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## Below-ground interactions in dryland agroforestry

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### Abstract

This paper discusses the effects of intercropping and tree pruning on root distribution and soil water depletion in an alley cropping system with *Acacia saligna* and *Sorghum bicolor* in northern Kenya. Root distribution was determined by destructive sampling, and the soil water suction was measured with tensiometers and gypsum blocks, both up to 150 cm depth. The root systems of the intercropped trees and crops were distinguished using the natural <sup>13</sup>C discrimination between C<sub>3</sub> and C<sub>4</sub> plants. The root carbohydrate contents were used to estimate plant water stress integrated over time. The highest root length density was always measured in the topsoil, regardless of season or cropping system. In the dry season, the proportion of roots under the tree row compared to the alley was higher than during the wet season; the same was found for the proportion of roots in the subsoil compared to the topsoil. Pruning decreased the total root length density of sole cropped trees by 47%. The highest root length density was found when the pruned trees were intercropped with *Sorghum*. If the trees were not pruned, combining trees and crops did not increase root length density. Intercropping resulted in a spatial separation of the root systems of trees and crops between the hedgerows, *Sorghum* having more roots in the topsoil and the trees having more roots in the subsoil under alley cropping than in monoculture. At the hedgerow of the agroforestry system, however, the root systems of trees and crop overlapped and more roots were found than the sum of roots of sole cropped trees and crops. Soil water depletion was higher under the tree row than in the alley and higher in alley cropping than in monocultural systems. Water competition between tree and crop was confirmed by the carbohydrate analyses showing lower sugar contents of roots in agroforestry than in monoculture. The agroforestry combination used the soil water between the hedgerows more efficiently than the sole cropped trees or crops, as water uptake of the trees reached deeper and started earlier after the flood irrigation than of the *Sorghum*, whereas the crop could better utilize topsoil water. Under the experimental conditions, the root system of the alley cropped *Acacia* and *Sorghum* exploited a larger soil volume utilizing soil resources more efficiently than the respective monocultures. © 1998 Elsevier Science B.V.

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## 1. Introduction

The proposed advantages of agroforestry systems are numerous and have been frequently stated (e.g. Young, 1991). However, especially in simultaneous agroforestry systems, strong competition has been observed between annual and perennial crops, which can seriously reduce crop yields (Sanchez, 1995). Below-ground interactions are the most important aspects concerning yield reduction in the semi-arid tropics where water is the prime factor limiting crop growth (Ong et al., 1991).

Therefore, the central hypothesis of agroforestry (Cannell et al., 1996) is that “the trees must acquire resources that the crop would not otherwise get”. In order to overcome negative aspects of tree-crop combinations, annual and perennial plants should have root systems that capitalize on different soil zones, the tree having deep roots and the crop, shallow roots (Ong et al., 1996). On the other hand, e.g. Schroth (1995) demanded that agroforestry systems have a more closed nutrient cycling than monocultural systems and enrich the soil with nutrients and organic matter. This would require the interaction of the root systems of associated crops.

Studies about root distribution of trees and crops in agroforestry systems are rare, and information about the interactions between root systems are lacking (Schroth, 1995). Very often, it is difficult to distinguish between roots of different plant species (Schroth and Lehmann, 1995; Schroth and Zech, 1995), which then makes it impossible to study the individual root systems in mixed cropping.

In this study, we examined the effects of intercropping and tree pruning on root distribution and soil

water depletion in an alley cropping system with *Acacia saligna* (Labill.) H. Wendl. and *Sorghum bicolor* (L.) Moench in northern Kenya. The following questions were addressed: (1) How does the root distribution of annual and perennial crops react to intercropping? (2) Is the soil moisture uptake of alley cropped trees and crops complementary or do they compete for available soil water.

## 2. Materials and methods

### 2.1. Study site and treatments

The present study was conducted at the experimental plots described by Lehmann et al. (1998a) near Kakuma in northern Kenya from March to August 1996. The natural vegetation was thornbush savanna with *Acacia tortilis* (Forssk.) Hayne and *Acacia reficiens* Wawra. The mean annual precipitation was 318 mm (14 years; W. I. Powell, and Turkana Drought Control Unit, unpublished data), and totals were 302 and 330 mm year<sup>-1</sup> in 1995 and 1996, respectively. The soils were classified as calcareous Fluvisols (FAO, 1990) and were deep and usually loamy, sometimes sandy, with high pH and EC, low organic carbon and nitrogen contents; the bulk density was relatively low and the soils had a high silt and fine sand content (Table 1).

In this study, we were comparing sole cropped (monoculture) and intercropped *Sorghum bicolor* and *Acacia saligna* with and without pruning giving a total of five treatments. During 1994, the alley cropping experiment was laid out with 4 m distance between the tree rows and 1 m distance between the

Table 1  
Chemical and physical characterisation of the soil at Kakuma, northern Kenya

| Depth<br>(m) | Horizon | Bulk density<br>(kg m <sup>-3</sup> ) | pH H <sub>2</sub> O | Organic C<br>(g kg <sup>-1</sup> ) | N<br>(g kg <sup>-1</sup> ) | Particle size distribution (%) |                     |              |                |
|--------------|---------|---------------------------------------|---------------------|------------------------------------|----------------------------|--------------------------------|---------------------|--------------|----------------|
|              |         |                                       |                     |                                    |                            | Coarse sand<br>200–2000        | Fine sand<br>60–200 | Silt<br>2–60 | Clay<br>(2 μm) |
| 0–7          | Ah      | 1.50                                  | 8.6                 | 5.3                                | 0.42                       | 4                              | 35                  | 49           | 12             |
| 7–14         | 2A      | 1.38                                  | 8.9                 | 2.5                                | 0.21                       | 12                             | 65                  | 17           | 6              |
| 14–30        | 3Ah     | 1.25                                  | 8.6                 | 6.4                                | 0.62                       | 5                              | 16                  | 61           | 18             |
| 30–60        | 3Bt     | 1.34                                  | 8.9                 | 5.1                                | 0.43                       | 0                              | 11                  | 74           | 15             |
| 60–107       | 3Btn    | 1.36                                  | 9.2                 | 8.0                                | 0.56                       | 1                              | 4                   | 67           | 28             |
| 107–170      | 4Btz1   | 1.44                                  | 8.7                 | 5.3                                | 0.32                       | 8                              | 23                  | 47           | 22             |
| 170+         | 4Btz2   | 1.41                                  | 8.2                 | 2.3                                | 0.24                       | 3                              | 16                  | 64           | 17             |

trees within the row ( $2500 \text{ trees ha}^{-1}$ ). At the end of March 1996, the trees were pruned at 150 cm height for the first time and the biomass was removed and used as animal fodder. Seven rows of *Sorghum* were planted between the tree rows in the alley cropping system. The *Sorghum* in the monoculture and the agroforestry system were planted with a distance of 50 cm between the rows and 25 cm within the *Sorghum* rows two times in 1995 and once in 1996. On 9 May 1996, 2–4 seeds of *Sorghum* per stand were sown 5 cm deep into the moist soil; stands where no plants emerged were resown after two weeks. The *Sorghum* was thinned to one plant per stand. On 9 August the *Sorghum* was harvested.

The agroforestry experiments were conducted within a runoff irrigation system, which is necessary for a reliable crop production in the dry environment of northern Kenya. Each of the five treatments (*Sorghum* and *Acacia* monoculture, alley cropped *Sorghum* and *Acacia* with pruned and unpruned trees) was randomly arranged within three irrigated basins resulting in a randomized complete block design. The individual plots had a size of  $24 \times 13 \text{ m}$  with five tree rows per plot. The irrigation water was generated from runoff of a nearby mountain range and was guided into channels and the basins. During one heavy rain, the basins could be filled with a maximum of about 500 mm of water. The water was left to infiltrate into the soil, which took from 10 to 15 days depending on the soil water content before the flood. On April 18, 20 and 28 1996, three floods were guided into the basins with a total amount of about 640 mm, which infiltrated by May 5 (Fig. 1). More information about the irrigation system can be drawn from Lehmann et al. (1998a).

## 2.2. Root sampling and processing

Root length distribution was determined by destructive sampling at 0–15, 15–30, 30–60, 60–90, 90–120 and 120–150 cm depth increments with 8–10 cm diameter augers as described in Lehmann et al. (1998a). In the tree plots, additional samples were randomly taken within 0–25, 25–75 and 75–200 cm distance from the tree row. Instead of specific distances, a range was chosen, since this procedure allowed the calculation of root length density per unit area. Three samples per depth and position were obtained in March, five in

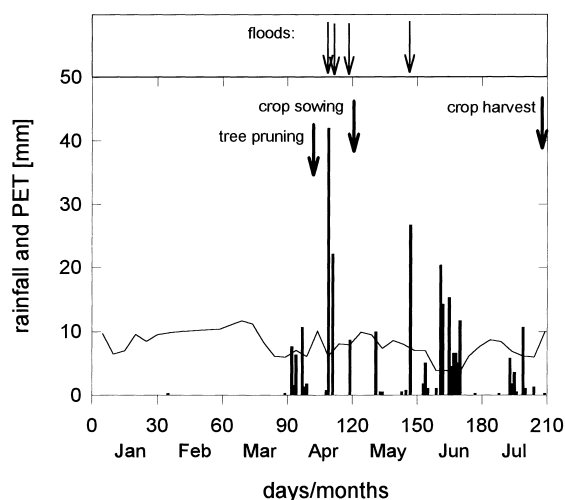


Fig. 1. Rainfall distribution (bars), potential evapotranspiration (line) (K. Droppelmann, personal communication), and management practices at the experimental site near Kakuma, northern Kenya, from January to August 1996.

July 1996, and combined, respectively. With the root sampling at *Sorghum* flowering or early grain filling in July, it was intended to measure the maximum rooting depth of the crop (Robertson et al., 1993). Then, a weighed soil subsample was washed over a 0.5 mm sieve. Live and dead roots were separated according to visual (colour, existence of intact cells) and mechanical criteria (elasticity, stability (Lehmann and Zech, 1998)). In cases of uncertainty, the roots were inspected with a microscope. The consistency of the criteria was verified by the same person throughout the entire study. The excavated roots derived exclusively from either the trees or the *Sorghum*, with the abundance of the spontaneous vegetation being negligible due to a very dry topsoil following the floods. Additionally, the plots were weeded each week to ensure the absence of roots other than from *Acacia saligna* or *Sorghum bicolor*. The root length density was determined by counting the number of intercepts of the roots on a grid of known dimensions according to the line intersect method described by Tennant (1975).

## 2.3. Measurement of the soil water suction

Measurements of soil water suction were made only in the sole cropped and intercropped *Sorghum* and *Acacia* with tree pruning. In the topsoil, gypsum

blocks with a mobile meter were used, since they are more reliable at lower water suctions than tensiometers; the gypsum blocks were calibrated at 0.01, 0.03, 0.1, 0.5 and 1.5 MPa and results were fitted to the manufacturers calibration curve. Tensiometers, however, were found more useful in the subsoil and were operated with a needle insertion meter. During 1994, the tensiometers were inserted at 45 and 150 cm depths at the tree row and in the centre of the alley at a 2 m distance from the trees. In order to prevent preferential water flow along the tubes, the tensiometers were installed with an angle of 60° to the soil surface, and the hole around them was sealed with swelling clay from the site and rubber discs. At 10 cm depth, gypsum blocks were placed at the same positions. In two replicates per treatment, two parallel instruments were installed, but five (monocropped systems) and six (intercropped system) parallel instruments in the third replicate to give better estimates of the spatial variability of the measured data. The readings were done at least once a week, but not during flood events, to ensure that the water flow alongside the tubes was not measured. The readings were shown as soil water suction (kPa), indicating the relative water uptake between the cropping systems as soil water depletion.

#### 2.4. $\delta^{13}\text{C}$ isotope analyses

The natural abundance of the stable isotope  $^{13}\text{C}$  was used to distinguish crop and tree roots. *Sorghum* is a  $\text{C}_4$  plant species, whereas the *Acacia* is a  $\text{C}_3$  plant. It is a well established fact that these two metabolisms discriminate against the heavier  $^{13}\text{C}$  isotope to a different extent (e.g. Ehleringer, 1991). This process can be used to distinguish plant tissues of  $\text{C}_3$  and  $\text{C}_4$  plants (see e.g. Svejcar and Boutton, 1985).

The root samples were dried at 40°C for 48 h and were weighed with an accuracy of 0.01 mg. The relative abundance of  $^{13}\text{C}$  and  $^{12}\text{C}$  was analysed by using an elemental analyser (Fisons 1108) for Dumas combustion of the samples coupled via a ConFlo II Interface with a delta S isotope mass spectrometer (FINNIGAN MAT).  $\delta^{13}\text{C}$  was calculated according to (e.g. Ehleringer and Rundel, 1989):

$$\delta^{13}\text{C} = \left( \frac{(^{13}\text{C}/^{12}\text{C})_{\text{sample}}}{(^{13}\text{C}/^{12}\text{C})_{\text{standard}}} - 1 \right) \times 10^3 \quad (1)$$

with PDB as the standard. Root mass differences were then calculated comparing the root  $\delta^{13}\text{C}$  values of the sole cropped trees and crops and the alley cropping system. The proportions of *Sorghum* and *Acacia* live roots were computed and multiplied by the total live root masses in the tree+crop combination to calculate the root mass of each species (for root mass data see Lehmann and Zech, 1998).

#### 2.5. Determination of carbohydrates

Three replicates of the oven-dried root samples were combined and ground. The samples (5–20 mg) were hydrolyzed with 4 M trifluoroacetic acid (TFA) at 100°C for 4 h in a  $\text{N}_2$  atmosphere. The monosaccharides were purified using charcoal and Dowex 50 resin, and measured with an HP 5890 gas chromatograph using a DB-5 fused column and a FID detector. The carbohydrates could not be fully extracted with the applied TFA hydrolysis, but the comparisons between sampling dates, depths and treatments provide useful information about relative physiological stress and vitality of the roots (e.g. Sandhage-Hofmann, 1993).

#### 2.6. Statistical analysis

Root length distribution was compared across treatments by analysis of variance using a split-block design with the main factor treatment and the subplot factors depth and distance to the tree row (Little and Hills, 1978). The dynamics of the soil water suction were statistically analysed by three-way MANOVA of log transformed data for all depths using a split-plot split-block design with the main factor treatment (sole and intercropped trees and crops with pruned *Acacia* in all distances to the tree row), and the subplots distance to the tree row and time. The individual depths were analysed separately with ANOVA using the same structure. If interactions were significant ( $p < 0.05$ ), a multiple comparison of means was computed using LSD (Little and Hills, 1978).

### 3. Results

#### 3.1. Root distribution

The highest root length density was always found in the topsoil at 0–15 cm depth for all treatments

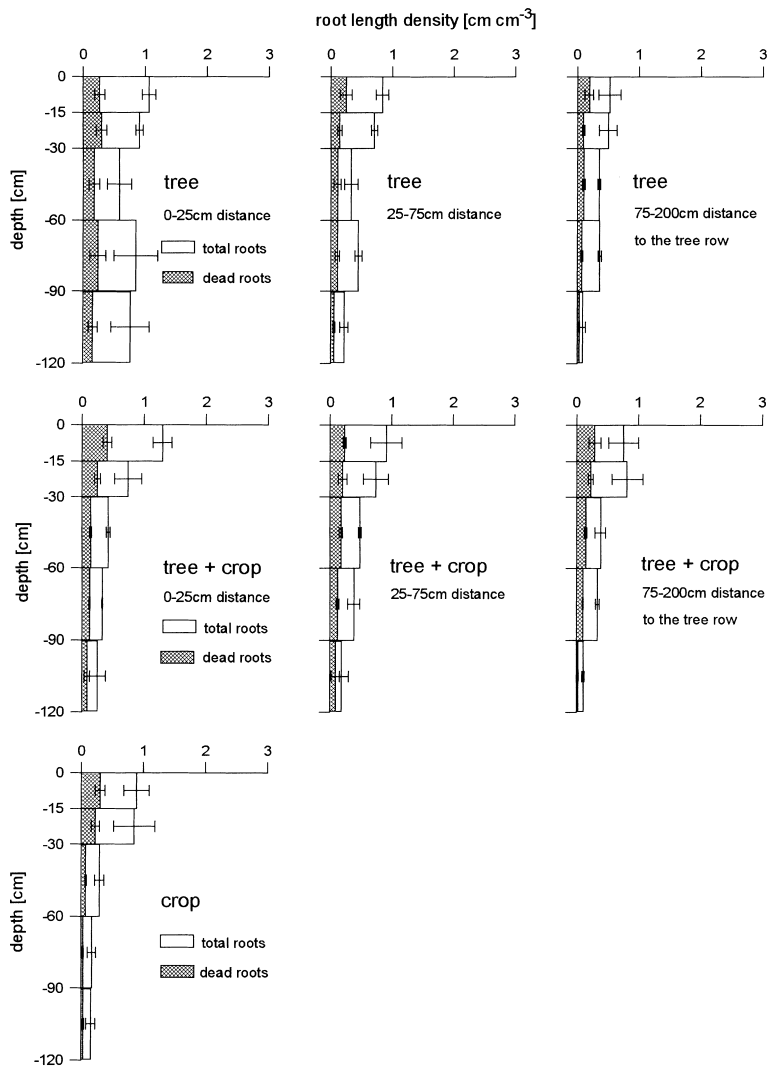


Fig. 2. Root length density distribution of sole cropped and intercropped *Sorghum bicolor* and *Acacia saligna* in Kakuma, northern Kenya, during the dry season in March 1996; dead and total roots ( $n=3$ ); means and standard errors.

(Figs. 2–4; ANOVA  $p<0.05$ ). During the wet season in July 1996, root length density decreased more with depth than during the dry season in March ( $p<0.05$ ). Especially under the tree rows in the tree monoculture, the root length density in March hardly decreased with depth and was higher than during the wet season. Root length density decreased more with depth in the crop and tree+crop systems than in the tree monocultures. Intercropping crops and pruned trees significantly increased root length density compared to the mono-

cultures ( $p<0.05$ ). With increasing distance to the tree row, root length density in the sole cropped trees decreased more during the dry season than during the wet season with 49%, 29% and 22%, and 42%, 32% and 26% for 0–25, 25–75 and 75–200 cm distances to the tree row, respectively (Figs. 2 and 3, significant decrease at  $p<0.05$ ). In the pruned tree+crop combination, root length density did not change with increasing distance to the tree row during the dry season. In July, total root length density at

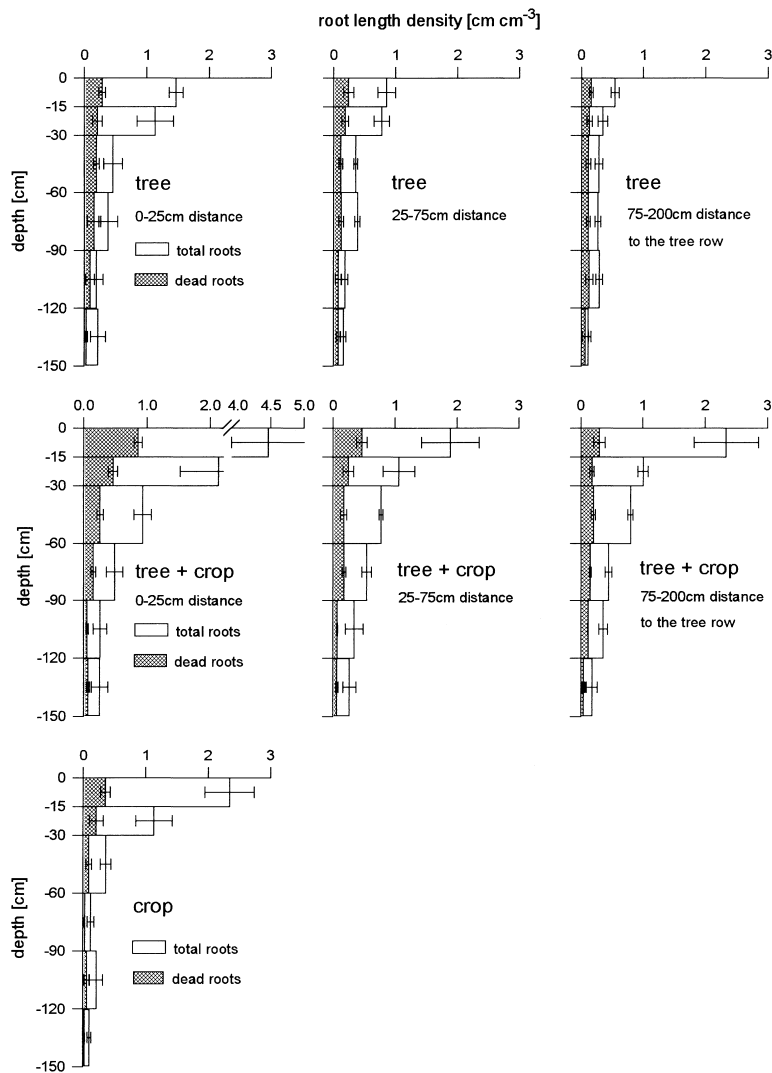


Fig. 3. Root length density distribution of sole cropped and intercropped *Sorghum bicolor* and pruned *Acacia saligna* in Kakuma, northern Kenya, at *Sorghum* flowering in July 1996; dead and total roots ( $n=3$ ); means and standard errors.

0–30 cm depth and 75–200 cm distance to the tree row was similar to that of the sole cropped *Sorghum*; in the tree position, it exceeded the sum of the sole cropped tree plus sole cropped *Sorghum* roots.

When the sole cropped trees were not pruned, total root length density was more than three times higher compared to the tree pruning treatment ( $p<0.01$ ; Figs. 3 and 4). The higher root length density of unpruned trees than pruned trees was observed uniformly through all depths, with root distribution

between top and subsoil being the same. In the tree+crop combination, however, root length density slightly decreased when the trees were not pruned (not significant). This was confirmed by a significant interaction pruning $\times$ intercrop ( $p<0.05$ ).

The ratio of live to dead roots of the sole cropped and pruned trees was similar between wet (2.4) and dry season sampling (2.7), and did not differ from the other cropping systems in March. During the wet season, however, the ratios were higher in the sole

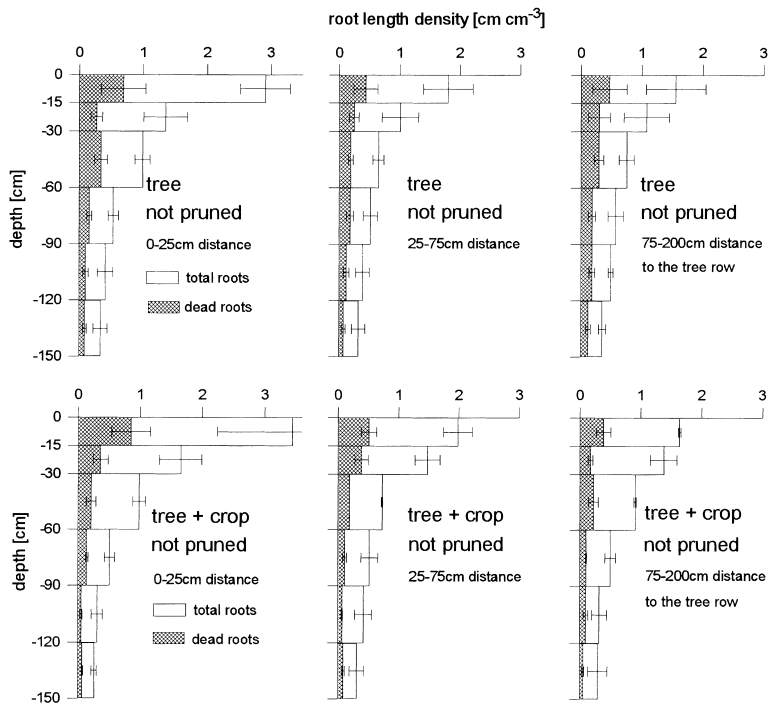


Fig. 4. Root length density distribution of sole cropped *Acacia saligna* and intercropped *Sorghum bicolor* and *Acacia saligna* in Kakuma, northern Kenya, when the *Acacia* were not pruned at *Sorghum* flowering in July 1996; dead and total roots ( $n=3$ ); means and standard errors.

cropped *Sorghum* (3.9) and the tree+crop system (3.4) than the trees ( $p<0.05$ ). The same differences were observed when the trees were not pruned (2.6 for tree monocrop and 3.7 for tree+crop). In March, the ratios were always smaller in the topsoil than below 15 cm depth; in July, they were equal or higher.

### 3.2. Crop and tree root distinction by $\delta^{13}\text{C}$ analyses

The root  $\delta^{13}\text{C}$  values of both sole cropped *Sorghum* and *Acacia* amounted to  $-13.2$  and  $-29.1$  [‰], respectively, and did not significantly change with depth or distance to the tree row (standard errors 0.11 and 0.38 with  $n = 13$  and 30, respectively). Therefore, only the mean values of all depths are shown in Fig. 5 for the sole cropped *Sorghum* and *Acacia* and were then used for the calculation of root mass changes (Fig. 6). When the trees were not pruned, almost all roots derived from the trees at all depths and distances to the tree row. Also under the pruned tree rows below 15 cm depth, the majority of

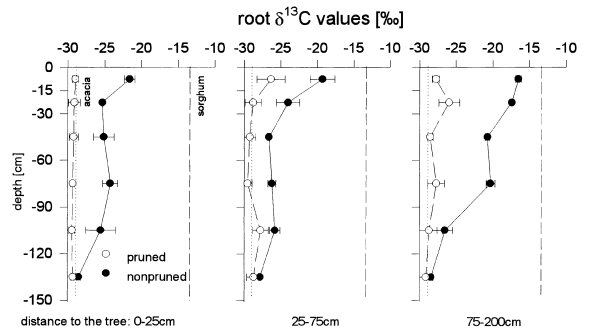


Fig. 5. Proportion of tree and crop live roots of intercropped *Sorghum bicolor* and *Acacia saligna* with pruned and nonpruned trees in Kakuma, northern Kenya, shown as  $^{13}\text{C}$  values ( $n=3$ ); means and standard errors; means of the sole cropped trees and crop values were shown as dotted lines.

roots derived from the trees; in the topsoil, however, already 48% of the total roots were *Sorghum* roots. In the topsoil of the first *Sorghum* row, 62% of the roots were crop roots; in the subsoil, the proportion of crop to total roots was lower than at the tree row. In the alley

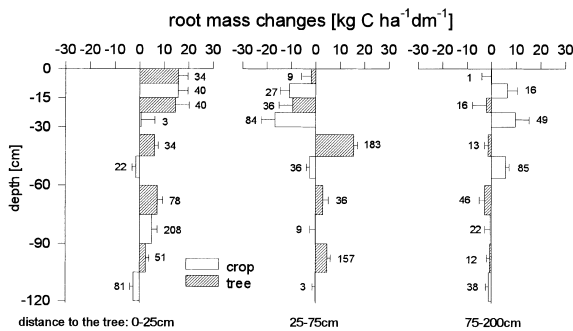


Fig. 6. Gains and losses of live root biomass in intercropped *Sorghum bicolor* and *Acacia saligna* in Kakuma, northern Kenya, compared to sole cropping ( $n=3$ ); numbers at the bars indicate the root mass changes as percentage of the sole cropped systems; means and standard errors.

between the tree rows, the majority of the roots derived from the crop up to a depth of 90 cm.

There were more tree roots under the hedgerow when the trees were cropped in association with the crop rather than in monoculture (Fig. 6). Also, more *Sorghum* roots (40%) could be found in the topsoil (0–15 cm) and at 60–90 cm depth, even though there was naturally no *Sorghum* row at the hedge position. At 25–75 cm distance from the tree row, the amount of topsoil tree and crop roots was lower by up to 84% in the tree+crop combination compared to sole cropping; below 30 cm, the amount of tree roots was lower and the amount of crop roots was higher than in the monocultures. In the alley (75–200 cm distance to the hedge), fewer tree roots were found in the agroforestry system than in the monoculture throughout the whole sampling depth, whereas crop roots were more abundant when alley cropped compared to sole cropping by up to 49% in the topsoil.

Table 2

Carbohydrate concentrations ( $\text{mg g}^{-1}$ ) of live fine roots (<2 mm diameter) of sole cropped and intercropped *Sorghum bicolor* and *Acacia saligna* in the dry season (March 1996) and in the wet season (July 1996) at different depths and distances to the tree row; predicted carbohydrate concentrations of the tree+crop combination from sole cropping and calculated proportions of tree and crop roots

| Season | Depth (cm) | Crop | Tree ( $\text{mg g}^{-1}$ ) |       | Tree+crop measured |       | Tree+crop predicted |       |
|--------|------------|------|-----------------------------|-------|--------------------|-------|---------------------|-------|
|        |            |      | Tree row                    | Alley | Tree row           | Alley | Tree row            | Alley |
| Dry    | 0–30       | 3    | 3                           | 15    | 7                  | 21    | nd                  | nd    |
|        | 60–120     | 32   | 61                          | 28    | 25                 | 45    | nd                  | nd    |
| Wet    | 0–30       | 114  | 57                          | 59    | 50                 | 73    | 84                  | 103   |
|        | 60–120     | 70   | 59                          | 52    | 89                 | 81    | 61                  | 57    |

### 3.3. Dynamics of the soil water suction

Over the whole experimental period, the dynamics of the soil water suction were not significantly different between the three cropping systems ( $p>0.11$ ) or between the tree and alley positions ( $p>0.06$ ); only the suction at 10 cm depth in the alley of the sole cropped trees was significantly lower than in the tree row and in all other treatments ( $p<0.05$ ). Before the first flood, the soil water suction was higher in the tree plots compared to the sole cropped *Sorghum* at 45 and 150 cm depths (Fig. 7). At all depths, the soil water suction decreased after the first flood below 10 kPa. Thereafter, the water suction at 150 cm depth did not change throughout the whole study. During periods when daily rainfall events were always below potential evapotranspiration (approx.  $10 \text{ mm day}^{-1}$ ; Fig. 1), the soil water suction increased at 10 cm depth; after mid June, it increased both at 10 and 45 cm depths. After the last heavy rain in mid June, soil water suction was significantly higher in tree than in alley positions of the tree+crop systems at 10 and 45 cm depths ( $p<0.05$ ), and in the tree system at 10 cm depth ( $p<0.001$ ); no differences between the soil water suction in tree and alley positions were observed at 150 cm depth in sole or intercropped tree plots. During the same period, the soil water suction in the sole cropped and intercropped *Sorghum* was higher than in the sole cropped tree plots.

### 3.4. Carbohydrate contents of the roots

The root carbohydrate contents in the dry season were lower than during the wet season at *Sorghum* flowering (Table 2), and generally higher in the



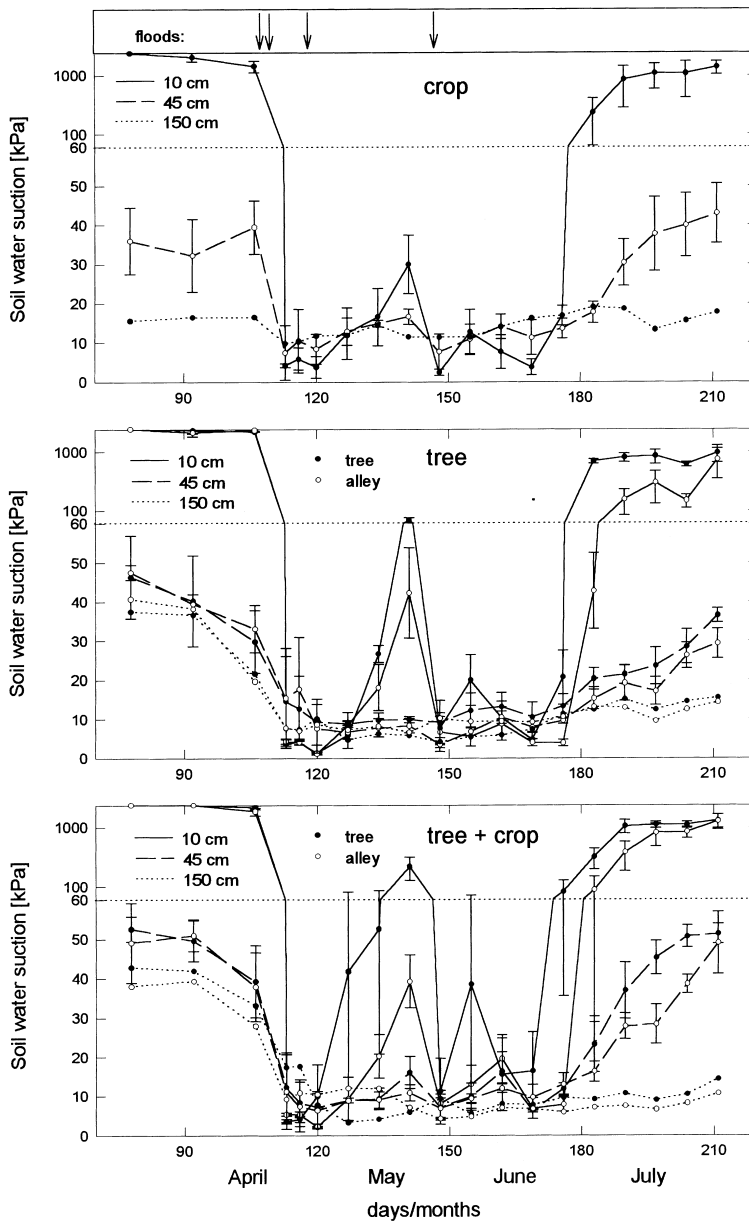


Fig. 7. Soil water suction of sole and intercropped *Sorghum bicolor* and *Acacia saligna* as a function of depth and distance to the tree row in Kakuma, northern Kenya, from January to August 1996 ( $n=3$ ); means, standard errors for reasons of clarity only of 15 and 45 cm depths.

subsoil (60–120 cm) than in the topsoil (0–30 cm). The difference between top and subsoil sugar content was less pronounced during the wet season than during the dry season; in the sole cropped *Sorghum* and in the alley of the sole cropped trees

it was even reversed. The theoretical root carbohydrate contents of trees and crops in the agroforestry combination were above the measured contents for the topsoil, in the subsoil, it was the other way round (Table 2).

## 4. Discussion

### 4.1. Root systems of annual and perennial crops

Through  $^{13}\text{C}$  isotope analyses, our data suggest that tree roots did not reach into neighbouring control plots, as root  $\delta^{13}\text{C}$  values were not lower in the sole cropped *Sorghum* plots than reference values of *Sorghum* roots. Thus, no apparent overlap between annual and perennial roots from different plots occurred in our experiment, which has been described as a major obstacle in alley cropping research (Coe, 1994).

Crop root length density was well within the range reported by other authors for humid tropical (Schroth and Zech, 1995) and temperate environments (Van Noordwijk and Brouwer, 1991). *Sorghum* root length in a runoff irrigation experiment in Mali, however, was up to 80% lower than in our study (Carter and Miller, 1991). Obviously, crop growth conditions were sufficiently improved by establishing the irrigation system to support a comparatively high root abundance even in the dry area of northern Kenya.

The amount of tree roots was in the range of results from other studies in tropical alley cropping systems (e.g. Schroth and Lehmann, 1995). During the dry season in March, the tree roots were uniformly distributed within the sampling depth; in the wet season, however, the highest root length density was found in the topsoil. In humid Côte d'Ivoire, Schroth et al. (1995) also found the root maximum of nine tree legumes in the upper 10 cm, whereas in an arid region in north-western India, five out of 12 tree species had more roots in 15–30 cm than in 0–15 cm (Toky and Bisht, 1992). The tree root data also suggest that plant rooting conditions were favourable in the runoff irrigation system in northern Kenya compared to other studies even from humid regions.

### 4.2. Seasonal root changes

Most of the tree roots were always found in the topsoil even during long and pronounced dry seasons, and the ratio of live to dead roots did not change when the topsoil was depleted of plant available soil moisture. The root carbohydrate content, however, decreased in the topsoil during the dry season, suggesting that carbohydrates may have been retranslocated from the topsoil to the subsoil roots, because

water supply was not sufficient in the upper 30 cm. Similar results were reported by Erdmann et al. (1993) in Nigeria who found increasing starch contents of roots of *Gliricidia sepium* during the wet season. The topsoil roots have probably been dormant with a low vitality in our study and may be rapidly reactivated after the onset of the rains. Thus, the tree established a permanent root system even in the topsoil although the topsoil dried up periodically.

Below 60 cm depth, the soil water suction may have been low enough for root growth that was not restricted by soil water, since the sugar content of the trees in July equalled that of March. During the dry season in March, the trees exhibited an increasing subsoil root system compared to the topsoil, in order to reach zones of high soil moisture reserves. This was apparently not as necessary during the wet season as during the dry season. This may offer a possibility for the demanded complementary use of soil resources in tree+crop combinations (Sanchez, 1995), when the tree root system expanded into the subsoil due to lack of soil water in the topsoil but sufficient soil moisture in the subsoil. Then, the crop can occupy soil volume for root development at the onset of the rainy season, and tree-crop competition may be reduced during the vegetation period.

### 4.3. Effects of intercropping on root distribution

When intercropping trees and crops, the tree root system expanded more into the subsoil and contracted below the tree canopy; between the tree rows, the amount of *Sorghum* roots increased in the topsoil. Huxley et al. (1994) and Eastham et al. (1990) also found a deeper root penetration of trees influenced by an annual intercrop. But a spatial separation of the root systems of trees and crops were not the only result of intercropping *Acacia* and *Sorghum* in our study. The observed high root abundance under the tree row was not a mere overlapping of the two root systems, but an invasion of *Sorghum* roots into the main root zone of the tree. This has not been described in the literature up to now, possibly due to the difficulty of distinguishing the root systems.

What are the reasons for the two observations, separation and overlapping of the two root systems in the agroforestry combination? The separation of the root zones can be explained by competition and

complementary use of soil resources. When grown in association, trees, with their deeper root system, may invest more into the subsoil root zone to avoid competition for water and nutrients (see below). The observed contraction of the tree root system during the dry season could have been advantageous for the spatial separation of the root systems especially in this dryland agroforestry system as discussed above. That this more efficient use of soil volume and moisture reserves is beneficial for the total net outcome can be demonstrated by the 50–60% higher biomass production in the agroforestry combination than in either *Sorghum* or *Acacia* monocultures when the trees were pruned (Lehmann et al., 1998b).

The second structure, the overlapping of the root systems, can have two possible reasons: first, the crop was more aggressive in securing soil resources and was able to replace the tree root system. Similar observations were made in alley cropping with different leguminous trees in Togo, where intercropped maize grew better without root barriers between crop and tree than when root penetration was prevented in either direction (Schroth and Lehmann, 1995). The crop was able to use the soil resources underneath the tree and was more competitive than the tree. But the extent to which the *Sorghum* was able to establish a root system beneath the *Acacia* (in 0–15 cm even 40% more than in a *Sorghum* monoculture), suggests a second explanation. Lehmann et al. (1998b) found a higher amount of mineral N and soil solution N in the topsoil under the tree row than in the alley after the flood and tree pruning, and increasing foliar N contents in the *Sorghum* with increasing proximity to the tree row. Thus, a higher N availability was possibly stimulating root production, and the crop roots were able to exploit these nutrient resources. The trees could also have acted as a ‘hydraulic lift’ (Richards and Caldwell, 1987) and supplied the annual intercrop with water, especially when the shoot–root ratio drastically decreased as with pruning. Dawson (1993) could demonstrate that plants neighbouring trees which conduct hydraulic lift can utilize a significant proportion of this water source and exhibit less water stress.

#### 4.4. Effects of tree pruning on root distribution

Root shedding after shoot pruning was also described by Fiala and Studený (1988) for a grassland

stand in eastern Europe. Similar to our study, the ratio of live to dead roots decreased when the trees were pruned. Our results suggest that below-ground competition may be effectively reduced by shoot pruning, as the root length density of sole cropped trees was 70% lower when pruned than not pruned. This is opposed to results from Van Noordwijk and Purnomosidhi (1995) who argued that shoot pruning may have negative effects on root distribution and increase tree-crop competition. In our study, however, the unpruned trees did not develop a deeper root system when intercropped with an annual crop, and the total root length density of the unpruned trees was very high compared to pruned trees or the *Sorghum*. Shoot pruning seemed to favour a separation of the root zones and the complementary use of soil resources.

The marginal increase of roots in the unpruned tree+crop combination compared to the sole cropped trees coincided with the low above-ground biomass production of the *Sorghum* intercrop of 0.7 Mg DM ha<sup>-1</sup> (5.3 Mg DM ha<sup>-1</sup> with tree pruning; Lehmann et al., 1998b). According to our study, root competition was one important reason for the low biomass production when the trees were not pruned. A positive relationship between cutting frequency of hedgerows and intercrop yield was found by Korwar and Radder (1994) in an alley cropping experiment in semi-arid India, stressing the importance of shoot pruning for crop performance; the lower crop yields when trees were not pruned were attributed to higher water competition between annual and perennial crops.

#### 4.5. Do trees and crop compete for water?

Soil water dynamics before the floods indicate that the crop did not take up water from 150 cm depth in contrast to the tree; simultaneous soil water use of both trees and crops would then only occur at 10 and 45 cm depths. Thus, *Acacia* and *Sorghum* encountered competition for water in the tree+crop combination at 10 and 45 cm but not at 150 cm depth, as seen from the higher soil water suctions in the agroforestry system than in either tree or crop monocultures, and from the higher suctions at the tree row than in the alley. The result was confirmed by the carbohydrate measurements: the sugar contents in the roots under alley cropping were lower than expected from the analyses of the roots in tree and crop monocultures. This would

indicate lower plant available soil moisture in the topsoil of the agroforestry system than of the monocultures according to results from Sandhage-Hofmann (1993) who found a close relationship between soil water suction and the carbohydrate content of spruce roots in southern Germany.

The soil suction dynamics also indicate that apart from competing, trees and crops were utilizing soil water in a complementary way. The crop did not take up water from as deep as 150 cm as mentioned before, whereas the trees could utilize this. On the other hand the crops were able to use soil water in the topsoil more efficiently, as seen from the higher soil water suction in the crop based systems than the tree monoculture.

Ong et al. (1991) stated that competition for water is the main problem of alley cropping in the semi-arid tropics. *Sorghum* biomass production in our study, however, was not lower in the proximity of the tree row than in the alley, and grain yield of intercropped *Sorghum* was even higher than that of sole cropped *Sorghum*. Although the crop probably encountered water stress near the tree row due to water competition, that did not lead to a net decrease of biomass production or grain yield compared to the alley position or control. The trees, on the other hand, were affected by the higher water depletion when crops were planted between the hedgerows: intercropped *Acacia* yielded 22% less biomass than when grown alone (Lehmann et al., 1998b).

#### 4.6. Towards harmonizing tree-crop interactions

The root distribution in the presented alley cropping system seemed to meet the central requirements stated for agroforestry systems that benefits of growing trees with crops will occur only when trees are able to acquire resources of water, light and nutrients that the crops would not otherwise get (Cannell et al., 1996). This is especially true for soil water. But an important aspect of agroforestry systems is also the positive effect of trees on crops and vice versa, as mentioned by Schroth (1995): agroforestry systems are expected to lead to a more closed nutrient cycling and to a soil enrichment of organic matter and nutrients through root turnover. This not only requires to minimize interactions as competition, but also to maximize positive effects of trees on crops. These requirements

for simultaneous agroforestry systems will always conflict with each other.

## 5. Conclusions

The tree root systems reacted to the change of dry and wet seasons, and contracted and grew deeper during drought periods. Consequently, soil water depletion was significantly lower in the topsoil between the tree rows than in any other position or treatment even during the following wet season. This 'unused' soil water was utilized by an annual intercrop sown between the tree rows. The fact that the root system of the perennial tree was transferring its activity into the subsoil due to external circumstances like drought (not related to the cropping system) is of high value when designing agroforestry systems. This and related processes need further attention in agroforestry research.

The agroforestry combination was only successful if the trees were pruned, as tree pruning was then reducing below-ground competition. When trees and crops were combined, a further separation of the root zones was observed. Under the tree row and in the topsoil at 25–75 cm distance, however, both tree and crop roots increased compared to sole cropping. The joint exploitation of soil resources or a nutrient transfer can only be realised by an overlapping of the root zones of annual and perennial crops. Thus, external and internal conditions may cause a spatial separation or an overlapping of tree and crop root systems in simultaneous agroforestry systems. In both cases, it can have beneficial effects on the utilisation of soil resources, total biomass production and crop yield.

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