the field at minimum competition cost. For this, information about the distribution and dynamics of tree roots under different site and management conditions, their competition with different crops and their effects on soil fertility is required. Young (1989) suggested that ‘mutually beneficial effects of roots could compensate for competition, and research is needed’.

The present research compares the effects of three tree species on maize in alley cropping. The effects of hedge mulch on crop yields and foliar nutrient levels was investigated. Root effects were studied by the installation of root barriers in subplots. Gradients of maize yields as a function of hedge distance, with and without root barriers, were measured in order to deter-

mine the extension of hedge root effects, to select tree species of low competitiveness for the study site and to quantify the influence of alley width on crop yields.

2. Study site and methods

2.1. Location and climate

The trial was conducted near Kazaboua in the sub-humid savanna of central Togo (1°5'E, 8°26'N, approximately 300 m above sea level). Mean annual rainfall between 1980 and 1992 was 1165 mm, with a unimodal rainy season from April to October. In the experimental year 1992 the rainfall was relatively high with 1259 mm. The study site was situated on a very gentle slope (approximately 1%) with southward inclination. The soils were Plinthic and Ferric Acrisols according to FAO/Unesco (1990). Soil fertility was low (Table 1). The loamy-sandy topsoil was very low in total C and N. The available P contents were relatively high in the topsoil, but very low in the subsoil (Olsen and Sommers, 1982). The Zn levels were below the critical value for maize (0.8 mg kg⁻¹) (Council on Soil Testing and Plant Analysis, 1980). The sandy-clayey subsoil horizon was often hardened and was present at depths varying between about 20 and over 100 cm within the area of this experiment.

2.2. Trial design

The field experiment consisted of three tree species and a control without trees as the four main plot treat-

Table 1
Analytical data from a soil profile in the center of the experimental area (Plinthic Acrisol)

Depth (cm)	Texture class	Bulk density (g cm ⁻³)	pH (H ₂ O)	C _{tot} (mg g ⁻¹)	N _{tot} (mg g ⁻¹)	P ^a (mg kg ⁻¹)	ECEC	Ca ^b	Mg ^b	K ^b	BS (% ECEC)	Zn ^a (mg kg ⁻¹)
0–19	LS	1.53	6.49	7.5	0.49	44.8	3.74	2.89	0.65	0.06	96	0.33
19–56	LS	1.77	6.08	4.1	0.31	0.4	2.62	1.84	0.53	0.09	94	0.16
56–87	SL	1.95	6.35	0.3	0.31	0	2.35	1.33	0.78	0.10	95	0.14
87–106	SC	1.37	5.70	ND	0.32	0	1.66	0.59	0.50	0.07	70	0.16
106+	SC	1.83	5.69	ND	0.37	0	3.04	1.07	1.44	0.13	87	0.30

^aAvailable fractions extracted with double acid.

^bExchangeable fractions (cmol_c kg⁻¹).

ECEC, effective cation exchange capacity (cmol_c kg⁻¹); BS, base saturation; ND, not determined.

LS, loamy sand; SL, sandy loam; SC, sandy clay.

ments. The tree species were *Gliricidia sepium* (Jacq.) Steud., *Calliandra calothyrsus* Meissn. and *Senna siamea* (Lam.) Irwin & Barneby (syn. *Cassia siamea* Lam.). The non-N-fixing *Senna* was known to be well adapted to the long dry season and the shallow sandy soils. The N-fixing species *Gliricidia* and *Calliandra* were tried as alternatives to *Leucaena leucocephala* which had given unsatisfactory results in some earlier experiments. The main plots were arranged in a randomized complete block design with four replications. The size of the main plots, either tree plots or control, was 24 m × 12.8 m. Each tree plot contained two hedges of 24 m length at 6.4 m distance. The hedges were oriented E–W, and the distance between the trees within the hedges was 0.25 m. The hedges were established in June 1990. *Gliricidia* was planted, while *Senna* and *Calliandra* were sown directly. Missing trees were repeatedly replaced during 1990 and 1991. In May 1991 all hedges were pruned to 50 cm, and in July 1991 the *Gliricidia* hedges were again pruned to 50 cm, while the other two species showed slower regrowth and were only cut back laterally to avoid shading of the crops.

The hedge prunings were applied as mulch on the field strips. Instead of applying half of the prunings of a hedge on either side of this hedge, the prunings from one hedge were distributed on the alley between the two hedges within a plot, and those from the second hedge were distributed on a band of similar width on the other side of this hedge (Fig. 1). Thus, every plot

consisted of two regularly mulched field strips, of which one was limited on both sides by hedges ('closed alley'), while the other one ('open alley') was limited on only one side by a hedge and on the other side by a cropped band of 8 m width, which served as a buffer strip between two adjacent plots. This design allowed us to test the effects of the hedges on the crops under normal alley cropping conditions in the closed alleys, and to quantify gradients in crop yield with increasing distance to the hedges in the open alleys. A buffer strip of several meters width around the whole trial area was also cropped.

The effect of the tree roots on the crops was tested by dividing each main plot into two subplots of 12 m length and separating the rooting zone of the hedges and the crops of the open alley in one randomly chosen subplot per main plot (Fig. 1). The separation of the rooting zones was accomplished by digging a U-shaped trench along the hedge to 75 cm depth, unless a continuously hardened subsoil horizon was encountered in a lower depth. A 0.8 mm PVC sheet was placed in the trench at 40 cm from the hedge. The trenches were refilled with subsoil followed by topsoil between the PVC sheet and the hedge, thereby restoring the original soil horizons as far as possible and leaving the cropped soil unaltered. The barriers were installed in October 1990 when tree roots had not yet colonized the field strips beyond the trenches.

Thus, each main plot contained three subplots (Fig. 1): two open alley plots with and without root barriers,

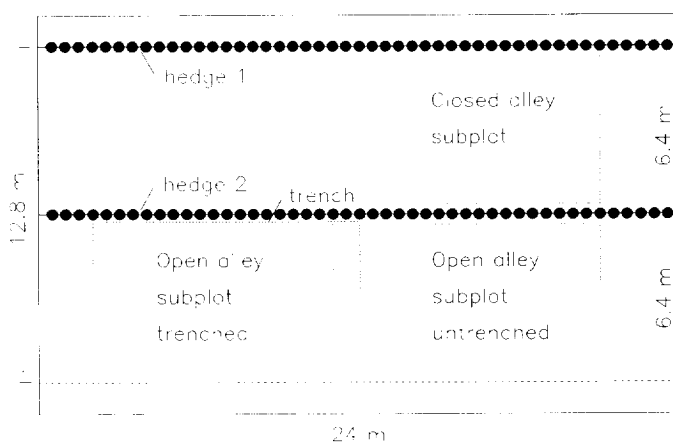


Fig. 1. Layout of a main plot with the dimensions 24 m × 12.8 m, containing three subplots of 8 m × 5.6 m. The plot contains two hedges, a closed alley between the hedges and an open alley below hedge 2. The prunings of hedge 1 are applied as mulch to the closed alley, and the prunings of hedge 2 to the open alley. The trial consisted of four blocks, each block being composed of four main plots.

and one closed alley plot. The cropped surface was 8 m × 5.6 m (seven crop rows) for the subplots with hedges and 8 m × 6.4 m (eight crop rows) for the subplots of the control. To avoid artefacts due to modified development of the unilaterally confined hedge root systems, the closed alley plot was always situated in that part of the closed alley which was bordered by hedges without root barrier. To avoid effects of slope or exposition on yield gradients in the open alleys, these were situated on the northern, upslope side of the hedge in two blocks and on the southern, downslope side of the hedge in two other blocks.

The experiment was only destructively sampled 2 years after the end of the trial, when roots of all tree species had passed below the barrier and grown into the alleys. According to this and similar observations from other experiments (Singh et al., 1989), it must be assumed that root exclusion was already incomplete during the experiment, and crop yield increases due to the barrier are minimum estimates for tree root competition. The alternative strategy of repeatedly trenching tree roots at the interface instead of the permanent barrier was avoided, because the nutrient release from cut off tree roots would have been likely to lead to an overestimation of tree root competition (Schroth et al., 1995).

2.3. Crops

The site was cropped with groundnuts in 1990 and with soya beans in 1991. These served as cover crops until full establishment of the hedges, and no measurements were conducted on them.

On 21 and 22 May 1992, traditional soil tillage was carried out by hand-hoe ('daba'), forming ridges of about 30–40 cm height, 80 cm apart, parallel to the hedges. The first ridge was 80 cm from the hedge. On 22–24 May, all hedges were pruned to 50 cm height and biomass applied to the ridges as mulch. The biomass was weighed, the leaf to branch ratio determined on 12 plants per plot, and the dry weight of leaves and branches was determined by drying subsamples at 70°C until constant weight. These were retained for nutrient analysis.

On 26 May, maize of the variety Poza Rica was sown in the mulched ridges at 80 cm × 40 cm, two grains per hill, after an intensive rainfall. Missing plants were replaced on 5 June. On 1 and 2 July, the hedges were

pruned again and the biomass applied as mulch between the maize rows. Weeding was carried out by hand hoe, and no fertilizer was applied for easier detection of positive and negative effects of the hedges on the crops. At silking stage, the cob leaves of three maize plants were taken in the first, second, fourth and seventh rows from the hedge from all subplots of the open alleys. The leaves were washed in tap water and dried at 70°C to constant weight. The maize was harvested on 26 September. Plant number and grain dry weight (105°C) were determined per row in each subplot.

2.4. Root distribution

The distribution of tree roots in the alleys was studied in the *Senna* plots between 27 June and 6 August. Soil cores were taken in the open alley plots without barrier with a soil corer of 8 cm diameter. The samples were taken from 0–10 cm depth between the ridges at distances of 0.4, 1.2, 2.8 and 3.6 m from the hedge. Samples from the ridges would have contained higher proportions of dead tree roots. Three cores from the same plot and distance were mixed after cutting long roots into pieces of a few centimeters length, and a subsample of 100–400 g was washed over a 0.5 mm sieve for root extraction, taking larger subsamples for higher distances. The method has been described by Schroth and Kolbe (1994). *Senna* roots were separated from other roots and organic debris under ×10 magnification, when necessary, without distinguishing live and dead roots. Root length was measured after Tennant (1975), and root mass was obtained after drying at 70°C for 48 h. All root weights were converted to 45% C to correct for adhering soil particles. The soil water content was measured by drying subsamples at 105°C to constant weight, and total mass and volume of the soil sample and mass of the subsample for root extraction were used to convert root length into cm cm⁻³ of soil and root mass into kg ha⁻¹ dm⁻¹. Initially it was intended to conduct root studies on all hedge species, but intensive preliminary studies revealed that *Gliricidia* and *Calliandra* fine roots could not be distinguished from weed and maize roots with sufficient precision. *Senna* roots were easily identified by their black color, but no visual or mechanical criteria could be established for distinguishing live and dead roots.

Table 2
Analysis of variance table for maize yield data

Source of variance	d.f.	F	F (5%)	F (1%)
Sub-subplots	223			
Subplots	31			
Main plots (MP)	15			
Blocks (B1)	3			
Species (Sp)	3	0.726	3.86	6.99
MP error	9			
Root barrier (RB)	1	3.157	4.75	9.33
Sp × RB	3	2.389	3.49	5.95
Subplot error	12			
Distance (D)	6	3.157*	2.66	4.01
Error c	18			
D × Sp	18	2.585**	1.79	2.28
Error d	54			
D × RB	6	1.638	2.66	4.01
Error e	18			
D × Sp × RB	18	2.070*	1.79	2.28
Error f	54			

* $P < 0.05$; ** $P < 0.01$.

2.5. Plant analysis

In the ground maize and hedge samples, N was measured gas-chromatographically with a CN-analyzer. For the other elements, subsamples were dry-ashed at 560°C for 14 h and the ash dissolved in 10% HCl. P was measured photometrically with the molybdenum blue method, and cations by atomic absorption spectrometry. A composite sample of *Senna* roots of each of the diameter classes 0–0.5 mm and 0.5–2 mm was analyzed for C, N and S with an Elementar Analyzer and for other nutrients with the same methods as the other plant samples.

2.6. Statistical analysis

The data were analyzed by analysis of variance followed by *F*-test. In case of significant *F*-tests at $P < 0.05$, treatment means were compared by least significant difference tests. The results from the closed and the open alleys were analyzed separately. For the closed alleys, the design was a randomized complete block design with individual rows as split-block factor (Little and Hills, 1978). For the open alleys, the design was a randomized complete block design with the root barrier as split-plot factor and individual rows as split-block factor (Table 2). In addition, an ANOVA was

computed separately for every hedge species for the open alley yields, which allowed to test for interactions between root barrier and hedge distance for every species.

3. Results and discussion

3.1. Productivity of the hedges

Despite temporary die-back symptoms of *Calliandra* branches at the end of the dry season of 1991/1992 as described by National Research Council (NRC, 1983), all of the tested tree species seemed to tolerate the difficult site conditions, although the productivity of *Gliricidia* and *Calliandra* was low (Table 3). *Calliandra* is best adapted to more humid climates (NRC, 1983; Panjaitan et al., 1993). During 1992, *Senna* was much more productive than the other species (Table 3), mainly because it continued to grow rapidly during the dry season. The regrowth of *Gliricidia* after the pruning in July 1991, however, was very slow, suggesting that this species should not be pruned for at least 2 months before the onset of the dry season at this site. The nutrient transfer in the *Calliandra* prunings was lower than in the *Gliricidia* prunings because of a lower percentage of leaves in the biomass. Also, the

Table 3
Mulch and nutrient application per unit of cropped surface (5.6 m² m⁻¹ hedge) with two prunings in May and July 1992

Hedge species	Total mulch (kg ha ⁻¹)	Leaf mulch N (kg ha ⁻¹)	P (kg ha ⁻¹)	K (kg ha ⁻¹)	Ca (kg ha ⁻¹)	Mg (kg ha ⁻¹)	Fe (g ha ⁻¹)	Mn (g ha ⁻¹)	Zn (g ha ⁻¹)	Cu (g ha ⁻¹)	
<i>Gliricidia</i>	1683	903	41.1	2.6	13.1	11.8	4.8	175	57	14	26
<i>Calliandra</i>	1890	527	26.5	1.9	5.9	7.2	2.4	112	62	23	23
<i>Senna</i>	4092	1809	42.2	3.0	17.0	41.6	5.2	257	122	39	61
LSD 5%	1265	356	13.1	ns ^a	4.8	9.5	1.5	73	35	12	17

^aF-test not significant at $P < 0.05$.

concentrations of N, P, K and Mg were highest in the *Gliricidia* biomass, which also showed the most rapid nutrient release from decomposing leaves and roots (Lehmann et al., 1995). *Senna* compensated low nutrient concentrations in the biomass by high biomass production.

3.2. Maize yields in the closed alleys

Despite favorable rainfall, the maize yields were low because of the low fertility of the site and the absence of mineral fertilization during the past 3 years. Considering the whole plot area including the 12.5% of the surface that was occupied by the hedges, the control gave the highest yield (1.42 g ha⁻¹), and the *Calliandra* plots gave the lowest yield (1.03 g ha⁻¹); *Gliricidia* (1.20 g ha⁻¹) and *Senna* (1.19 g ha⁻¹) were intermediate. The differences were not significant.

The low yield in the *Calliandra* plots was a result of yield depressions at the tree–crop interface, which did not occur in the proximity of the other hedge species (Fig. 2). Interestingly, the yields of the rows next to the *Gliricidia* and *Senna* hedges were even slightly higher than those of the following rows. In the central part of the alleys, the yields per row were similar in all hedge treatments and in the control. The yield reduction in the first rows of the *Calliandra* plots was partly a result of reduced plant numbers (Fig. 2), but mainly of reduced yields per plant. No reduction in plant numbers was observed in the proximity of the other hedge species. This may indicate an allelopathic effect of *Calliandra* on maize germination, possibly through extracts of leaves or roots, which have particularly high polyphenol contents (Lehmann et al., 1995), or an increased activity of seed predators near the *Calliandra* hedges. Allelopathic effects on germination and growth

of herbaceous plants have been demonstrated with leaf and root extracts of several agroforestry species (Suresh and Vinaya Rai, 1987; Chaturvedi and Jha, 1992; Hauser, 1993) and may be a widespread phenomenon. Increased plant losses due to seed predators like mice and birds hiding under perennial plants have also repeatedly been observed in agroforestry systems (Lal, 1989; Schroth, 1994; Schroth et al., 1995).

The lower per-hectare yields in the tree plots compared with the control (see above) shows that alley cropping with 6.40-m-wide alleys was agronomically not advantageous in the third year after the establishment of the hedges. There was no tendency for yield increases in the alleys of any of the hedge species which could have compensated for the surface occupied by the hedges, while the maize yields were depressed in the proximity of the *Calliandra* hedges.

3.3. Effect of hedge distance on maize yields in the open alleys without root barrier

In alley cropping with single hedges, the biomass of the hedge prunings per unit of cropped surface decreases with increasing alley width. However, the use of paired or multiple hedges allows the alley width to be increased without changing the pruning biomass per unit area, thus reducing the direct influence of the hedges on the crops. Fig. 3 shows how far this strategy would have been useful for the three investigated tree species. The open alleys in this trial approximate the situation in alleys with 14 maize rows (11.2 m width of cropped area) between paired hedges.

The results from the open alleys were consistent with those from the closed alley plots (Fig. 2). A pronounced yield depression at the tree–crop interface was observed in the *Calliandra*, but not *Gliricidia* and

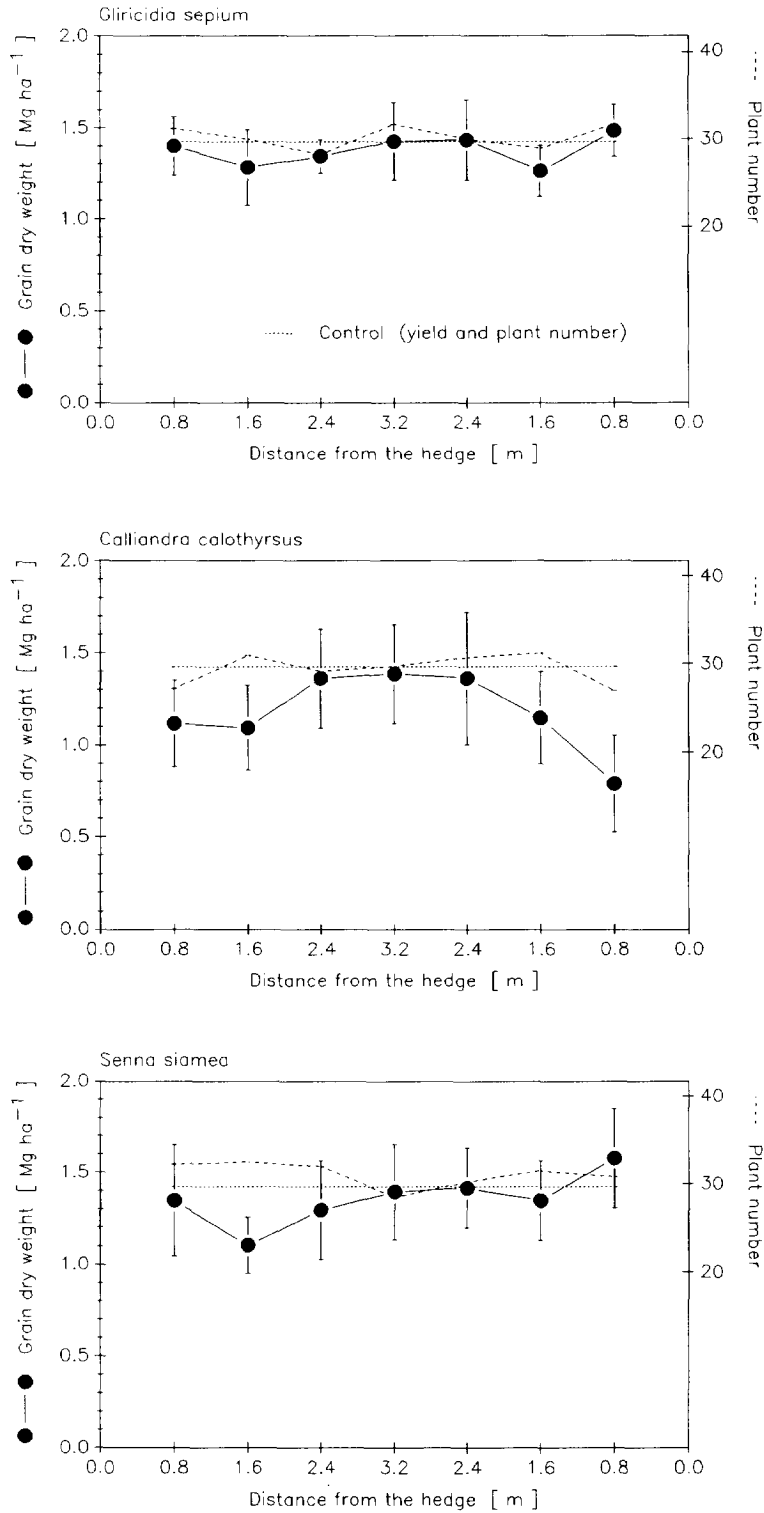


Fig. 2. Maize yields (means and SE) and plant number per row in the closed alleys. The control yield does not take the larger cropped surface compared with the hedge treatments into account.

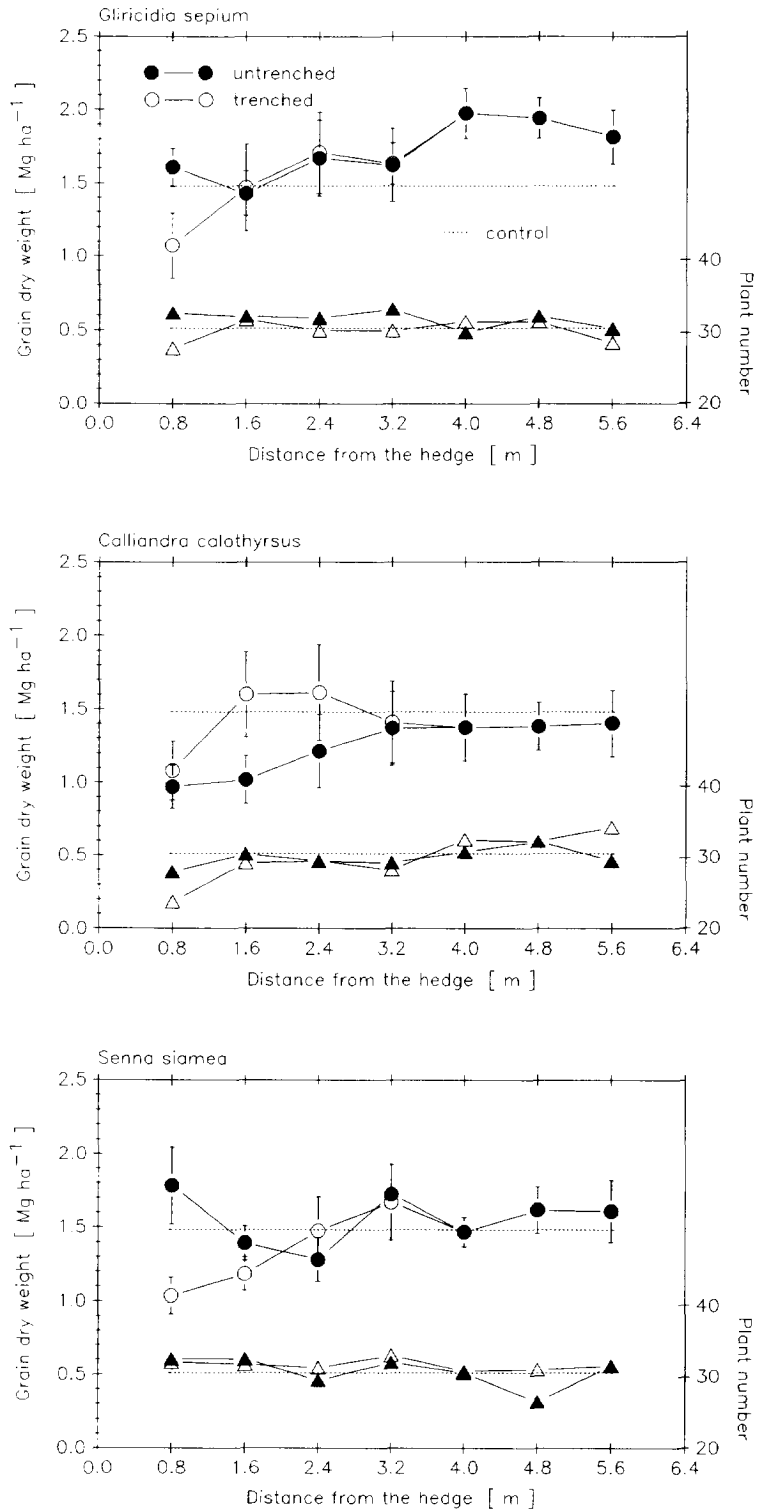


Fig. 3. Maize yields (circles, means and SE) and plant numbers (triangles) per row in the open alleys. The plastic sheet for root separation was installed at 0.4 m distance from the hedges. For hedge distances of 4 m and more, only average yields of subplots with and without root barrier are shown. The control yield does not take the larger cropped surface compared with the hedge treatments into account.

Table 4

Nutrient concentrations in the dry matter of maize ear leaves at silk, taken from rows 4 and 7 of the open alleys (mean of subplots with and without root barrier). For statistical results see text

Species	N (mg g ⁻¹)	P (mg g ⁻¹)	K (mg g ⁻¹)	Ca (mg g ⁻¹)	Mg (mg g ⁻¹)	Zn (mg kg ⁻¹)	Cu (mg kg ⁻¹)	Mn (mg kg ⁻¹)
<i>Gliricidia</i>	14.4	1.40	18.9	2.94	1.86	11	12	26
<i>Calliandra</i>	12.4	1.28	17.5	2.40	1.75	10	11	24
<i>Senna</i>	12.3	1.43	16.8	2.69	1.61	10	12	24
Control	11.7	1.33	17.0	2.65	1.61	10	11	21

Senna plots without root barrier, where the yields again increased slightly in the first row next to the hedges. The overall species effect on maize yields was not significant, but the interaction between species and distance was highly significant (Table 2), reflecting a differing reaction of maize yields to increasing distance from the hedges. In the *Calliandra* plots, increasing alley width would have progressively reduced the negative interface effects, but the growth conditions of maize were never better than in the sole cropping control. In the *Senna* plots, maize yields per row seemed to be independent of hedge distance and similar to those of the control, so that a compensation for the reduced surface was equally not possible. *Gliricidia* was the only hedge species that increased maize yields per row in comparison to the control, thus showing a potential for the improvement of per-area yields in wide alleys. However, if calculated for the whole surface of the open alleys including the surface occupied by the hedges, the yields were almost similar in *Gliricidia* and control plots with 1.51 g and 1.48 g ha⁻¹, respectively. Although the alley cropping system was thus not yet advantageous, Fig. 3 suggests that, at a given amount of hedge prunings per unit cropped surface, the probability of achieving net yield increases in alley cropping increased with alley width at this site.

The differing yield effect of the hedges was at least partly due to the nutrients in the mulch. Foliar analysis of maize showed deficient levels of N, P and Zn, and K was at the lower end of the sufficiency range (Jones et al., 1990) (Table 4). N-deficiency was also recognized by leaf coloration. The concentrations of most nutrients in maize leaves were highest in the *Gliricidia* plots, although the differences were only significant at the 6% and 7% levels, respectively, for N and K. The *Calliandra* biomass had added significantly less nutrients to the cropped soil than the other species (Table

3). A better response of maize to *Gliricidia* compared with *Calliandra* mulch has also been found by Gutteridge (1992). The more favorable effect of *Gliricidia* compared with *Senna* on the maize may be explained by the slower nutrient release from the *Senna* biomass (Lehmann et al., 1995), which may have reduced the uptake of the nutrients by the crop.

3.4. Effect of root barriers on maize yields

Maize yields in the control treatment, where root barriers were also installed, gave no indication that the plastic sheet had an influence on the maize when installed between two maize rows instead of a maize row and a hedge (data not shown). Little influence of digging alone has also been found by Willey and Reddy (1981) in a similar experiment.

The yield response of maize to the root barrier differed between treatments, as reflected by a significant three-way interaction between the presence of root barriers, hedge distance and tree species (Table 2). In the *Calliandra* plots, the yield depression at the interface was eliminated by the root barrier from the second row on, resulting in a significant interaction of barrier treatment and distance ($P < 0.05$). While the yield depression in the first row from the hedge was partly due to a reduction of plant numbers, the barrier effect was entirely due to differing yields per plant. This shows that the *Calliandra* hedges exerted a significant root competition on the maize until about 2.5 m distance from the trees, and that the barrier was still effective in reducing this 2 years after their installation. Yield increases due to root separation have also been reported from associations with *Leucaena leucocephala* (Singh et al., 1989; Ong et al., 1991; Rao et al., 1991). At 1.6 m hedge distance, where the barrier effect was the most intense, the concentrations of most nutri-

Table 5

Nutrient concentrations in the dry matter of maize ear leaves at silk, taken from the second row of the open alleys in the *Calliandra* plots. For statistical results see text

Subplot	N (mg g ⁻¹)	P (mg g ⁻¹)	K (mg g ⁻¹)	Ca (mg g ⁻¹)	Mg (mg g ⁻¹)	Zn (mg kg ⁻¹)	Cu (mg kg ⁻¹)	Mn (mg kg ⁻¹)
With barrier	13.3	1.21	18.1	2.65	1.92	11	11	24
No barrier	12.2	1.50	17.1	2.32	1.53	8	8	19

ents in the maize leaves were higher in the subplots with than without root barrier (Table 5), suggesting that root competition was partly for nutrients. However, owing to considerable variability the difference was only significant at the 5% level for Zn and Cu ($P < 0.06$ for K). A reduction of foliar Zn levels of maize under high tree competition has earlier been reported from this site (Schroth et al., 1995).

In the *Gliricidia* and *Senna* plots, maize yields were reduced rather than increased by the root barrier, which provoked a marked yield depression at the interface. In the first crop row from the hedges, the reduction was significant at $P < 0.01$ in the case of *Senna* (LSD test). This suggests that a major effect of the barriers was to limit the rooting volume of the maize by excluding its roots from the soil beneath the hedges. The intrusion of maize roots into the soil under *Grevillea robusta* hedgerows has been reported (Huxley et al., 1994). A similar explanation was given by Willey and Reddy (1981) for growth reductions and pale leaf color of millet when its rooting zone was separated from that of intercropped groundnuts. Foliar nutrient levels of maize were not significantly reduced by the root barriers (data not shown), but water uptake may have been affected. The greater rooting volume of the maize at the interface may explain why in the subplots without barrier the yield of the crop row next to the *Gliricidia* and *Senna* hedges tended to be slightly higher than that of the adjacent row (Figs. 2 and 3).

Two years after their installation, the root barriers were certainly less efficient in excluding tree roots from the alleys than in excluding maize roots from the soil

below the hedges. This may partly explain the yield depressions at the interface in the *Gliricidia* and *Senna* subplots with root barrier. Further factors may have been some shading during the final stages of maize development in the *Gliricidia* (and *Calliandra*) plots, poor germination and increased seed predation as indicated by the reduced plant numbers in the same treatments (Fig. 3), and presumably an increased percentage of resown plants which gave lower yields per plant. In the subplots without barrier, these negative influences of the trees were apparently entirely compensated by the increased rooting volume of the maize at the interface, so that yield depressions did not occur (Figs. 2 and 3). The *Calliandra* hedges, however, were apparently too competitive, so that the maize could not profit from the increased rooting volume at the interface.

A more speculative reason for the yield depression of the maize in the *Gliricidia* and *Senna* subplots with root barrier is that the tree roots may have had a favorable effect on the crop by improving soil physical, chemical and biological properties of the soil, or through nutrient release from hedge roots killed during soil tillage (Table 6), and that these were reduced at least temporarily by the root barrier. Yamoah et al. (1986a) reported increased maize yields near *Leucaena* hedges in unfertilized alley cropping plots with prunings removed and explained this with litterfall, but Young (1989) suggested favorable root effects as an additional explanation. In fertilized plots this was outweighed by tree competition. Our soils were inherently nutrient poor and unfertilized, and the mulch produc-

Table 6

Macronutrients (kg ha⁻¹ dm⁻¹) contained in the *Senna* roots shown in Fig. 4 as obtained by linear interpolation of the root mass between the points of measurement from 0.4 to 3.2 m and multiplication with nutrient concentrations

N	S	P	K	Ca	Mg
5.6	0.6	0.4	2.3	4.9	1.0

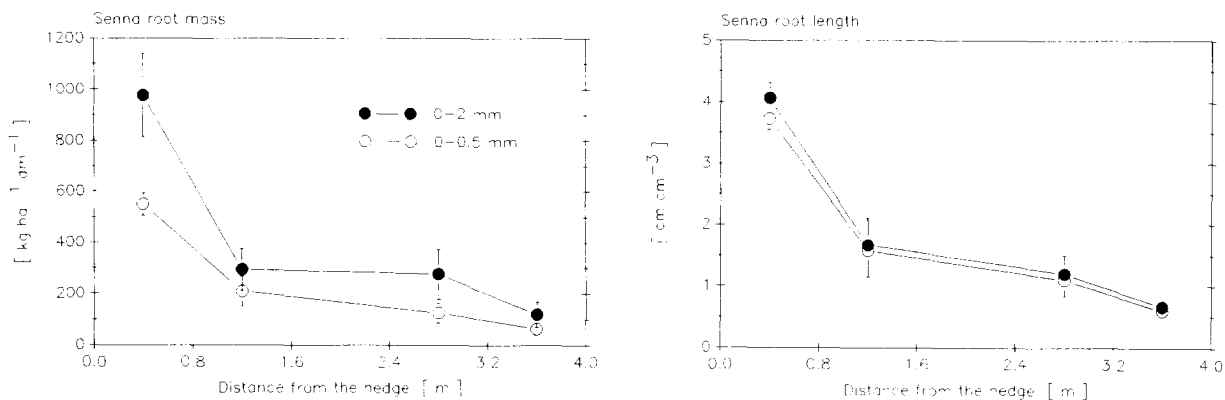


Fig. 4. Root mass and root length density of *Senna siamea* in 0–10 cm soil depth between the ridges as a function of the distance from the hedges in the open alleys (live + dead roots; means and SE).

tion of the hedges was low. It seems likely that positive effects of tree roots on crop growth are most easily detected under conditions of poor soil fertility in combination with low external inputs.

The low root density of *Gliricidia sepium* and consequently low root competition with crops has repeatedly been observed (Budelman, 1990; Schroth and Zech, 1995), although the spreading growth habit of this species favors competition for light. *Senna siamea*, however, is notorious for its intense and competitive root system when grown as a tree (Von Maydell, 1986; Schroth et al., 1995), and *Senna* roots were found up to a distance of 3.6 m from the hedges (Fig. 4). However, the root system of regularly pruned hedges of *Senna siamea* seems to be less competitive than that of trees of this species, probably because of their lower biomass and consequently nutrient and water consumption. Yield depressions of rice and maize in alley cropping with *Senna siamea* have been reported by Danso and Morgan (1993a,b), but the trial design did not allow differentiation between shoot and root competition.

The high competitiveness of the *Calliandra* root system may have been due to high nutrient and water consumption, as the *Calliandra* hedges regrew vigorously after the July pruning, but allelopathic effects must also be considered in future studies. Although the root density of *Calliandra* could not be quantified (see Methods), it seemed to be quite dense. Gichuru and Kang (1989) observed no yield depression of maize adjacent to *Calliandra* hedges, while yield reductions of cowpea were attributed to shading. This trial was

carried out on a much more fertile site than our experiment, so that nutrients and water may have been less growth-limiting.

4. Conclusions

Numerous above- and below-ground processes may occur simultaneously at the tree–crop interface, from modifications in microclimate and pest activity to reciprocal root competition, changes in soil fertility and allelopathic interactions. The sum of these effects determines whether crop growth at the tree–crop interface is depressed, not affected or even improved. Because of the complexity of these processes and the incompleteness of root separation by mechanical barriers (Singh et al., 1989; Schroth and Zech, 1995), these are hardly suited to quantify root competition exactly, but may give qualitative information about the relative competitiveness of different tree root systems. From the results of this experiment it is clear that the root system of *Calliandra* was markedly more competitive than those of *Gliricidia* and *Senna*, resulting in yield depressions at the tree–crop interface, which could be reduced by root barriers, in the association with *Calliandra*, but not the other two tree species. This makes *Calliandra* more suited for fallow improvement than for tree–crop associations at this site. Possible reasons for this competitiveness include high root length density, high nutrient and water uptake rates, allelopathic effects or possibly even the promotion of root diseases. More research should be conducted on

the identification of those characteristics which determine the net effect of a tree root system on associated crops under different management conditions in agroforestry.

This work gives also some indication that the proximity of tree root systems can increase crop yields. This was probably due to an increased volume of the crop rooting zone at the tree–crop interface, but favorable effects of tree roots on soil fertility also seem possible. The question of whether or not a crop can profit from favorable effects of neighboring trees depends on the competitiveness of the trees, and probably on soil conditions.

In addition to tree species selection, the choice of alley width influences final crop yields by determining the percentage of the cropped surface that is influenced by interface effects. The results presented suggest that on the site of this study, wide alleys between multiple hedges would be preferable to narrow alleys between single hedges.

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