

## Fine root turnover of irrigated hedgerow intercropping in Northern Kenya

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### Abstract

Fine root turnover (<2 mm) was determined from repeated measurements of root distribution up to 120 cm soil depth by core sampling in four month intervals. Sole cropped *Sorghum bicolor* and *Acacia saligna* were compared with the agroforestry combination in an alley cropping system in semiarid Northern Kenya. Three methods for the calculation of root production were used: the max-min, balancing-transfer and compartment-flow method. The highest root biomass was found in the topsoil for all cropping systems, though trees had a deeper root system. Trees and crops had a similar amount of below-ground biomass during the vegetation period (0.3 and 0.4 Mg DM ha<sup>-1</sup> 120 cm<sup>-1</sup>), but in the agroforestry combination root biomass was more than the sum of the sole cropped systems (1.1 Mg DM ha<sup>-1</sup> 120 cm<sup>-1</sup>). The tree system showed a very static root development with little fluctuation between seasons, whereas root biomasses were very dynamic in the crop and tree + crop systems. Root production was highest in the tree + crop combination with 2.1 Mg DM ha<sup>-1</sup> a<sup>-1</sup>, with about 50% less in sole cropped trees and crops. Root N input to soil decreased in the order tree + crop > tree > crop system with 13.5, 11.0 and 3.2 kg N ha<sup>-1</sup> a<sup>-1</sup>, and cannot be estimated from total below-ground biomass or carbon turnover, as N is accumulated in senescing roots. Such low N input to soil stresses the need for investigating other processes of nutrient input from roots to soil. Areas of highest N input were identified in the topsoil under the tree row in the tree system. Resource utilisation and C and N input to soil were highest with a combination of annual and perennial crops.

### Introduction

The nutrient and organic matter input to soil through roots is believed to be an important factor for soil fertility maintenance and carbon sequestration, as the below-ground biomass forms a substantial proportion of the total biomass in an ecosystem. Root turnover may have 4 to 5 times higher C return than above-ground litter (Fogel, 1983), this being the source of 30–60% of the organic soil pool (Heal et al., 1997). Nye and Greenland (1960) assumed that while 20–50% of root litter only 10–20% of leaf litter is transformed into soil organic matter.

In agroforestry, recent studies have mentioned beneficial effects of trees on soil fertility and crop yield for alley cropping systems (e.g. Lehmann and Zech,

1997; Schroth and Lehmann, 1995). The importance of root turnover for the maintenance of soil fertility in agroforestry systems has been frequently stated, and research needs have been stressed (Sanchez, 1995; Young, 1991).

Studies about root turnover are scarce in relation to information about above-ground biomass production, and almost no studies are existing in tropical agroforestry systems (Schroth and Zech, 1995; Smucker et al., 1995). The procedures to measure root turnover are time consuming and expensive, and can be subject to large sources of error (Kummerow et al., 1990; Publicover and Vogt, 1993). Three different methods to calculate root production are described in the literature: the max-min method (Persson, 1978), the balancing-transfer method (Fairley and Alexander, 1985) and the compartment-flow method (Santantonio and Grace, 1987). The compartment-flow method includes a mod-

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Table 1. Chemical and physical characterisation of a representative soil profile at the experimental site

Depth (cm)	Horizon	Bulk density (kg m <sup>-3</sup> )	pH H <sub>2</sub> O	Organic C (g kg <sup>-1</sup> )	N (g kg <sup>-1</sup> )	Particle size distribution (%)			
						Coarse sand (200–2000)	Fine sand (60–200)	Silt (2–60)	Clay (<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

Table 2. Decomposition rates of fine roots (<2 mm) obtained from three different experiments as% day<sup>-1</sup>; for the litter-cylinder method upper and lower values are indicated depending on the time interval chosen; means followed by the same letter are not significantly different at  $p < 0.05$  (LSD calculated from ANOVA); only litter-cylinder applications were compared

Experiment	<i>n</i>	<i>Acacia</i>			<i>Sorghum</i>		
		Mass	C	N	Mass	C	N
Litterbag <sup>1</sup>	4	1.31	1.42	0.60	nd	nd	nd
Litter-cylinder uppervalue <sup>2</sup>	3	1.45 a	1.54 a	1.41 a	1.05 c	1.19 c	0.61 bd
Litter-cylinder lowervalue <sup>2</sup>	3	0.66 b	0.67 b	0.64 b	0.68 b	0.52 bd	0.44 d
<i>In situ</i> measurement <sup>2</sup>	3	nd <sup>3</sup>	nd	nd	0.74	0.82	0.58

<sup>1</sup>Calculated from exponential curve fitted to decomposition data.

<sup>2</sup>Calculated after Publicover and Vogt (1993).

<sup>3</sup>nd, not determined.

el for root decomposition, the other two methods calculate root turnover entirely from fluctuations of live and dead (balancing-transfer) or live root data only (max-min).

This study compares the root biomass distribution, root C and N turnover of sole cropped *Acacia saligna* and *Sorghum bicolor* and their combination in an alley cropping system using runoff irrigation in Northern Kenya. The results are discussed with respect to the applied methodology and their dependency on season, depth and distance from the tree row.

## Materials and methods

### Study site

The present study was conducted near Kakuma in Northern Kenya (34°51' E and 3°43' N, altitude 620 m a.s.l.). Rainfall distribution is bimodal with a maximum during April–May and September–October with mean annual precipitation of 318 mm (from 14 y; W I Powell, and Turkana Drought Control Unit, unpubl.

data), 302 and 330 mm in 1995 and 1996. The soils are classified as calcareous Fluvisols (FAO, 1990); they are deep and loamy, sometimes sandy, with high pH and EC, low organic carbon and nitrogen contents (Table 1; see Lehmann et al. (1997a) for detailed description).

### Experimental design and treatments

An alley-cropping system with *Acacia saligna* (H. Wendl.) was established with hedgerows 4 m apart with a 1 m distance between trees within the row (2500 trees ha<sup>-1</sup>). The treatments used in the present study comprised sole-cropped and intercropped *Sorghum bicolor* and *Acacia saligna* in 3 replicates. The experiment was installed in an irrigation system, which is the precondition of reliable crop production in the studied area. During March to June 1994, the runoff irrigation system was built using a design of leveled basins (Lehmann et al., 1997a). Four basins, each 210×30 m, were laid out in the contour with an individual plot size of 13×24 m. The runoff water originates from a nearby mountain range. The basins could be filled in April/May and August 1994, in May and September

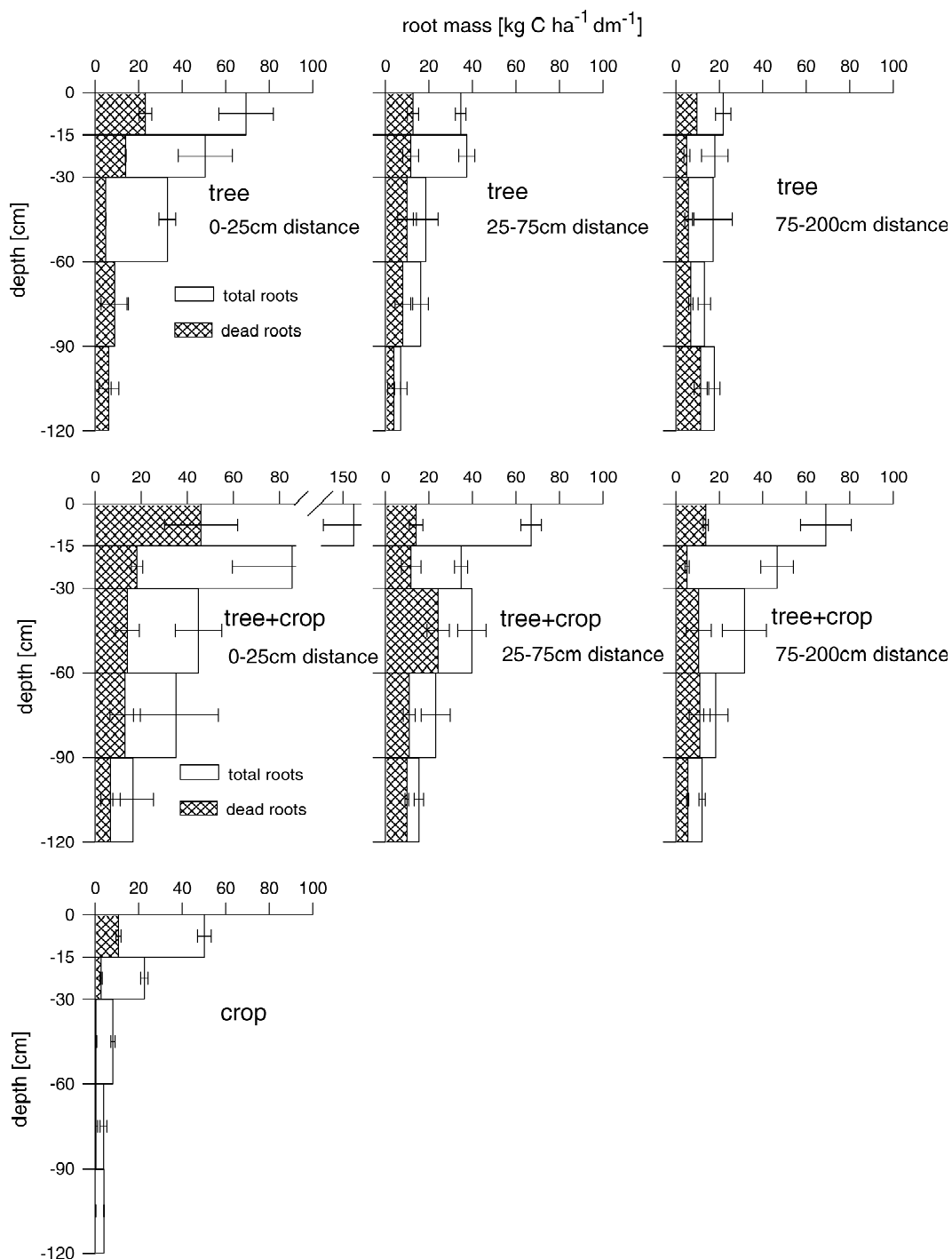


Figure 1. Vertical root C distribution of *Sorghum bicolor*, and vertical and horizontal root distribution of sole cropped *Acacia saligna* and intercropped *Acacia saligna* and *Sorghum bicolor* at *Sorghum* flowering in July 1996; dead and total roots ( $n = 3$ ); means and standard errors.

Table 3. N concentrations of live and dead roots of *Sorghum bicolor* and *Acacia saligna* at *Sorghum* flowering; values followed by the same letter are not significantly different at  $p < 0.05$  (pairwise *t*-test); means and standard errors (SE)

Species	Live root N (mg g <sup>-1</sup> )	Dead root N (mg g <sup>-1</sup> )	<i>n</i>
<i>Acacia saligna</i>	17.8 a	19.8 b	81
SE	0.03	0.38	
<i>Sorghum bicolor</i>	8.9 c	15.8d	26
SE	0.59	0.79	

1995 and in April and August 1996 (see Figure 3) up to a level of about 500 mm. In March 1996, the trees were pruned to a height of 1.5 m, the biomass was taken out of the system and used as fodder. *Sorghum* was sown in rows 0.5 m apart with 0.25 m distance between plants in the row. In this study, three *Sorghum* cropping cycles are presented: from June to August 1995, from September to December 1995, and from April to July 1996.

#### Root sampling and processing

Root distribution was determined by destructive sampling at 0–15, 15–30, 30–60, 60–90, and 90–120 depths (for detailed description see Lehmann et al., 1997a). In the tree plots, samples were randomly taken within 0–25, 25–75 and 75–200 cm distances from the tree row. Instead of specific distances, a range was chosen, since this procedure allows the calculation of root mass per unit area. Three samples per depth and position were obtained (five for July 1996) and combined. A weighed subsample was then washed over a 0.5 mm sieve according to the root sampling procedure outlined by Schroth and Kolbe (1994). The roots were individually separated from other organic material in a petrie dish. Live and dead roots (<2 mm diameter) were sorted according to a catalogue of visual (colour, existence of intact cells) and mechanical criteria (elasticity, stability) which were gathered through microscopic inspection: live *Sorghum* roots were clear and shiny and showed intact cells and a complete stability when taken at one end with a pair of tweezers, dead roots were dark or milky, without stability and no intact cells could be discerned. Live *Acacia* roots were yellowish-white with great stability showing root tips and hairs, and intact cells could be seen after removing the cortex; dead roots could be discerned by their darker colour, and they could be

broken without showing intact cells inside the cortex. When roots fell apart in the petrie dish without the interference of the operator, they would be classified as soil organic matter and not counted as roots. In cases of uncertainty, individual roots were always inspected with the microscope. The consistency of the criteria was verified by the same person throughout the entire study. The excavated roots were derived exclusively from either the trees or the *Sorghum* with a negligible amount of spontaneous vegetation, as the topsoil dried up very quickly after a flood. The plots were weeded each week during the wet season to ensure the absence of roots other than from *Acacia saligna* or *Sorghum*. There was also no contamination of the crop plots with tree roots from the neighbouring plots as it was proven by <sup>13</sup>C measurements (Lehmann et al., 1997b).

Root sampling was done at times of extremes: at *Sorghum* flowering when the most roots were expected and at the end of the dry season, when the lowest abundance of roots was expected. Clear cycles of root development could be seen (Figure 3), which justified the utilization of all root mass differences for the calculation of root turnover and not only significantly different root masses as demanded by Publicover and Vogt (1993) for forest ecosystems. Root mass distribution was given as a function of depth and distance to the tree row for one vegetation and one dry season sampling. Then root mass, C and N dynamics were presented and their turnover calculated.

#### Root decomposition

For the calculation of root turnover, decomposition rates (DR) were determined using three different techniques: (1) a litterbag study with *Acacia* roots, where the roots were exposed to soil in a root-soil mixture and separated by hand from the soil; (2) a litter-cylinder experiment with a root-soil mixture, where dead and live roots obtained from planting pots were exposed in the field; (3) *in situ* measurement of *Sorghum* root abundance after removal of the above-ground biomass in the field, and subsequent determination of the DR.

In the litterbag study, 0.8 g of excavated *Acacia* roots with a diameter <2 mm were mixed with 350 g soil resulting in a root mass of 1390 kg C ha<sup>-1</sup> dm<sup>-1</sup> (*Sorghum* roots were not available at the beginning of the experiment). The roots were placed in 0.5 mm mesh bags at 10 cm depth in four replicates for 13, 47, 125 and 209 days before the cropping season in March 1995. They were dry separated from the soil and analysed for their C and N content. DR was calculated

with a nonlinear curve fit of the residual C and N content using an exponential decay function.

In the litter-cylinder experiment, soil with *Sorghum* or *Acacia* roots was washed over a sieve to gain the root material, and roots were dried from the adhering water. 0.2 g fresh fine roots (<2 mm diameter) were mixed with soil and filled into plastic cores with a volume of 240 cm<sup>3</sup>, giving a total root mass of 181.1 and 231.4 kg C ha<sup>-1</sup> dm<sup>-1</sup> for *Sorghum* and *Acacia*, respectively. The cores were closed on both sides with a steel net (0.5 mm sieve openings). They were placed in the intercropping treatment at 10 cm depth before the cropping season in March 1996 with three replicates. After 72, 118 and 223 days, the cores were removed, the roots were washed from the soil and the mass of live and dead roots was determined as described above. In contrast to the litterbag experiment, the average root diameters were slightly smaller, because they were washed over a sieve and not hand-sorted, and root decomposition was determined using both live and dead root masses. The DR was calculated for each time interval with changes in dead and fine root biomass from the equation for trench plots of Publicover and Vogt (1993) assuming that disappearance only occurs from the dead root fraction:

$$DR = 1 - \frac{DFR_t - \frac{LFR_{t-1} - LFR_t}{2}}{DFR_{t-1} + \frac{LFR_{t-1} - LFR_t}{2}} \quad (1)$$

given DFR as dead fine roots and LFR as live fine roots.

With *in situ* measurements, the *Sorghum* root DR was directly determined from the root mass dynamics obtained from the core sampling described earlier. The decrease of root mass from December 1995 to March 1996 was taken as a decomposition trial. The *Sorghum* was removed after the sampling in December and the plots were kept free from weeds or *Sorghum* regrowth until March through continued weeding. The DR was again calculated using Equation (1).

#### Calculation of root turnover

Root turnover was determined for total amounts of root masses, N and C as well as for topsoil (0–30 cm) and subsoil (30–120 cm) and different positions to the tree row, i.e. under the trees and in the alley. The root turnover was computed with three different methods: the max-min method, the balancing-transfer method and the compartment-flow method. For the max-min method, production (P) is calculated by summing up

all increases of live root biomasses between sampling dates (Persson, 1978):

$$P_t = LFR_t - LFR_{t-1} \quad (2)$$

The balancing-transfer method uses a decision matrix and considers the direction and magnitude of changes of both live and dead root biomass between the sampling dates (Fairley and Alexander, 1985). In the compartment-flow method, the process of root decomposition is incorporated into the model. The decomposition rates can be calculated from litterbag or trench plot studies, and mortality (M), production (P) and disappearance (D) can be obtained by computing (Santantonio and Grace, 1987):

$$M_t = \frac{kt(DFR_t - DFR_{t-1}e^{-kt})}{1 - e^{-kt}} \quad (3)$$

given

$$k = -\ln(1 - DR) \quad (4)$$

$$P_t = LFR_t - LFR_{t-1} + M_t \quad (5)$$

$$D_t = DFR_{t-1} - DFR_t + M_t \quad (6)$$

where production is the flux in the live fine root fraction, mortality is the flux of roots from the live to the dead fine root fraction and disappearance is the flux from the dead fine root fraction.

The three procedures were used to estimate the errors and advantages of each method and evaluate the reliability of the obtained results. The comparison of methods was only done with the root C turnover data. The root N, root mass turnover and the comparison of subsoil to topsoil turnover were only computed with the compartment-flow method since it generally gives the best estimate of the true turnover rates (Publicover and Vogt, 1993). The respective DR were used for *Acacia* and *Sorghum* from the decomposition experiments, and the means of both DR were taken as the best estimate of root decomposition in the tree + crop combination. Root C was determined and shown in addition to root masses, as real root mass may be obscured by adhering soil particles in some samples. A correction of masses to a mean C content was not calculated since *Sorghum* and *Acacia* had different C concentrations of live roots, and changes of root C concentrations over time cannot be entirely excluded.

Table 4. Production, mortality and disappearance of fine root C of tree (T), crop (S) and tree + crop (T+S) calculated with the max-min, balancing-transfer and compartment-flow method (using mean DR from Table 2); only methods were statistically compared and significant effects are shown (\* $p < 0.05$ , \*\*  $p < 0.01$ , \*\*\*  $p < 0.001$ , ns not significant); values in one column followed by the same letter are not significantly different at  $p < 0.05$  (LSD calculated from ANOVA;  $n = 3$ ); means and standard errors (SE)

Method	Production			Mortality (kg C ha <sup>-1</sup> 120 cm <sup>-1</sup> a <sup>-1</sup> )			Disappearance		
	T	S	T+S	T	S	T+S	T	S	T+S
Max-min	122 a	143 a	323 a						
SE	32	19	19						
Balancing-transfer	161 b	144 a	416 b	39 a	83 a	295 a	24 a	68 a	256 a
SE	47	19	31	17	37	64	9	17	77
Compartment-flow	276 c	254 b	505 c	153 b	92 a	290 a	139 b	130 b	252 a
SE	52	26	42	22	6	13	18	8	18
Effect of methods	**	*	*	*	ns	ns	*	*	ns

Table 5. Production and disappearance of fine root mass, C and N of tree (T), crop (C) and tree + crop (T+C) calculated with the high and low decomposition rates (DR) of the litter-cylinder experiment (Table 2) using the compartment-flow method, and percentage of results obtained with low DR compared to high DR; values followed by the same letter are not significantly different at  $p < 0.05$  (LSD calculated from ANOVA;  $n = 3$ ); the cropping systems and different DR were only compared within each column and row; production, mortality and disappearance were not statistically compared

DR	Production			Disappearance			
	T	C	T+C	T	C	T+C	
(kg ha <sup>-1</sup> 120 cm <sup>-1</sup> a <sup>-1</sup> )							
Mass	high	944 a	1020 a	2080 b	692 a	639 a	1238 b
	low	484 b	762 c	1422 d	223 b	291 bd	368 cd
%		51	75	68	32	46	30
C	high	376 a	309 a	702 b	239 a	212 a	448 b
	low	204 b	295 ab	441 c	62 bc	77 bc	104 c
%		54	96	63	26	36	23
N	high	18.6 a	6.1 bc	25.5 d	11.0 a	3.2 b	13.5 c
	low	10.0 b	5.0 c	17.1 c	1.8 bd	2.4 cd	6.7 e
%		54	82	67	16	75	50

### Chemical analyses

The soil samples were air-dried and ground. Roots were dried at 40 °C for 48 h and weighed with an accuracy of 0.01 mg. C and N were analysed gaschromatographically after dry combustion with an automatic C/N Analyser.

### Statistical analysis

Decomposition rates were compared with a three way analyses of variance using a *split-split plot design* with the factors time × species × element (Little and Hills,

1978). The different calculation methods (Table 4) and the cropping systems with different DR (Table 5) were compared with a *randomized complete block design*. Two way ANOVA were computed with the factors cropping-system × depth and three way ANOVA with the factors intercropping × distance × depth using a *split-plot design* in order to determine the effect of intercropping and species (*Sorghum* or *Acacia*) or position (canopy or alley) on root depth distribution. Individual cell means were statistically compared using LSD, which was computed from the errors of the respective effects or interactions according to Little and Hills (1978).

### Results

At *Sorghum* flowering in July 1996, the highest root mass was found in the topsoil (0–15 cm) for all species and distances (apart from the 25–75 cm distance of the sole cropped *Acacia*; Figure 1). Root mass is given here as root C and thus corrected for adhering soil particles. In sole cropped *Sorghum*, 71% of the root C was in the upper 30 cm, 56 and 34% in sole cropped *Acacia* and 59 and 58% in the intercropped fields for 0–25 and 75–200 cm distance, respectively. The total amount of roots per unit area decreases with increasing distance to the tree row to a lesser degree in the sole cropped tree plots (40–32–28%) compared to the intercropped tree plots (47–28–25%).

During the dry season in March 1996, the proportion of topsoil roots decreased to 67% in the sole cropped *Sorghum*, and to 43 and 33% in the sole cropped trees for 0–25 and 75–200 cm distance, respec-

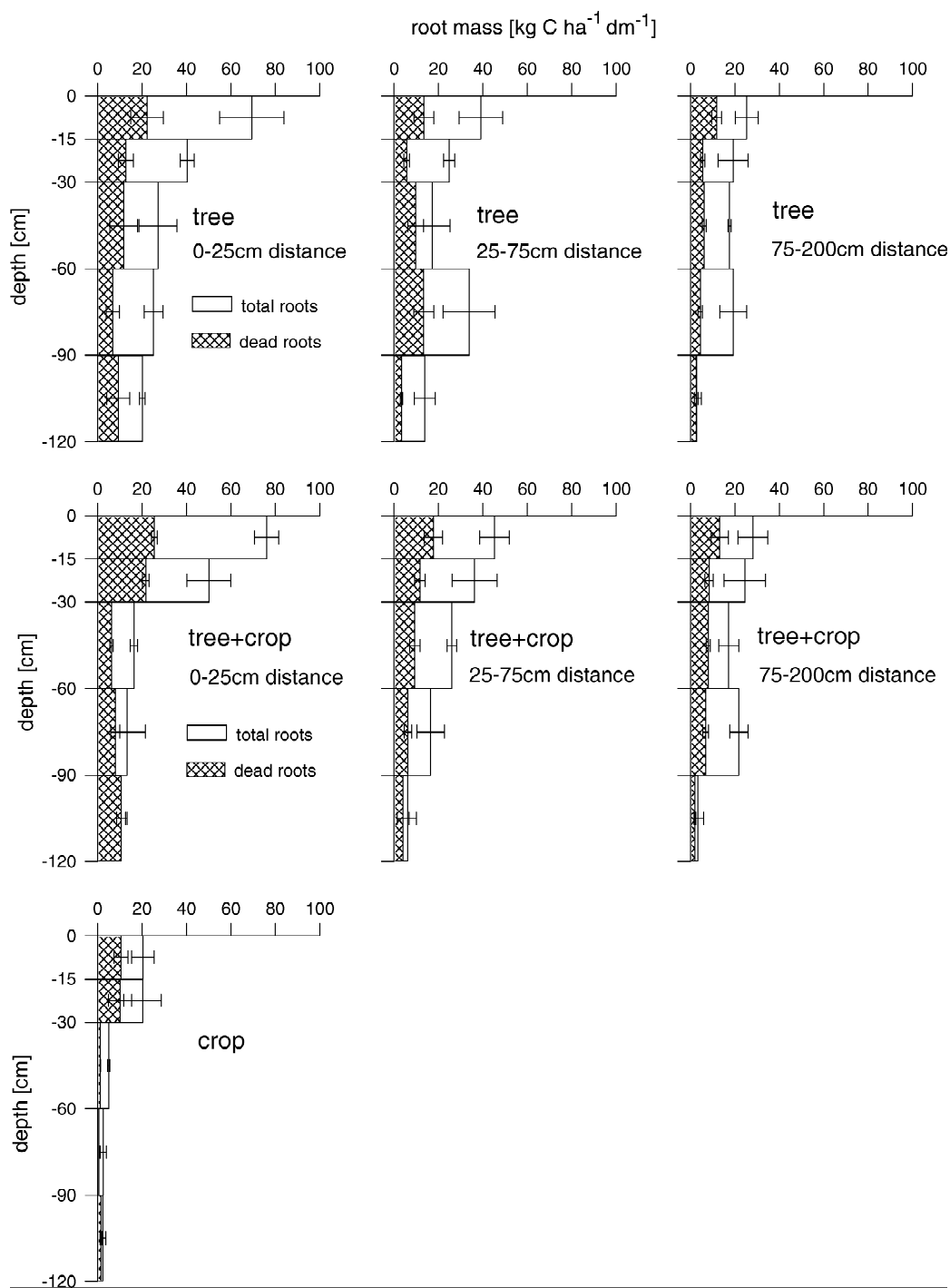


Figure 2. Vertical root C distribution of *Sorghum bicolor*, and vertical and horizontal root distribution of sole cropped *Acacia saligna* and intercropped *Acacia saligna* and *Sorghum bicolor* at the end of the dry season in March 1996; dead and total roots ( $n = 3$ ); means and standard errors.

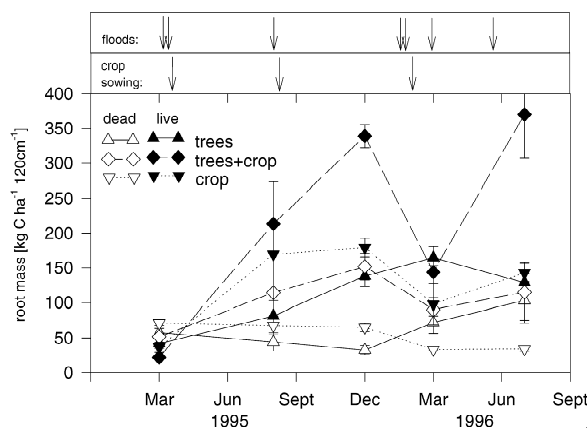


Figure 3. C dynamics of live and dead roots of sole cropped and intercropped *Sorghum bicolor* and *Acacia saligna* ( $n = 3$ ); means and standard errors.

tively (Figure 2). In the intercropped plots, root C remained at 62% in the tree row (0–25 cm) and decreased to 38% in the alley between the tree rows (75–200 cm). In contrast to the situation in July, the differences of total root C per unit area between distances to the tree row were more pronounced in the sole cropped trees (44–34–22%) than in the intercropped plots (39–35–26%). Calculated for the whole system, total root C in July increased in the order crop < tree < tree + crop with 177, 232 and 485 kg C ha<sup>-1</sup> 120 cm<sup>-1</sup> (4.0, 9.8 and 18.1 kg N ha<sup>-1</sup> 120 cm<sup>-1</sup>) as opposed to March crop < tree + crop < tree with 131, 233 and 236 kg C ha<sup>-1</sup> 120 cm<sup>-1</sup> (4.9, 10.8 and 11.7 kg N ha<sup>-1</sup> 120 cm<sup>-1</sup>). Total root mass was also highest in the tree + crop with 1.1 Mg DM ha<sup>-1</sup> 120 cm<sup>-1</sup> compared to crop (0.4) and tree systems (0.3) in the wet season. The ratio of live to dead roots was higher at 15–30 than 0–15 cm depth for all systems during both dry and wet season sampling, in the subsoil the ratio decreased. The ratio of live to dead *Sorghum* roots was significantly lower in March (2.4) than in July (4.7;  $p < 0.05$ ); in the tree system, it slightly decreased from 2.1 to 1.4, and in the tree + crop system it slightly increased from 1.7 to 2.6 at the same time.

The intercropping system exhibited the largest differences of live and dead roots between sampling dates (Figure 3), the sole cropped tree system the lowest. At the beginning of the experiment in March 1995, all three systems had similar root abundance. Throughout all sampling dates after March 1995, there were more live roots than dead roots.

In order to calculate the root turnover, decomposition rates (DR) had to be determined from field experiments. The three different experiments gave similar results: DR decreased in the order C > mass > N apart from the litter-cylinder lower value where C decomposed faster than root masses (Table 2). The DR of the litter-cylinder experiment can be calculated for each time interval, and the lowest and highest DR are presented as they were significantly different at  $p < 0.05$ . Both litterbag DR and DR obtained from *in situ* measurement were in the range of the upper and lower value of the DR determined by the litter-cylinder experiment; thus, only the latter were used for further calculations. The slower N release than C decomposition was confirmed by the significantly higher N concentrations of dead roots compared to live roots (Table 3). *Acacia* live roots had a 10% lower N content than dead roots, whereas live root N of *Sorghum* was 45% lower than that of the dead roots. The two plant species showed a different effect on C or N decomposition and between time intervals (significant interaction species × element and species × time). The root N contents of the field observations did not significantly change between sampling dates calculated for live and dead roots and all cropping systems; however, N contents of *Acacia* live roots were higher in the dry season (18.7 mg g<sup>-1</sup>) than in the preceding and following wet season (Table 3;  $p < 0.05$ ).

Production, mortality and disappearance differed less for crop and tree + crop systems than for the sole cropped trees comparing the three methods (Table 4). For the sole cropped trees, up to 6 fold higher turnover was calculated when using the compartment-flow method instead of the max-min method; the balancing-transfer method was intermediate. If the compartment-flow method was used, the values for the tree + crop system were always higher than for the sole cropped systems, and higher for sole cropped trees than for *Sorghum* ( $p < 0.05$ ; Table 5). Only for *Sorghum* was root disappearance matching root production; in the other systems, production was always higher than mortality or disappearance when the means of the whole year were compared.

Production and disappearance obtained with low DR were considerably lower compared to calculations using high DR ( $p < 0.01$ ; Table 5); production decreased to 51–96%, mortality and disappearance to even 16–75%. The effect of using a lower DR on root production was less pronounced for the sole crop than for the tree + crop or tree systems with a decrease to 75–96%, 63–67% and 51–54%, respectively. Using



**Table 6.** Comparison of production and disappearance of fine root C and N of tree (T), crop (C) and tree + crop (T+C) as affected by depth and distance to the tree row calculated with the compartment-flow method using high DR (Table 2); means followed by the same letter are not significantly different at  $p < 0.05$  (LSD calculated from ANOVA;  $n = 3$ ); only significant differences of the cropping systems and depths are presented; production, mortality and disappearance were not statistically compared

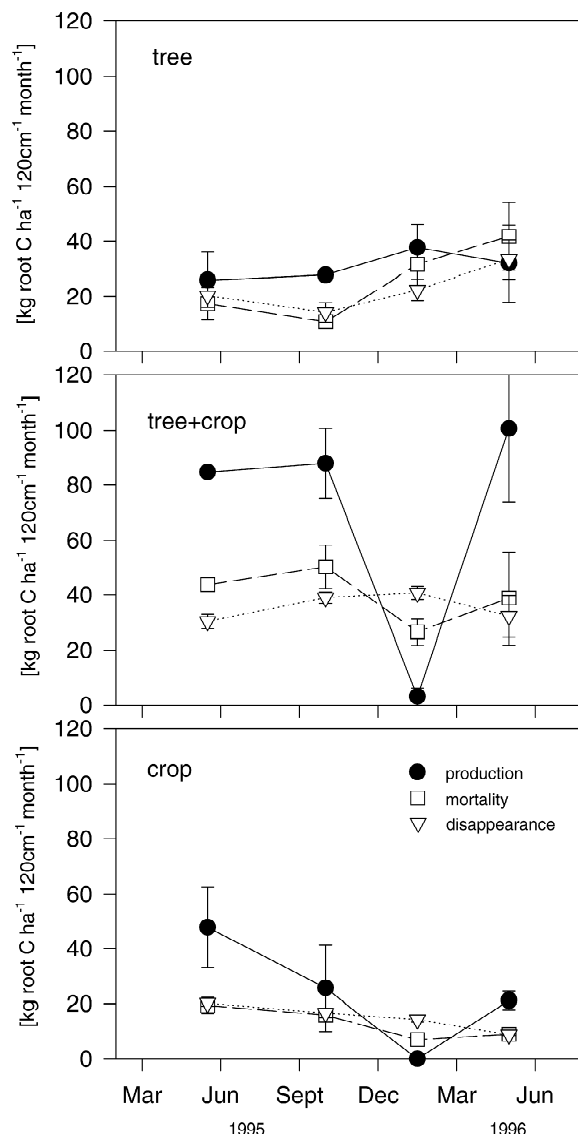
	Distance to tree row <sup>1</sup> (cm)	Depth (cm)	Production			Disappearance		
			T	C <sup>1</sup>	T+C	T	C	T+C
(kg ha <sup>-1</sup> dm <sup>-1</sup> a <sup>-1</sup> )								
C	0–25	0–30	97 a	63 b	127 c	63 a	48 a	80 b
		30–120	41 b	13 c	50 bd	21 bc	6 b	24 c
	75–200	0–30	52		96	40		73
N	0–25	0–30	4.6 a	1.0 b	4.7 a	2.6 a	0.6 bc	2.1 d
		30–120	1.8 b	0.2 c	1.4 b	0.8 b	0.2 c	0.2 c
	75–200	0–30	2.3		3.3	1.6		2.3
		30–120	0.8		0.8	0.2		0.3

<sup>1</sup> For monocropped *Sorghum* no distance to the tree row available.

high DR values, production and disappearance of root masses and C were clearly higher in the intercropping system than in sole cropping. For root N however, the sole cropped trees showed nearly the same production of the tree + crop combination: root mass production was 45–51% lower in sole cropped *Sorghum* and *Acacia* than if *Sorghum* and *Acacia* were intercropped, whereas root N production was only 17% lower in tree monocultures compared to the combination of tree and crop. In crop monocultures, however, N production was 76% lower than in the tree + crop combination. Root N production was very low in the sole cropped *Sorghum* with 6.1 compared to 25.5 kg N ha<sup>-1</sup> 120 cm<sup>-1</sup> a<sup>-1</sup> in the intercropping sites.

The root C production of the sole cropped trees remained at the same level throughout the experiment (Figure 4). Crop and tree + crop systems, however, were more dynamic than sole cropped trees and showed a pronounced decrease of root C production in the dry season from December 1995 to March 1996, when production was lower than mortality and disappearance. From the end of 1995 onwards, tree root mortality and disappearance equaled that of the intercropping system. Mortality and disappearance increased in the tree plots to the level of the production, whereas they decreased in the crop plots during the experiment.

Root C production and disappearance were highest in the topsoil (0–30 cm) and under the tree row (Table 6). This was true to an even higher extent for root N (with the exception of disappearance in the inter-



**Figure 4.** Dynamics of production, mortality and disappearance of fine root C of sole cropped and intercropped *Sorghum bicolor* and *Acacia saligna* ( $n = 3$ ); means and standard errors.

cropping system). A higher root C production at the topsoil/tree row position was found in the tree + crop system compared to the sole cropped *Sorghum* (50% of tree + crop) and tree (76% of tree + crop). This proportion decreased when production was calculated for the whole plot (44 and 54%, respectively; Table 5); similar results were obtained for mortality and disappearance. Intercropping *Sorghum* between the tree hedges did not affect the root depth or distance distribution (not significant interaction intercropping × depth and

intercropping  $\times$  distance). Root N production and disappearance were equal or higher for the sole cropped trees than the intercropping system in the topsoil under the tree row, as opposed to the results for root C. This was confirmed by a nonsignificant interaction cropping-system  $\times$  depth for C ( $p > 0.05$ ) as opposed to N ( $p < 0.01$ ). Root N production of the crop as a proportion of the tree system was lower in the topsoil (22%; Table 6) than when it was calculated for the whole sampling depth (33%; Table 5).

## Discussion

### *Root mass distribution*

The majority of roots of the sole cropped *Sorghum* was in the topsoil during the wet season. *Acacia* also had the highest root concentration in the topsoil, but with a high amount of roots found also below 30 cm depth. This coincides well with results from alley cropping of *Gliricidia sepium* in a humid savanna in Côte d'Ivoire (Schroth and Zech, 1995). *Acacia saligna* generally has the majority of the first order lateral roots at 0–25 cm depth (Hoffman and Mitchell, 1986). Root mass of the tree + crop combination ( $1.1 \text{ Mg DM ha}^{-1} 120 \text{ cm}^{-1}$ ) was higher than the sum of root masses of the sole cropped systems at the peak of the wet season ( $0.3+0.4 \text{ Mg DM ha}^{-1} 120 \text{ cm}^{-1}$ ). Fredericksen and Zedaker (1995) also found a higher live fine root biomass in mixed hardwood tree stands compared to pure stands in the southeastern United States; these authors explained the higher root abundance in the mixed cropping system with a complementary use of soil volume by the different plant species. This was also proposed by a preliminary study at the same site (Lehmann et al., 1997a), but cannot exclusively explain the higher root mass in the intercropping system compared to sole cropping (Lehmann et al., 1997b): the increase of roots was caused not only by a separation of tree and crop roots but also by a higher *Sorghum* root production and overlapping of the two root systems underneath the tree row. Root growth may also have been stimulated by more favourable conditions in the agroforestry combination. Soil analyses showed that N-availability was higher under the tree row than in the alley, probably stimulating root growth in this position (Lehmann et al. 1997d). Haggard et al. (1993) could show that soil N contents were enhanced by below-ground processes in agroforestry compared to monoculture in Costa Rica. These results

support the explanation that root growth of the N deficient *Sorghum* (Lehmann et al., 1997d) was stimulated by a higher N supply under the *Acacia* due to root turnover or other rhizosphere effects as discussed later. Improved soil physical conditions may also have contributed to a higher root growth under the tree, increasing infiltration rate and root penetrability as shown by Torquebiau and Kwesiga (1996) with *Sesbania sesban*.

In the dry season, the subsoil tree root system was expanding in contrast to the topsoil. High evaporation rates and rapidly decreasing water content in the topsoil (Lehmann et al., 1997a) may have forced the trees to invest more in the subsoil root system. This is confirmed by the increasing ratio of live to dead roots with depth, which was more pronounced during the dry season. Even the proportion of *Sorghum* root biomass in the topsoil to total root biomass was lower in our study (71%) than reported by Mayaki et al. (1976) for irrigated (86%) and nonirrigated *Sorghum* (79%) in Kansas, indicating an even deeper root system for an annual crop at the site in Northern Kenya.

The tree + crop combination, and to a lesser extent the crop monoculture, had a very dynamic root system with high root masses during the vegetation period and low root masses in the dry season. The sole cropped *Acacia*, however, showed a much more static root development. With the extreme differences of dry and wet annual cycles in Northern Kenya, the perennial acacias seem to be able to exploit soil resources more efficiently with their continuous root system than the annual *Sorghum*. The agroforestry system may have been superior to the monoculture, combining the continuous root level of the perennial with the dynamic root system of the annual crop; in times of high water supply, this system may make optimal use of the available soil water (Lehmann et al., 1997a).

### Root production calculations

The use of the correct DR is vital for the reliable interpretation of root production, since the different DR values significantly influenced the effect of cropping systems on root production (DR  $\times$  cropping system;  $p < 0.001$ ). DR were found to be quite consistent between the three decomposition experiments and in the range of DR which were deduced from root dynamics of an alley cropping experiment in a humid savanna (Schroth and Zech, 1995). Sandhu et al. (1990) reported slightly lower DR with 0.53 for root biomass and  $0.42\% \text{ day}^{-1}$  for N decomposition of *Leucaena*

*leucocephala* in semiarid India. DR calculated from Lehmann et al. (1995) ranged from 0.90–1.79 (*Gliricidia sepium*), 0.76–1.25 (*Senna siamea*) to 0.27–0.40% day<sup>-1</sup> (*Calliandra calothyrsus*) in an alley cropping experiment in central Togo. It can be concluded that our DR were well in the range of results from other studies, considering the relatively high water content due to irrigation despite the semiarid conditions.

Comparing the three methods for the calculation of root turnover, several authors have found that the compartment-flow method best characterises root dynamics (Publicover and Vogt, 1993; Santantonio and Grace, 1987). Our experiments differentiate these results: when a root system is very dynamic with large changes in root mass, the differences between the methods are small as seen from the crop production systems in our study. When the root masses do not change with time, however, the simpler max-min and balancing-transfer methods may seriously underestimate root production, mortality and disappearance as seen for the sole cropped *Acacia*. The advantage of the compartment-flow method is the incorporation of a decomposition model, and the difficulties of determining the decomposition rates have been thoroughly discussed (Publicover and Vogt, 1993). To estimate the calculation error of using the wrong DR, we determined root turnover with an upper and lower estimate of DR calculated from three different decomposition experiments; additionally, we compared the obtained results with the results of the other two methods. This procedure allowed us to compute root turnover with an acceptable certainty. The compartment-flow method using a combination of decomposition studies was found to be superior to the other methods.

#### *Root turnover in tree-crop combinations*

In agroforestry systems, the below-ground biomass is believed to be as important as the above-ground biomass in maintaining soil fertility (Sanchez, 1995). Root turnover contributes the most to the formation of soil organic matter (Vogt et al., 1991). Fine root production was substantial with up to 2.1 Mg DM ha<sup>-1</sup> a<sup>-1</sup> in the tree + crop combination and 45 and 50% in the tree and crop monocultures. Total annual root production was higher than reported for an alley cropping system in Côte d'Ivoire (Schroth and Zech, 1995) but lower than for humid tropical forest stands in Venezuela with 0.9–8.1 Mg ha<sup>-1</sup> a<sup>-1</sup> for the upper 10 cm (Cuevas and Medina, 1988), for moist deciduous and evergreen forest sites in South India with 4.7–6.1

Mg ha<sup>-1</sup> a<sup>-1</sup> (Sundarapandian and Swamy, 1996) and dry tropical deciduous forests in Mexico with 4.2 Mg ha<sup>-1</sup> a<sup>-1</sup> (Kummerow et al., 1990). Higher root production in the mixed cropping system compared to monocultures was in contrast to results from Schroth and Zech (1995), but in accordance with results from mixed and sole cropped tree stands in a temperate ecosystem (Fredericksen and Zedaker, 1995). Higher root production in mixed cropping than monoculture was caused by a higher resource use efficiency and root growth stimulation: the available soil resources were exploited up to a greater depth with the combination of a shallow rooted crop and a deeper rooted tree; root growth increased due to higher soil nutrient contents and possibly better soil physical conditions induced by rhizosphere effects as discussed earlier.

Root production was twice as high as total root biomass in the crop and tree + crop systems, but more than three times higher in the tree system. These values were much higher than the 30–80% root turnover of total root biomass reported by Fogel (1983) for a range of coniferous forests. Total annual below-ground production amounted to 21% of the above-ground biomass production (reported by Lehmann et al. (1997a) for 1995; Lehmann et al. (1997d) for 1996) of sole cropped *Sorghum*, 38% of the tree and 37% of the tree + crop system during 1995 (17 to 19% during 1996). These values were above the 10% reported by Schroth and Zech (1995) for sole cropped maize and alley cropping with *Gliricidia sepium* in the humid savanna of Côte d'Ivoire. In the dry environment of Northern Kenya, plants must presumably invest more into their below-ground biomass in order to secure water uptake. The higher percentage of below-ground compared to above-ground biomass production in tree stands and even higher percentages in tree + crop mixtures, reflects the total above-ground biomass production which was highest in the tree + crop combination, followed by the tree monoculture and lastly, the crop monoculture (Lehmann et al., 1997d). A higher proportion of below- to above-ground biomass production and the exploitation of a larger soil volume has resulted in a higher above-ground biomass production.

#### *N input to soil through root turnover*

Root N input to soil was calculated using N decomposition and changes in root N contents similar to root C and mass turnover. This would require that no retranslocation of N occurred during root senescence and death. N retranslocation was believed to play a

minor role, since no root N changes were observed with time, and N accumulated rather than disappeared from dead roots. This is in accordance with results from Nambiar (1987).

The root N production and turnover determined with the compartment-flow method and experimental DR were considerably lower ( $2\text{--}26 \text{ kg ha}^{-1} 120 \text{ cm}^{-1} \text{ a}^{-1}$ ) than results calculated from the root C turnover and root N contents ( $10\text{--}40 \text{ kg ha}^{-1} 120 \text{ cm}^{-1} \text{ a}^{-1}$ ). The roots were accumulating N during decomposition, and the N contents of live roots were significantly lower than that of dead roots. To a lesser degree than in our study, Nambiar (1987) also found lower N concentrations in live than in dead fine roots. Thus, root N input to soil cannot be directly concluded from root turnover data. The N dynamics of decomposing roots must be taken into account.

Root decomposition and especially N release can vary considerably depending on plant species and root diameter, with root substrate quality giving information to predict decomposition (Lehmann et al., 1995). A lower N DR than C DR, and a higher N accumulation in dead roots than live roots explains the low N input to soil in relation to C. *Sorghum* had lower root N contents than *Acacia*, and consequently a lower DR assuming a lower substrate quality in accordance to Lehmann et al. (1995). Therefore, *Sorghum* root N turnover was much lower than that of *Acacia*, although both had similar C turnover. N rich root systems may increase root N input to soil through both high root N contents and fast root N mineralisation. Only high amounts or high release rates are not sufficient to guarantee high N input to soil.

Total annual root N input to soil is low in our experiment calculated with root N turnover, and it is doubtful whether it meets the expectations stated for nutrient input through root turnover in agroforestry systems (Young, 1991). Intensive tree fallows may be more effective with their higher root biomass, e.g. up to  $3 \text{ Mg ha}^{-1}$  as reported by Torquebiau and Kwesiga (1996) for *Sesbania sesban* in Zambia. We observed, however, a concentration of root N content and also root turnover in certain places of the cropping system: tree root N production and input to soil was 2–4 times higher under the tree row than in the alley and 3–8 times higher in the topsoil than in the subsoil. Lehmann et al. (1997d) found higher mineral N contents under the tree row after the onset of the rains (about  $9 \text{ kg N ha}^{-1} \text{ dm}^{-1}$  of soil extracted N and N in the soil solution) and an improved N nutrition of the intercropped *Sorghum*. Higher tree root N input to soil can help to explain

this observation. Still, this increase of soil mineral N cannot entirely be explained with the presented root turnover data. Results from Lehmann et al. (1997c) also indicate that short-term effects of root N release on the N content of particle size separates are not likely. We were able to assess the whole root turnover with our sampling interval of 4 months, because we successfully chose sampling dates with long-term maximum and minimum values providing the highest estimate of root turnover. Root production estimates were also shown to remain at an acceptable variability with increasing sampling intervals up to 4 months when using the compartment-flow method (Publicover and Vogt, 1993). Extremely short-term variations of root growth and death, however, may have a considerable impact on total root turnover and root N input to soil; these cannot be determined with destructive root sampling due to the high labour intensity of the method and the destruction of the experimental plots through the core sampling. In this case, rhizotron techniques may be supportive even with the shortcoming that no root masses or N contents can be determined. Direct and indirect effects of root exudates on nutrient availability may provide explanations for the observed difference between root N turnover and soil N availability, but the importance of these processes has not been adequately assessed and require further attention (Grayston et al., 1996). The transfer of N from tree legumes to associated crops may be further facilitated by direct uptake of legume N by the crop through arbuscular mycorrhiza, though recent studies have indicated a limited importance of this process (Hamel and Smith, 1991; Ikram et al., 1994).

In conclusion, it becomes clear that the incorporation of trees into cropping systems provides a denser and deeper root system. Moreover, root turnover is enhanced by the tree + crop combination, being an important aspect of soil fertility and resource use efficiency. This is especially true for N recycling, which was shown to be much higher in the tree based systems. Since total N input to soil through root N turnover was low in relation to reported soil N increases and improved N nutrition of the annual intercrop, the investigation of other processes of N input to soil and N transfer to associated crops should be strengthened in future research. Root turnover seems to be only one process of N recycling through below-ground biomass in agroforestry systems.

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