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Root length dynamics in agroforestry with *Gliricidia sepium* as compared to sole cropping in the semi-deciduous rainforest zone of West Africa

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Abstract

Tree root systems may improve soil fertility through carbon inputs, uptake of leachable nutrients and maintenance of soil biomass, but can at the same time reduce crop yields by competition for water and nutrients. Quantitative information about the positive and negative effects of tree roots and their changes in space and time are necessary for the optimization of agroforestry associations. An alley cropping experiment was layed out as a randomized complete block design on a Plinthic Lixisol/Ferralic Cambisol with *Gliricidia sepium* hedgerows at 5 m distance, including a sole cropping control. The development of root systems was monitored by sequential soil coring (eight samplings) during one year, with maize and groundnut as crops. Additional information is presented from a single sampling for rice during the foregoing year. Pronounced fluctuations of live root length density indicated an important variability in the nutrient and water uptake capacity of the vegetation. At low total root length density, the hedgerows affected the root development in the agroforestry plots directly by the presence of their root systems. At high root length density, they affected root development mainly by improving crop root growth and influencing the composition of the spontaneous vegetation. The root length density of the hedgerows was too low to compete with the crops for soil resources. The hedgerows tended to increase root length densities in the subsoil when few roots were present, thus possibly reducing the risk of nutrient leaching. However, the length density of the perennial root systems decreased during the cropping season, presumably as an effect of repeated pruning, and attained minimum values almost at the same time as the crops. Trees with denser root systems which are less frequently pruned may be more efficient in achieving closer nutrient cycles, though at the cost of higher root competition with crops.

Introduction

Plant root systems play a central role in the development of soil fertility. They are a source of carbon inputs into the soil organic matter pool; they take up mobile nutrients from the soil solution, thus protecting them from being leached; and they contribute significantly to the maintenance of soil biomass, among other functions. The creation of closer nutrient cycles and increases of carbon inputs into the soil through perennial root systems are among the major reasons for integrating trees into cropping systems in agroforestry (Young, 1989). However, the role of tree root systems is ambiguous: in some situations they may depress crop yields by root competition for water and nutrients (Ong et al., 1991; Rao et al., 1991; Schroth et al., 1994; Singh et al., 1989) and possibly allelopathic effects (Inostrosa and Fournier, 1982; Suresh and Vinaya Rai, 1987). When designing agroforestry systems, all of these possible effects of tree roots must be taken into consideration; however, in spite of major efforts into tree root research in agroforestry in recent years (Dhyani et al., 1990; Jonsson et al., 1988; Ruhigwa et al., 1992), the effects of tree roots on soils and associated crops in agroforestry associations are still poorly understood. Quantitative information about the positive and negative effects of tree roots, their variability in space and time, their quantity and efficiency relative to the crop roots and possibilities of their management are required. The following study was designed to contribute to this task by monitoring the development of root length density of the different components of an agroforestry and a sole cropping system.

Study site and methods

Location and climate

The study was carried out on the research station Sangoué of the "Institut des Forêts" at Oumé, Central Côte d'Ivoire (6° 17′ N, 5° 13′ W, altitude 200 m). The zonal vegetation is a semi-deciduous rainforest of the association *Celtis-Triplochiton* (Guillaumet and Adjanohoun, 1971). Mean annual precipitation is 1285 mm (1956–1992) with most of the rain falling in two rainy seasons from March to July and from September to November. During the study period, rainfall was below average with 1050 mm in 1991 and 851 mm in 1992.

The experiment was established on a northern, 6–7% slope. The soils were *Plinthic Lixisols* in the lower part of the slope where the study plots were situated (Table 1), and *Ferralic Cambisols* (FAO/Unesco, 1990) on the upper part of the slope, derived from granitic-gneissic rock. The mineralogy of the topsoils was kaolinitic. P availability was low. The subsoil was relatively compact below 80 cm. In the whole experiment, the soil conditions were slightly more favourable in the sole cropping than in the agroforestry plots.

Experimental plots and treatments

On the experimental site the original forest had been removed in 1966 for a plantation of *Terminalia superba* Engl. and Diels. Due to die-back of the *Terminalia*, the plantation had been invaded by other trees and undergrowth mainly of *Chromolaena odorata* (L.) R. M. King and H. Robinson. In 1989, the area was clear-felled and burned after removing the trunks of the bigger trees, and was homogeneously cropped with maize. In 1990, plots of 11 × 15 m were installed in a randomized complete block design with 5 blocks situated on the contour lines. The plots within one block were separated by 2 m wide alleys. The treatments were: 1) sole cropping; 2) sole cropping, mulched with hedgerow prunings as in the following treatment; 3) alley cropping with *Gliricidia sepium* (Jacq.) Steud. (Fabaceae) planted at 5 m × 0.25 m spacing, with the hedgerow prunings applied as mulch on the cropped surface of the plots; 4) alley cropping as treatment 3, for the examination of root interactions between hedgerows and crops the respective rooting zones were separated at 50 cm distance from the hedgerows with a plastic awning until 90 cm soil depth shortly after tree planting. In addition to these unfertilized treatments, fertilized alley cropping and sole cropping treatments were also included in the experiment, but are not considered here. Three hedgerows were planted in each agroforestry plot in June 1990, using 4 months old bagged plants. From the 5 m wide alleys between the hedgerows, only the central 4 m were tilled and cropped, leaving untilled areas of 0.5 m width on each side of a hedgerow. Only the central 7 × 10 m of a plot was used for measurements.

In 1990, the plots were cropped with yam (*Dioscorea alata* L.), which was harvested in December. The plots were tilled by hand hoe ("daba") to about 10 cm depth on 28th/29th March 1991, creating a flat seed bed, after cutting weeds and crop residues at soil level. In the unmulched sole cropping treatments, the biomass was burned according to local practice, and the ash was distributed in the plots. In the agroforestry and mulched sole cropping plots, the biomass was distributed on the soil surface as mulch after tillage. The same procedure was followed for every subsequent crop. Rice (*Oryza sativa* L., variety IAC 165) was sown at 25 × 25 cm, 4 seeds per hill, on 18th to 20th April, leaving 62.5 cm between a hedgerow and the nearest crop row. Two weedings were carried out by hand hoe. The harvest was in August/September. Groundnut (*Arachis hypogaea* L.) was grown during the second rainy season, but was not included in the root study. Maize (*Zea mays* L.) was sown on 13th April 1992 after tillage on 6th/7th April. Due to poor germination, it had to be resown on 9th May with the variety Ferke 81–28 at 75 × 50 cm spacing, two plants per hill. 62.5 cm were left between a hedgerow and the nearest crop row. Only one weeding was necessary on 21st May. The maize was harvested on 25th/26th August. After tillage on 2nd/3rd September, the sowing of local groundnut was delayed due to dry weather until 19th September. The groundnut was sown in paired rows with 15 × 15 cm within the double-rows and 60 cm between the double-rows to facilitate mulch application. 1 m was left between a hedgerow and the first double-row. Two weedings were carried out, and the crop was harvested on 22nd December.

The hedgerows were pruned four times per year with a cutlass at 50 cm height, removing all green branches also from lower depths. Slight back-cuttings were carried out in August 1991 and in November 1992 to reduce shading of the crops without affecting the

Table 1. Soil characteristics of the experimental plots of the root study at the beginning of the field experiment (March 1990; CIRAD analysis)

	Sole cropping		Alley cropping	
	0–15 cm	15–30 cm	0–15 cm	15–30 cm
Clay%	23	29	18	26
Silt%	12	10	11	10
Sand%	65	61	71	64
C_{org} (g kg^{-1})	13.5	5.3	10.9	5.0
N_{tot} (g kg^{-1})	1.52	0.82	1.30	0.74
P_{avail} (mg kg^{-1})	18	5	15	5
ECEC (cmol$_c$+ kg^{-1})	8.10	3.90	6.58	3.91
$Ca^{2+}{}_{ex}$ (cmol$_c$+ kg^{-1})	6.68	2.39	5.25	2.68
$Mg^{2+}{}_{ex}$ (cmol$_c$+ kg^{-1})	1.53	0.94	1.34	0.84
$K^{+}{}_{ex}$ (cmol$_c$+ kg^{-1})	0.53	0.45	0.57	0.34
pH (H_2O)	7.4	6.4	7.2	6.8
pH (KCl)	7.2	5.3	6.9	5.6

hedgerows more than necessary. The dry season vegetation was cut at soil level on 19th/20th April 1993, separated into *Chromolaena odorata*, other woody plants and herbs, weighed and subsamples dried at 105 °C until constant weight. In the agroforestry plots, the biomass was quantified separately at the following hedgerow distances: 0–0.5 m (untilled band), 0.5–1.5 m and 1.5–2.5 m. These distances corresponded to the positions for root sampling.

Root sampling and processing

Roots were sampled in June/July 1991 and eight times between March 1992 and April 1993. Only the unfertilized sole cropping and alley cropping treatments (treatments 1 and 3) were included in the root study. At rice and maize flowering (June/July 1991 and July 1992, respectively), the mulched sole cropping treatment was also sampled. Five replicate plots per treatment were sampled in 1991 and two in 1992/93. A sharpened iron tube of 8 cm diameter was driven into the ground at several points in a plot and in depth increments of 0–10 cm, 10–30 cm and 30–50 cm (not included in 1991). In the alley cropping plots, three distances from the hedgerows were sampled separately: 2.5 m, 1 m and 0.25 m (untilled bands beside the hedgerows, not sampled in 1991). The sampling dates were chosen according to presumed minima and maxima in the development of the live root mass.

At every sampling date, four soil cores per plot were taken in the 2.5 m position of the alley cropping plots (6 cores in 1991) and eight cores per plot in all other positions (8–12 cores in 1991). Half of the cores were taken in the middle between two plant rows and half of the cores in the plant rows. Of the latter, one half was taken between two plants and one half on a plant (groundnut) or immediately beside a plant (maize). In 1991, all samples were taken between the rows. The cores taken from the same plot, position and depth were combined, homogenized and a subsample of 300–450 g was taken for root extraction as described by Schroth and Kolbe (1994). This subsample was watered and stored in the refrigerator for one day. Roots of 0–0.5 mm and 0.5–2 mm diameter were extracted by washing over a 0.5 mm sieve and hand sorting under 10 × magnification. Live and dead roots were distinguished according to visual and mechanical criteria (turgescence, elasticity, colour, presence of fresh white root tips), and the length of live roots was determined with the line intersection method (Tennant, 1975). Root length density was used for the description of root systems as it is an important measure of the intensity with which roots penetrate the soil and their ability to acquire nutrients and water (Silberbush and Barber, 1983). The root dry weight (dried at 70 °C for 48 h) was determined with a precision of 0.1 mg. The carbon contents of the roots were measured with a CNS-Elementar Analyzer, and all weights were converted to 45% C content to adjust for mineral particles adhering to the roots. The separate quantification of the hedgerow roots was only possible in June/July 1991 and in July and September 1992.

In June/July 1991, the exclusion of the hedgerow roots from the alleys in the trenched treatment was tested by soil coring, and the root length density of the hedgerows was found to be 22% and 7% of that in the untrenched treatment at 1 m and 2.5 m from the hedgerows, respectively. In 1994 the awnings were excavated and it was found that they had been penetrated by very few tree roots (G.M. Gnahoua, pers. comm.).

Soil analysis

The soils were analyzed by the "Centre de Coopération Internationale en Recherche Agronomique pour le Développement" (CIRAD, Montpellier). Composite soil samples were taken in all plots in March 1990 and were analyzed after air-drying and sieving to pass 2 mm: texture by sieving of the sand fraction ($>50\ \mu$m) and pipette method after treatment with H_2O_2 and sodium hexametaphosphate; pH in destilled water and 1 *N* KCl at a soil-solution ratio of 1:2.5; carbon and nitrogen with a CN-Analyzer by dry combustion; available P after Olsen-Dabin (Dabin, 1967); cation exchange capacity with cobaltihexammine chloride (Fallavier et al., 1985).

Statistical analysis

Yields and root data of 1991 (n = 5) were analysed by ANOVA with a randomized complete block design for data from different plots and a split-block design for data from different positions within the agroforestry plots (roots only) (Little and Hills, 1978). No statistics were applied to the 1992/93 root and biomass data because of insufficient replications (n = 2).

Results and discussion

Development of root length density in cropped areas and effects of hedgerow integration

Although fine root data (0–2 mm) are generally given in this study, most of these belonged to the diameter fraction < 0.5 mm (very fine roots) in all positions. The average contribution of coarser roots (0.5–2 mm) to the total fine root length in 0–50 cm soil depth increased from the sole cropped plots (2%) to the agroforestry plots, and within the latter it increased with decreasing distance from the hedgerows, indicating an increasing contribution of the *Gliricidia* roots (5%, 6% and 9%, respectively, at 2.5 m, 1 m and 0.25 m hedgerow distance). However, even from the hedgerow roots alone, 93% of the fine root length belonged to roots < 0.5 mm in July 1992 and 78% in September 1992. This stresses the need to utilize fine sieves and avoid strong water pressure for washing also in tree root studies.

In the cropped areas, highest root length densities were found at the end of the long dry seasons and at maximum crop root development. These maxima were separated by phases of low rooting densities following the removal of either the spontaneous vegetation or a crop, combined with soil tillage (Fig. 1). The fluctuations in root length density during the year indicate a pronounced variability in the nutrient and water uptake capacity of the vegetation.

The root length densities of maize and groundnut (Table 2) lay within the range reported by other authors (Van Noordwijk and Brouwer, 1991; Zhang et al., 1993). The observed values for rice in 1991 were higher than those reported in the literature (Jones et al., 1979; Van Noordwijk and Brouwer, 1991), possibly due to a certain contribution of roots of graminaceous weeds, although the roots seemed to be very homogeneous. Gregory (1988) reported root length densities of 5–10 cm cm^{-3} in the top 10–15 cm of soil for dryland rice.

Differences in the relative importance of the root maxima in the three soil layers indicate a differing root distribution within the soil profile (Fig. 1). On the average of all positions, the root length densities of maize and groundnut were approximately similar in the topsoil (0–10 cm), while that of groundnut was less than half that of maize in the subsoil (30–50 cm). This indicates that maize had a better ability to use nutrient and water reserves in the subsoil compared to the typically shallow-rooted groundnuts (Norman et al., 1984). Besides the general advantage of maize in this respect, the development of a deep root system may have been favoured by water limitation, while an abundant water supply during the initial development of groundnut probably had the opposite effect.

The sole cropping plots showed lower root length densities in the topsoil than the cropped parts of the alleys under maize and (less clearly) groundnut. This could have been due to the presence of the *Gliricidia* roots and to a better development of the crop and weed root systems in the alleys. In July 1992, *Gliricidia* and maize roots (plus apparently few weed roots) could be distinguished (Table 2). At 0–10 cm depth, only 20% of the difference in root length density between alleys (average of 1 m and 2.5 m) and unmulched sole crop-

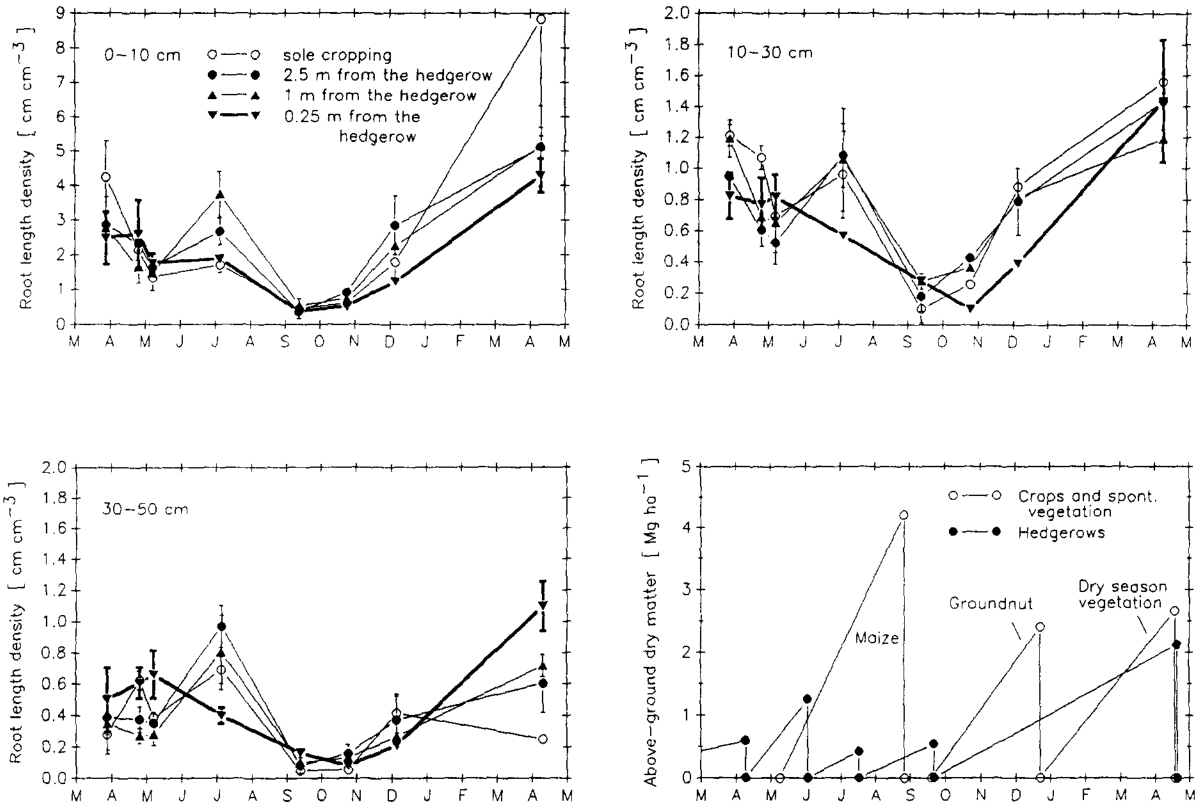

Fig. 1. Changes in length density of live fine roots (0–2 mm) in three soil depths between March 1992 and April 1993 in agroforestry and sole cropping treatments and as a function of the position in the alleys (means and S.E., n = 2), and their synchronization with the cropping cycle.

ping plots could be explained with the contribution of *Gliricidia* roots, 80% being due to a better development of the maize (and weed) root systems. Increased crop root development in agroforestry compared to sole cropping has also been observed by Yamoah et al. (1986). The better root growth in the topsoil seemed to be an effect of mulch application, as can be seen from the mulched sole cropping treatment (Table 2), and may reflect the increased nutrient availability during mulch decomposition and more favourable soil physical conditions under the mulch layer. In December, 58% of the difference in root length density in the topsoil between alleys and sole cropping plots could be explained by a higher root length density of weeds in agroforestry than in sole cropping (6.76 and 2.31 cm cm^{-3}, respectively).

In 1991, the topsoil root length density of rice also tended to be higher in the middle of the alleys compared to the sole cropping plots, with an almost negligible direct contribution of the *Gliricidia* roots (Table 2); however, the difference was not significant. At 1 m distance from the hedgerows, the rice was visibly suppressed by temporal shading from the hedgerows, and this was probably the main reason for significantly reduced root length densities in both topsoil and subsoil ($p < 0.001$ and $p < 0.05$, respectively).

Composition and root systems of dry season vegetation

The composition of the dry season vegetation was quantified after the relatively moist dry season 1992/93 (Fig. 2). In the sole cropping plots, 83% of the biomass belonged to herbaceous plants, mainly grasses. In the agroforestry plots, only 37% of the weed biomass belonged to grasses and other herbaceous plants and 61% to *Chromolaena odorata*, instead of 14% in the sole cropping plots. Herbaceous plants and *Chromolaena* had approximately equal biomass in the alleys, whereas *Chromolaena* contributed 88% and the herbaceous plants only 11% to the weed biomass in the untilled bands beside the hedgerows. The total biomass of the spontaneous vegetation was not reduced by their proximity to the hedgerows, demonstrating the high competitive ability of *Chromolaena* in compari-

Table 2. Length density (cm cm^{-3}) of live fine roots (0–2mm) of rice (June/July 1991), maize (July 1992), groundnut (December 1992) and *Gliricidia* in sole cropping plots (SC), mulched and unmulched, and at two hedgerow distances in the agroforestry plots (AF) (means of n = 5 in 1991 and n = 2 in 1992)

	Crop roots				*Gliricidia* roots	
	SC	SC	AF	AF	AF	AF
Mulch:	no	yes	yes	yes	yes	yes
Hedgerow distance:			2.5m	1 m	2.5m	1 m
Rice[a]						
0–10 cm	14.4	16.8	21.7	13.0	0.21	0.60
10–30 cm	3.36	4.38	4.06	2.76	0.10	0.27
0–30 cm	7.05	8.52	9.93	6.19	0.14	0.38
Maize[a]						
0–10 cm	1.71	4.29	2.33	3.48	0.34	0.27
10–30 cm	0.96	0.95	0.93	0.86	0.15	0.19
30–50 cm	0.69	0.46	0.87	0.74	0.10	0.06
0–50 cm	1.00	1.42	1.19	1.34	0.17	0.16
Groundnut[b]						
0–10 cm	1. 56					
10–30 cm	0.82					
30–50 cm	0. 38					
0–50 cm	0. 79					

[a] Rice and maize roots include weed roots.

[b] Groundnut and *Gliricidia* roots were not distinguished and data can only be given for unmulched SC (mulched SC was not included in the sampling).

Table 3. Crop yields (dry matter, kg ha^{-1}) in trenched and untrenched alley cropping and in sole cropping treatments during four cropping seasons[a]

	Sole cropping	Alley cropping	
		Untrenched	Trenched
Rice grains (unhusked) '91	1755	1816	1707
Groundnut pods '91	80	165	159
Maize grains '92	1608	1422	1301
Groundnut pods '92	445	522	488

[a] Maize and groundnut yields were strongly influenced by drought. The F-test of overall treatment effects was always non-significant at $p < 0.05$.

son to *Gliricidia*. Other woody plants which resprouted from old root stocks in the soil ("shrubs" in Fig. 2) were insignificant in all treatments. The differences in the weed flora between treatments and positions were mainly due to the easier establishment of *Chromolaena* with its perennial root system in the untilled bands beside the hedgerows, whereas the roots were regularly removed during soil tillage on the cropped positions. *Chromolaena* was cut down to soil level at every hedgerow pruning, but resprouted rapidly and invaded the field strips during the dry season. An additional factor may have been the more humid microclimate between the *Gliricidia* hedgerows (Schroth, 1994). A shift from grassy to broadleaved weeds in alley cropping has also been observed by Siaw et al. (1991).

The differing composition of the weed flora explains differences in the root systems of the dry season vegetation between the cropping systems. In the topsoil, the sole cropping plots had the highest (but highly variable) root length densities of all posi-

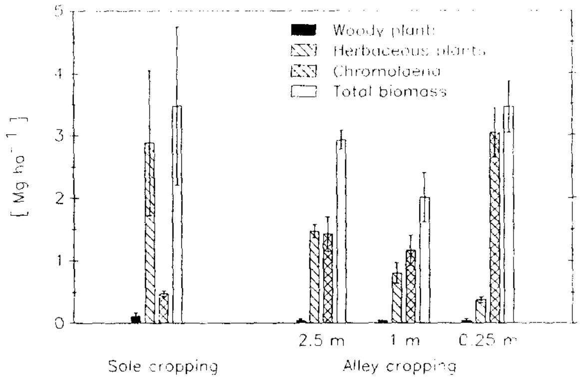

Fig. 2. Biomass of the spontaneous dry season vegetation in sole cropping and three positions of the agroforestry plots in April 1993 (dry matter, means and S.E., n = 2).

Table 4. Relation between the length densities of fine roots (0–2 mm) of maize and *Gliricidia* (n = 2),and of rice and Gliricidia (n = 5) at two distances from the hedgerows in the agroforestry plots at flowering of the crops. Weed roots were not distinguished from crop roots

	Maize/*Gliricidia*		Rice/*Gliricidia*	
Distance from hedgerow	1 m	2.5 m	1 m	2.5 m
0–10 cm	12.8	6.8	21.9	103.3
10–30 cm	4.5	6.3	10.3	40.2
30–50 cm	12.1	8.9		
0–30 cm	–	–	16.4	72.4
0–50 cm	8.6	7.1	–	–

tions at the end of both dry seasons, in contrast to the rest of the year, while the opposite was true in the subsoil. This was due to the high contribution of grasses with very dense, but shallow root systems. In the agroforestry plots, hedgerows and perennial weeds exploited the topsoils less intensively than the grasses, but had deeper root systems.

Development of root length density under the hedgerows

The root length density in the uncropped bands under the hedgerows (0.25 m hedgerow distance) showed a pronounced "anti-cyclic" development, with a marked decrease during the rainy season until September or October and an upsurge during the long dry season, reaching maximum values at the beginning of the cropping seasons in both years (Fig. 1). The decrease was probably a consequence of the frequent removal of the photosynthetic biomass of hedgerows and associated perennial weeds during the cropping season when the hedgerows were pruned, while the fine root systems were reconstituted during the long dry season. This is discussed in more detail elsewhere (Schroth, 1994). At maize flowering, the lowest rooting densities from all positions were found under the hedgerows. To these, the hedgerows contributed only 27% in the topsoil and 33% in 0–50 cm depth, the remaining being maize and weed roots. During the groundnut season, root length densities were also lower under the hedgerows than in the cropped parts of the systems (Fig. 1). The direct effect of the replacement of crops by trees with their less intensive root systems was thus a considerable decrease in total root length density in the proximity of the hedgerows.

Although the hedgerow roots were able to penetrate the whole field strips (Table 2), none of the crops in this experiment showed a significant positive yield response to root trenching between the hedgerows and the crops (Table 3). This can be explained with the much lower density of the hedgerow root systems compared to those of the cereals (Table 4). The situation was approximately similar for mature groundnut roots, which could not be quantitatively separated from the hedgerow roots in the alleys, but did not differ much from maize in their length density (Fig. 1). "The sharing of soil nutrient and water resources by competing plants is proportional to their effective rooting lengths" (Bowen, 1985), although other parameters like root diameter, mycorrhization, presence of root hairs, physiological uptake characteristics etc. also determine the efficiency of a root system in nutrient and water uptake (Eissenstat, 1992; Goss et al., 1993). However, these did not apparently compensate for the low root length density of the hedgerows.

The low density of the root system of *Gliricidia sepium* in alley cropping has also been found by other authors (Budelman, 1990; Rao et al., 1993). In contrast, *Leucaena leucocephala* has a more intensive root system than *Gliricidia* (Budelman, 1990; Rao et al., 1993), and root competition has repeatedly been reported from associations with this species (Ong et al., 1991; Rao et al., 1991; Singh et al., 1989).

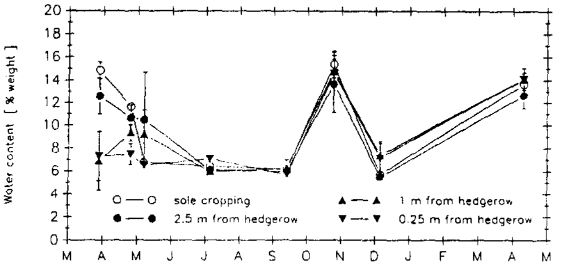

Fig. 3. Changes of the gravimetric water content in the soil (0–10 cm) in sole cropping and three position of the agroforestry plots (means and S.E., n = 2).

Effects of hedgerows on root length density at low crop and weed development

During phases without crops or a vigorous weed stand, a dense tree root system is desirable for the reduction of nutrient leaching. This is particularly relevant at the onset of the rains after the long dry season, usually leading to a mineralization flush in the soil (Greenland, 1962), between two successive crops within a year and after the harvest of the second crop in case of late rainfall.

At the beginning of rainy seasons, the hedgerows reduced the total root length density in the topsoil and increased it in the subsoil (30–50 cm). Also, the topsoil (but not the subsoil) water contents were reduced by transpiration and interception of the hedgerows (Fig. 3). This may indicate a certain protection against nutrient leaching, especially after the destruction of roots in the topsoil by tillage.

During the short dry season, the subsoil root length density was higher in the agroforestry than in the sole cropping plots (Fig. 4). The *Gliricidia* roots contributed 39 and 23%, respectively, to the total root length densities in 0–50 cm at 1 m and 2.5 m from the hedgerows in the alleys. Thus, the perennial roots may have had a certain protective effect against leaching in this situation, but it was limited by the low intensity of the root systems of hedgerows and perennial weeds themselves.

After the harvest in December, the soil was very moist due to some late rainfall. The spontaneous vegetation developed rapidly and probably took up most of the nutrients released by the groundnut residues. No root sampling was conducted at this stage, but the visual impression suggested that during the following weeks the most important effect of the hedgerows was to favour the rapid colonization of the alleys by *Chromolaena odorata*, while grasses and smaller dicotyledoneous plants dominated the vegetation of the control plots. Thus, the development of deeper root systems in the agroforestry plots and denser root systems in the topsoils of the control plots began already at this time.

Table 5. Root mass/length ratios (dry matter with 45% C content, means and standard errors) of live fine roots (0–2 mm) from 0–50 cm soil depth (0–30 cm for rice)

Species	Mass/length ratio (mg m^{-1})
Gliricidia	20.5 ± 3.5 (n = 12)
Maize	5.76 ± 0.46 (n = 6)
Rice	1.35 ± 0.04 (n = 28)
Groundnut	9.99 ± 2.12 (n = 2)
Spont. vegetation, sole cropping	
- March '92 and April '93	2.98 ± 0.30 (n = 4)
- Sept. and Dec. '92	5.78 ± 0.45 (n = 4)

Relating root length to below-ground biomass

The root weight/length ratio indicates the relationship between the intensity of soil penetration by a root system and belowground biomass allocation. *Gliricidia* needed about $3\frac{1}{2}$ times more biomass to produce a unit length of fine roots than maize and two times as much as groundnut (Table 5). Among the crops, rice had by far the finest roots (the mass/length ratio was more than 15 times lower than that of *Gliricidia* and 4.3 times lower than that of maize), and this was certainly a major reason for the ability of this crop to build up the highest root length densities observed in this study (Table 2). Comparable weight/length ratios have been reported for some grass species (Van Noordwijk and Brouwer, 1991). The root morphology of the spontaneous vegetation was variable. In the sole cropping plots, the lowest weight/length ratios were found at the beginning of the rainy seasons (March, April), when the vegetation was dominated by grasses with very fine roots. During the rainy season, the ratio was considerably higher, reflecting a higher contribution of dicotyledoneous weeds. Several root properties are related to diameter and thus weight/length ratios, like nutrient uptake rates, plasticity, longevity and mycorrhizal dependency (Eissenstat, 1992) and may influence the relative efficiency of tree and crop roots in agroforestry associations as well as the importance of different root systems for carbon dynamics. The

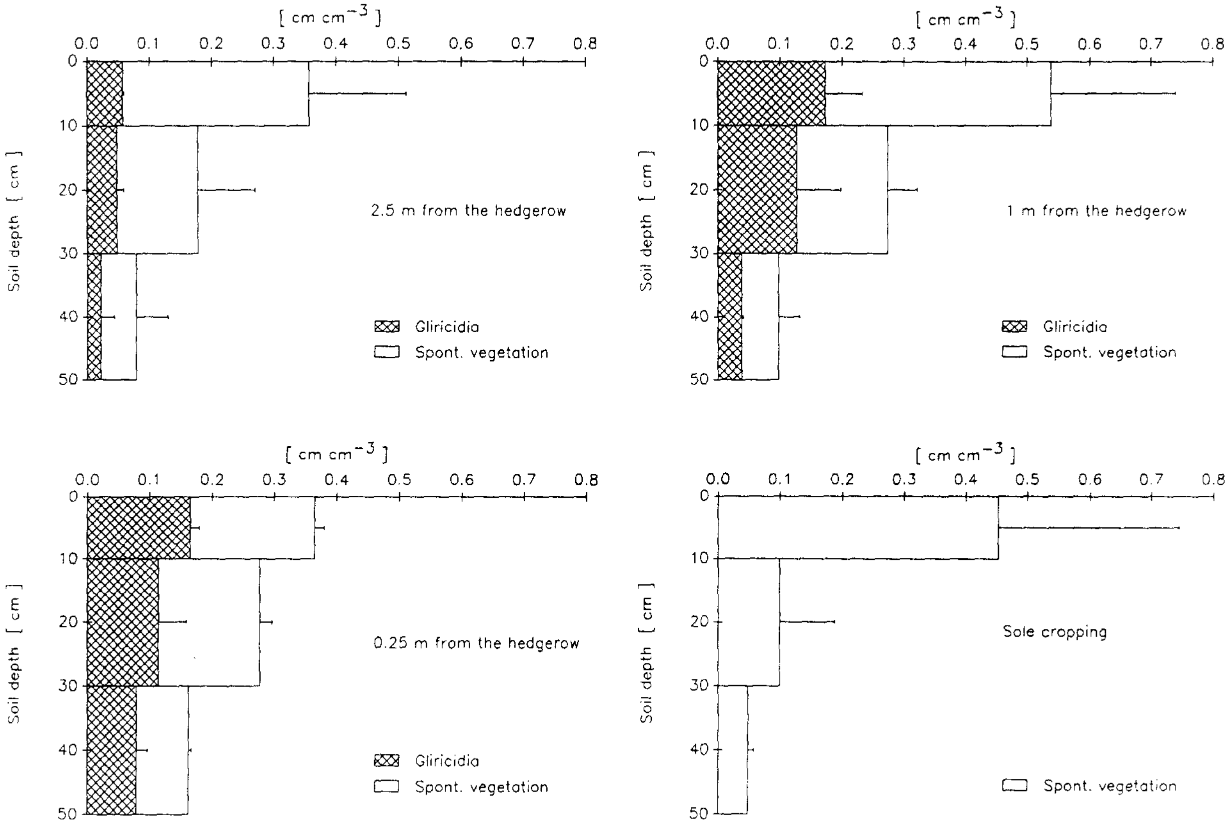

Fig. 4. Live fine root length density (0–2 mm) in sole cropping and three positions of the agroforestry plots during the short dry season in September 1992 (means and S.E., n = 2).

turnover of above- and below- ground biomass in this experiment is discussed elsewhere (Schroth, 1994).

Conclusions

The hedgerows not only influenced root length density in the agroforestry plots directly by the presence of their root systems, but also by improving crop root development through the favourable effect of mulch and by favouring the development of dicotyledoneous perennial weeds with their deeper root systems instead of shallow-rooted grasses.

The root length density of the hedgerows was too low to compete with crops for soil resources, and this explains why root trenching had little effect on crop yields in this experiment, despite severe water deficiency in both years. This property makes *Gliricidia sepium* particularly suitable for associations with crops which possess root systems of low own competitive ability, and for climates with a high risk of drought during the cropping season. This, however, is not only a positive aspect of the association with *Gliricidia sepium*. The protective effect of the perennial tree roots against nutrient leaching depends on a sufficient utilization of the soil resources at every instance, especially when no crops are present. There was a tendency for increased root length densities in lower parts of the investigated rooting zone in the agroforestry plots during critical phases for nutrient leaching. However, a major limitation of the potential effects of hedgerows and associated weeds on nutrient leaching was the decline of their root systems during the cropping season, leading to minimum rooting densities under the hedgerows almost at the same time as in the cropped areas. When the primary aim of associating crops and trees is to achieve a closer nutrient cycle, the introduction of tree species with denser root systems and less frequent tree pruning to avoid negative effects on the root systems may be preferable. This would of course also cause an increased danger of root competition between crops and trees.

This study shows that even the root systems of woody perennials can undergo pronounced fluctuations during a cropping season, and sampling dates have to be carefully selected if repeated sampling is not possible. Clearly, more dynamic root studies in agroforestry associations are necessary.

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