Nutrient interactions of alley cropped *Sorghum bicolor* and *Acacia saligna* in a runoff irrigation system in Northern Kenya

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Abstract

In a runoff irrigation system in Northern Kenya, we studied the nutrient interactions of sole cropped and alley cropped *Sorghum bicolor* (L.) Moench and *Acacia saligna* (Labill.) H.L. Wendl. The trees were pruned once before the cropping season and the biomass was used as fodder for animals. The nutrient contents in leaf tissue, soil and soil solution were monitored and the uptake of applied tracers (^{15}N, Sr) was followed. The grain yield of alley cropped sorghum was similar to or slightly higher than in monoculture and did not decrease near the tree-crop interface. Foliar N and Ca contents of the crop were higher in the agroforestry combination than in monoculture, corresponding to higher soil N and Ca contents. Soil solution and soil mineral N dynamics indicate an increase of N under the tree row and unused soil N at the topsoil in the alley of the sole cropped trees as well as below 60 cm depth in the crop monoculture. The N use efficiency of the tree+crop combination was higher than the sole cropped trees or crops. Competition was observed for Zn and Mn of both tree and crop whereas for Ca only the tree contents decreased. P, K, Mg and Fe dynamics were not affected by alley cropping at our site. The lower uptake of applied Sr by trees in alley cropping compared to those of the monoculture stand suggested a lower competitiveness of the acacia than sorghum, which did not show lower Sr contents when intercropped. The study showed the usefulness of combining soil and plant analyses together with tracer techniques identifying nutrient competition, nutrient transfer processes and the complementary use of soil nutrients, as the main features of the tree-crop combination.

Introduction

Agroforestry is proposed as a strategy to combat soil degradation, improve soil fertility and increase crop yields; especially in alley cropping systems, however, crop yields have been reported to decline rather than to increase after several years of cultivation (Sanchez, 1995). The reasons for this may be competition for light, water or nutrients but more often a complex interaction of all of them (Lehmann and Zech, 1997).

One of the most important benefits of alley cropping trees is the application of hedgerow prunings to the annual crop in order to improve crop nutrition (Palm, 1995). Below-ground interactions may also positively influence soil fertility and enhance crop production in alley cropping (Schroth, 1995). Haggar et al. (1993) concluded that the effects of below-ground biomass on soil fertility were even higher than those of mulch application in tropical alley cropping. However, competition between trees and crops may also negatively impact crop yields. In order to minimize tree-crop competition for nutrients, trees may be selected or managed in a way that they take up soil nutrients from below the root zone of the annual intercrop. However, if the objective of intercropping is the improvement of topsoil fertility through tree root

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turnover, it would require that the trees also have roots in the topsoil, which in turn increases nutrient competition (Schroth, 1995). In the present study, we focus on nutrient interactions in agroforestry in order to understand the positive and negative effects of alley cropping trees and crops on soil nutrient dynamics and mineral nutrition of plants. We addressed the questions (i) whether associated *Acacia saligna* and *Sorghum bicolor* competed for nutrients or whether their nutrition improved by alley cropping, and (ii) whether a spatial distribution pattern of soil nutrient depletion or replenishment can be observed.

Materials and methods

Study site

The study was carried out in a dry tropical savanna near Kakuma in Northern Kenya (34°51′ East and 3°43′ North, altitude 620 m a.s.l.) between 1994 and 1996. The rainfall distribution is bimodal with a peak in April and May and in September and October. The mean annual precipitation amounted to 318 mm (from 14 years; W. I. Powell, and Turkana Drought Control Unit, unpubl. data) with 302 and 330 mm in 1995 and 1996. The natural vegetation is the thornbush savanna and consists of *Acacia tortilis* (Forsk.) Hayne, *Acacia reficiens* Wawra. & Peyr., *Dobera glabra* (Forsk.) A. DC. and *Ziziphus mauritiana* Lam. The soils are classified as *calcareous Fluvisols* (FAO, 1990); they are deep and loamy, with high pH and low organic C, N and Zn contents (Table 1).

Experimental design and treatments

In November 1994, a hedgerow intercropping system was established with *Acacia saligna* (Labill.) H.L. Wendl and *Sorghum bicolor* (L.) Moench. Five tree rows were planted in east-west direction with 4 m wide alleys and a 1 m distance between trees within the row (2500 trees ha^{-1}) in plots of 13×24 m. In the alley, 7 rows of sorghum were sown 0.5 m apart from each other with 0.25 m distance between plants. The agroforestry system was compared to acacia and sorghum monocultures with the same planting arrangement ('T' and 'C' for sole cropped trees and crops; 'T + C' for intercropping) using a randomized complete block design with three replications. This study was part of a larger experiment, of which only the described three treatments are presented here (Lehmann et al., 1998a).
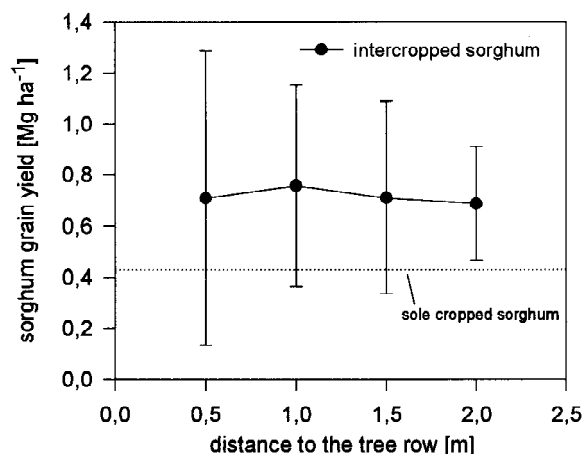

Figure 1. Grain yield of sole and intercropped *Sorghum bicolor* with increasing distance to the tree row (*n* = 3); means and standard errors.

Prior to the study in 1994, a runoff irrigation system was built, which ensured a sufficient water supply despite the dry climatic conditions. The irrigation system consisted of levelled basins which were filled with water in April/May, August and November 1994, in May and September 1995 and in April 1996 up to a level of about 500 mm. The irrigation water originated from flood events during heavy storms which were guided into the macrocatchments. The water infiltrated into the soil within one to two weeks. Afterwards, the trees or crops were planted in these basins and the plants used the water which was stored in the soil (Lehmann et al., 1998a).

Biomass determinations

The central 10 trees from three rows were used for the determination of pruned biomass (30 trees). On April 4–6 and August 1996, the trees were pruned at a height of 1.5 m by removing all branches and leaves leaving only the stem. This was considered to comprise the total above-ground biomass production, since stem biomass production was very low during the growth period. The prunings were separated into leaves and branches and then weighed. Subsamples were dried at 70 °C for 48 h and reweighed to correct for water content. All tree biomass was taken out of the system and used as fodder or construction material. The sorghum was sown in the first week of May 1996. If plants were not emerging, they were resown after two weeks. Sorghum plants were reduced to one plant per stand two weeks later, and plots were weeded weekly during the wet season. Grain yield and biomass were

Table 1. Chemical and physical characterisation of the lead profile (top) and the mean values of the carbon and nutrient contents of individual plots (bottom, *n* = 9) at the experimental site before the start of the experiment

Depth [cm]	Horizon	Bulk density [Mg m^{-3}]	pH H$_2$O	Organic C [g kg^{-1}]	N [g kg^{-1}]	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

Depth [cm]	C [g kg^{-1}]	N [g kg^{-1}]	P[a] [mg kg^{-1}]	K[a] [mg kg^{-1}]	Ca[a] [mg kg^{-1}]	Mg[a] [mg kg^{-1}]	Fe[a] [mg kg^{-1}]	Mn[a] [mg kg^{-1}]	Zn[a] [mg kg^{-1}]
0–15	5.7	0.26	12.1	242	5208	534	71.4	377	1.51
15–30	5.3	0.32	16.6	267	5587	596	69.9	371	1.53
30–60	6.0	0.31	14.2	224	5005	535	69.1	311	1.11

[a] Available nutrients according to Mehlich (1984).

measured at the harvest 90 days after planting in August 1996. Crop yields were determined by randomly selecting 12 plants per treatment and row. The plants were separated into grain and biomass, weighed, dried at 70 °C for 48 h and reweighed to obtain dry matter weight. In the intercropping treatments, crop yields were determined as a function of distance to the tree row. If the total yields of the different systems were compared (Table 2), the intercrop yield was calculated including the space occupied by the trees, which reduced crop yields on a hectare basis. If crop yields of individual rows were compared with each other or with the control (Figure 1), the yield per row was calculated per hectare.

Plant nutrient analyses

In order to characterise plant nutrition, leaf samples were taken from acacia and sorghum. The first fully developed acacia leaves from the upper part of the canopy and the second sorghum leaf from apex were taken at sorghum flowering in July 1996. The leaves were gently rinsed with deionised water to remove adhering particles and dried at 70 °C for 48 h. Afterwards, they were finely ground with a ball mill (Retsch).

C, N and S were determined after dry combustion with an automatic C/N/S Analyser (Elementar). For the other nutrients, 200 mg dry leaves were digested in 2 mL concentrated HNO$_3$ (suprapur) at 170 °C

Table 2. Biomass production and grain yield (Mg ha^{-1}) of sole (C) and alley cropped (T+C) *Sorghum bicolor* and biomass production of *Acacia saligna* (T); biomass or grain yield followed by the same letter are not significantly different at $p < 0.05$ (ANOVA; *n* = 3)

Treatments	Sorghum		Acacia
	biomass	grain	biomass[a]
C	6.6 a	0.42 a	–
T	–	–	5.0 ab
T + C	5.3 ab	0.63 a	3.8 b

[a] Droppelmann (1999).

for 8 h, and diluted to 20 mL with deionised water. K, Ca, Mg, Fe, Mn and Zn were analysed with an atomic absorption spectrometer (Varian), P was measured colorimetrically according to the molybdenum blue method (Olsen and Sommers, 1982).

Soil nutrient analyses

For soil characterisation, samples were finely ground with a ball mill and total C, N and S were measured after dry combustion with an automatic C/N/S Analyser (Elementar). Available soil nutrients were extracted according to the Mehlich 3 procedure (Mehlich, 1984). K, Ca, Mg, Zn, Fe and Mn were analysed with an atomic absorption spectrometer. P was

determined colorimetrically in the same extract by the molybdenum blue method (Olsen and Sommers, 1982). For the determination of soil mineral N dynamics, soil samples were taken before the floods in March, after the first floods had infiltrated in May and at sorghum flowering during July 1996. The samples were obtained with a Pürkhauer auger in the sorghum monoculture, in the sole and alley cropped tree plots under the hedgerow and at the center of the alley. Eight subsamples were collected at depths of 0–15, 15–30, 30–60 and 60–90 cm each and pooled by depth. The samples were immediately transferred to a cooling box and transported to a deep freezer. The frozen soil was sieved, 50 g soil was mixed with 100 mL of 1 N KCl and shaken for 5 min. The extract was filtered, and NH_4^+ and NO_3^- were measured colorimetrically with a Rapid Flow Analyser (Alpkem). The effect of intercropping on other soil nutrients were studied by comparing the soil P, S, K, Ca, Mg, Zn, Fe and Mn contents at the beginning of the experiment in June 1994 with the corresponding data from underneath the hedgerows (0–25 cm from the trees) and in the alleys (75–200 cm from the trees) in July 1996.

Soil solution collection and nutrient analyses

Ceramic suction cups with a length of 15 cm and an average pore diameter of 1 μm were inserted at an angle of 60° at 35 and 120 cm depth. Below the soil surface, the hoses which were attached to the cups were bent into a curve and guided a few decimeters further out of the soil to ensure that no preferential flow would contaminate the solution obtained through the cups. Vacuum was applied twice a week on individual sampling flasks by a portable electric pump and collected in weekly intervals; the suction cups were constructed in a way that the solution was automatically sucked into the flasks. The solution remaining in the cups and in the capillary system could be completely removed by a repeated application of the vacuum. The extent of the vacuum was adjusted to the soil water suction measured by tensiometers at the same site (Lehmann et al., 1998b). Before vacuum application, the flasks were treated with chloroform to avoid the growth of algae. Soil solution was extracted as long as it could be obtained from the cups before the soil dried out again in July. The collected soil solution was treated with chloroform, deep frozen and transported to Germany for further analyses. NO_3^- and NH_4^+ were analysed colorimetrically

with a Rapid Flow Analyser (Alpkem), K, Ca and Mg with ICP–AES.

Nitrogen mineralisation

Resin cores were used to determine the net N-mineralisation (modified after Hagedorn et al., 1997; Kolberg et al., 1997) in the upper 10 cm in the tree row and in the center of the alley of the tree+crop combination and the tree monoculture (the sorghum monoculture could not be investigated due to technical difficulties). They were placed in the field after the flood had infiltrated at the beginning of June 1996 and removed at the end of the experiment in August after 70 days. PVC tubes with a diameter of 7.8 cm and a length of 10 cm were filled with soil from 0–10 cm depth. Disturbed soil was taken corresponding to the conditions after soil preparation with hoes, as it was practiced in the studied area. Resin cores were attached to the bottom of the soil cores to determine the amount of mineral N leached from the soil column and to obtain the total amount of mineralised N (Hagedorn et al., 1997). The resin cores were 5 cm long with the same diameter as the soil cores. 50 mL of a combined anion and cation exchange resin (Amberlite MB 20; 0.7 meq H^{+-}; 0.7 meq OH^-) was mixed with 250 mL of acid washed sand, filled into the cores and slightly compacted to give similar bulk densities as the surrounding soil. A 2 cm extension at the bottom, filled with acid washed sand, ensured a good contact of the core with the soil. The three core sections (soil, resin-sand mixture, sand) were separated by nylon mesh (0.5 mm dia.). Preliminary infiltration studies showed good correlations of cores filled with soil and with the resin-sand mixture when steady state water flow was reached (data not shown). At the start of the experiment and after removing the cores, the mineral N was extracted from the soil with 1 N KCl and analysed as described above. The column of the resin–sand mixture was cut into two layers, 0–2.5 and 2.5–5 cm, in order to verify that the capacity of the resin was sufficient and no nutrients were lost from the resin core, and to ensure that no N entered the measured layer of the resin core by capillary rise. The thickness of the layers was adjusted after preliminary experiments. The total amount of each resin core layer was weighed, and a subsample was dried and its mineral N content analysed after extraction with 1 N KCl as described above. The total net-N-mineralisation was calculated as the sum of the difference between initial and final

soil mineral N contents and the amount of N leached into the resin cores.

Nutrient competition

Two experiments with tracer applications were used to study the nutrient competition between trees and crops by either broad application over the whole soil surface (^{15}N) or amendment at a specific distance from the tree row (Sr). ^{15}N was applied as $(NH_4)_2SO_4$ with 10 at. % excess ^{15}N at a rate of 5 kg N ha^{-1} twice, once after the trees had been planted in December 1994 and before the first flood in March 1995. The soluble tracer was injected at 5 cm depth in a grid of 15 cm in order to prevent that wind erosion removed the added ^{15}N. The tracer was applied in subplots of 6×8 m for the tree + crop combination. Plots were fenced by iron sheets to minimize lateral flow of the ^{15}N. The stable N isotope composition was determined in the leaf samples at sorghum flowering and tree pruning. All samples were analysed using an Elemental Analyser (Carlo Erba NA 1500) for Dumas combustion connected to an isotope mass spectrometer (FINNIGAN MAT delta E) via a split interface. The δ^{15}N values were calculated with the atmospheric N isotope ratio as the standard:

$$\delta^{15}N = \left(\frac{^{15}N/^{14}N \, (sample)}{^{15}N/^{14}N \, (standard)} - 1 \right) \times 10^3$$

$SrCl_2 \cdot 6H_2O$ was applied in a strip 5 cm broad and 6 m long at a rate of 12 g Sr per strip (total of 5 kg Sr ha^{-1}) in June 1996, corresponding to 4 mg Sr cm^{-2} (=400 kg Sr ha^{-1}). A shallow groove (1 cm depth) was prepared at 50 cm distance from the tree row of the tree + crop combination (location of the first sorghum row next to the hedge), at 50 cm distance from the tree row of the tree monoculture and at one sorghum row of the crop monoculture. Sufficient water was added to the strip to let the tracer infiltrate to a depth of 15 cm, the main root zone of the crop (Lehmann et al., 1998a). The depth of infiltration was tested before-hand outside the experiment and was verified during the experiment by measuring the depth of the wetted soil. After one month, leaf samples were taken from adjacent acacia and sorghum rows, and the Sr was measured with an Atomic Absorption Spectrometer after digestion with HNO_3 (see above).

Statistical analyses

All data from yield and foliar analyses were statistically explored by analyses of variance using a randomized complete block design with three replications (ANOVA of STATISTICA Version 5). The nutrient contents in the soil solution were compared using the logarithmic values due to unequal variances. The effects of distance to the tree row and time were computed as split block and split plot repeated measurement designs (Little and Hills, 1978). ANOVA of soil mineral N dynamics were computed at individual depths and times. Soil nutrient changes of P, S, K, Ca, Mg, Zn, Fe and Mn as shown in Table 6 were compared by means of ANOVA with regard to two different approaches, (1) comparing the two sampling dates and the effect of time on depth distribution and treatment effect, and (2) testing the effect of soil depth and treatment on changes of the soil nutrient contents. In case of significant effects or interactions, individual means on the respective level were compared using LSD at $p < 0.05$ (Little and Hills, 1978).

Results and discussion

Biomass production and grain yield

Biomass production of sole cropped *Sorghum bicolor* equaled that of sorghum intercropped with *Acacia saligna* (Table 2). Sorghum grain yield tended to be higher when cropped in association with the trees, but differences were not significant. During the growth period biomass production was lower for *Acacia saligna* than for sorghum (Table 2, not significant) especially considering the slightly longer measurement interval of acacia than sorghum. Tree biomass production was even more reduced when grown in association with sorghum (significantly different to sorghum monoculture; $p < 0.05$). The observed grain yield of 0.42–0.63 Mg ha^{-1} was low compared to other reports from runoff irrigated sorghum in Mali with 2.8 Mg ha^{-1} (Klemm, 1989) and 1.2–2.2 Mg ha^{-1} in Botswana (Carter and Miller, 1991). Lack of soil water, however, cannot be the main reason for the low productivity at our site, as water availability was considered to be sufficient during the experimental period (Lehmann et al., 1998b). This was also confirmed by the fact that considerably lower plant available soil moisture during an earlier experiment at the same site did not result in lower yields of sole cropped sorghum with 0.3 Mg ha^{-1} (Lehmann et al., 1998a) compared to this experiment with 0.4 Mg ha^{-1}. Other factors seemed to have limited plant production in the runoff irrigation system, of which mineral nutrition probably was one of the most important as discussed below.

Table 3. Foliar nutrient contents of sole cropped (C) and alley cropped (T + C) sorghum with *Acacia saligna* as a function of distance to the tree; values in one column followed by the same letter are not significantly different at $p < 0.05$ (LSD); (*) and * significant at $p < 0.1$ and $p < 0.05$, respectively; means and standard errors ($n = 3$)

Plot	Row	N [g kg^{-1}]	P [g kg^{-1}]	S [g kg^{-1}]	K [g kg^{-1}]	Ca [g kg^{-1}]	Mg [g kg^{-1}]	Fe [mg kg^{-1}]	Mn [mg kg^{-1}]	Zn [mg kg^{-1}]
C		16.8 b ±1.3	1.86 ±0.20	1.89 ±0.17	17.0 ±1.17	1.73 a ±0.20	1.15 ±0.32	134 ±15	29.7 ±5.7	28.3 a ±7.4
T + C	1	19.2 a ±1.3	2.11 ±0.10	1.95 ±0.10	17.3 ±0.6	2.27 b ±0.37	1.29 ±0.13	208 ±24	20.2 ±1.6	18.0 b ±1.6
	2	18.0 ab ±1.1	2.11 ±0.11	1.83 ±0.10	17.2 ±0.6	2.10 ab ±0.42	1.04 ±0.13	146 ±19	22.4 ±2.0	17.2 b ±2.1
	3	14.4 c ±1.5	2.00 ±0.15	1.75 ±0.09	16.9 ±0.4	1.90 ab ±0.38	0.98 ±0.15	135 ±10	20.0 ±2.8	18.8 b ±0.5
	4	18.7 ab ±1.3	2.01 ±0.08	1.87 ±0.14	16.9 ±0.7	2.18 ab ±0.30	1.11 ±0.10	165 ±27	23.5 ±3.2	18.9 b ±0.8
Distance		*	ns	ns	ns	(*)	ns	ns	ns	*

Plant mineral nutrition

The N content of sorghum plant tissues in our study fell below the critical level of 18 g kg^{-1}. The foliar Ca, Mg and to a lesser extent the Zn contents indicated an unsufficient supply according to Lockman (1972). The crop supply of P, K, Mn and Fe was sufficient (Table 3). This is in accordance with results from DRIS-analyses (Diagnosis and Recommendation Integrated System) of F. Von Willert (unpubl. data) at the same site who found N to be the most important growth limiting factor, followed by Mg, Ca and Zn. The importance of N was further stressed by a fertilisation experiment: sorghum grain yield increased four times up to 2.1 Mg ha^{-1} after the application of 100 kg N ha^{-1} (Lehmann et al., 1997). Therefore, an adequate N supply was crucial for the success of the runoff irrigation system with sorghum at our site.

The contents of N and Ca in leaves of intercropped sorghum were higher than in the sole cropped control ($p < 0.05$), whereas Mn (not significant) and especially Zn ($p < 0.05$) showed lower contents when cropped in association with the tree. Additionally, the foliar Zn content of sorghum was reduced with adjacent tree rows (significant effect of distance, Table 3). Consequently, we assume that trees and crops strongly competed for Zn and to a lesser extent for Mn. N and Ca nutrition, however, benefited from alley cropping trees and crops. Foliar P, S, K and Mg contents did not differ among treatments. Similar results were reported by Schroth et al. (1995) who found higher foliar N contents of maize when alley cropped with *Gliricidia sepium* than in monoculture on a Cambisol in the humid rainforest of the Côte d'Ivoire. Beneficial effects of alley cropping on mineral nutrition of maize (N and K) were also shown for alley cropping with *Gliricidia sepium* and *Senna siamea* on an Acrisol in central Togo, as well as negative effects of competition for Zn (Schroth and Lehmann, 1995).

Intercropping did not reduce the foliar N content of acacia, but its Ca, Mn and Zn contents were reduced (Table 4). According to Zech and Drechsel (1991), Mn and Zn levels near 45 and 16 g kg^{-1}, respectively, in the foliage of many tropical and subtropical tree species can be considered as low. The trees did not show lower foliar N levels due to competition in the agroforestry combination, possibly because they were able to acquire atmospheric N_2 by biological fixation.

Soil nutrient changes

Since N was identified to be the key element for limiting growth of crops at the experimental site, major interest was dedicated to the analysis of the mineral N

Table 4. Foliar nutrient contents of the sole (T) and intercropped (T + C) *Acacia saligna* at crop harvest in August 1996; effect of intercropping computed with ANOVA, (*) and * significant at $p < 0.1$ and $p < 0.05$, respectively; means and standard errors ($n = 3$)

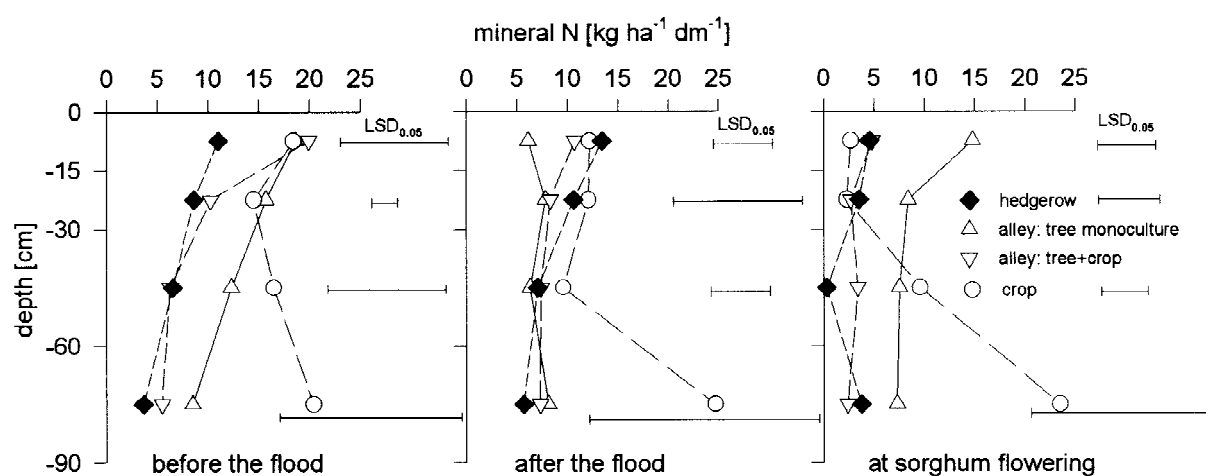| Treatment	N [g kg^{-1}]	P [g kg^{-1}]	S [g kg^{-1}]	K [g kg^{-1}]	Ca [g kg^{-1}]	Mg [g kg^{-1}]	Fe [mg kg^{-1}]	Mn [mg kg^{-1}]	Zn [mg kg^{-1}]
T	27.8 ±2.2	1.89 ±0.2	7.4 ±0.9	14.8 ±1.3	9.96 ±2.4	2.94 ±0.4	137 ±6.5	67.4 ±13.2	23.4 ±2.3
T + C	26.1 ±2.9	2.35 ±0.3	6.4 ±0.9	13.7 ±1.8	5.01 ±0.9	2.24 ±0.1	158 ±35.3	45.5 ±5.3	16.5 ±1.6
Effect	ns	ns	ns	ns	*	ns	ns	(*)	(*)

Figure 2. Total mineral nitrogen in soil extracts at 0–15, 15–30, 30–60 and 60–90 cm depth under the tree row and in the alley of sole and intercropped *Sorghum bicolor* and *Acacia saligna* before and after the flood and at sorghum flowering; only combined values for the hedgerow of sole and intercropped trees shown (not significantly different); means and LSD ($p < 0.05$; $n = 3$).

Table 5. Net-N-mineralisation and percentage of N found in the resin of soils from sole (T) and alley cropped (T + C) trees under the tree row (R) and in the alley (A) between June and August 1996 (70 days); values followed by the same letter are not significantly different at $p < 0.05$ (LSD; $n = 3$)

Treatments	Net-N-mineralisation [kg mineral N ha^{-1}]	Proportion in the resin [%]
T + CR	67.28 ab	88
T + CA	54.53 ab	85
TR	89.95 a	87
TA	54.82 b	84

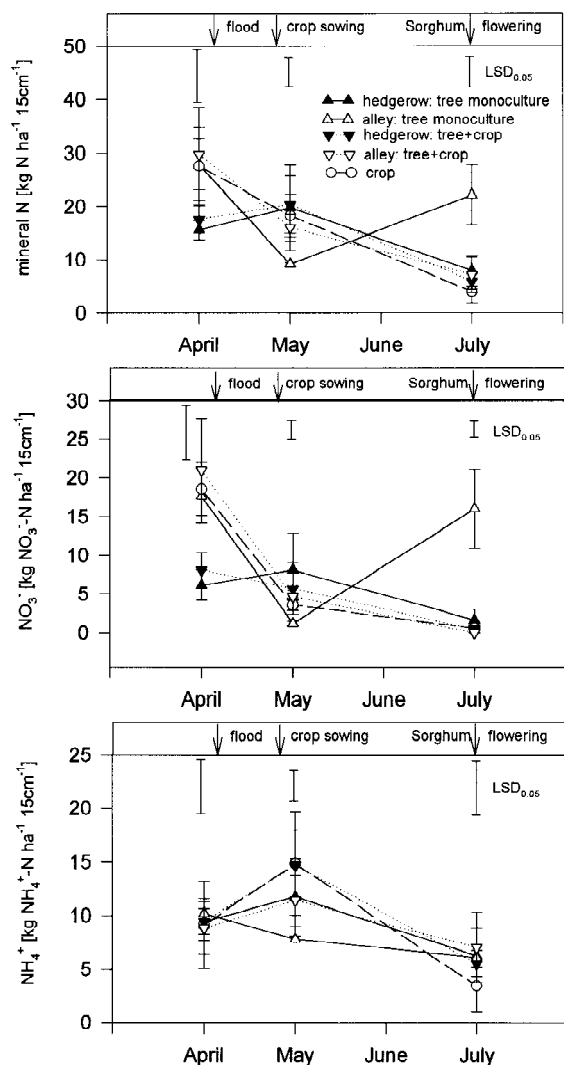*Figure 3.* Total mineral nitrogen, NO_3^- and NH_4^+ in soil extracts at 0–15 cm depth under the tree row and in the alley of sole and intercropped *Sorghum bicolor* and *Acacia saligna* from April to July 1996; means, standard errors and LSD ($p < 0.05$; $n = 3$).

fraction. Before the flood, the mineral N contents were lower in the soil under the tree row than at the center of the alley or in the sorghum monoculture ($p < 0.05$; Figure 2). After tree pruning and flooding of the fields, N contents remained constant in the subsoil (Figure 2). Mineral N contents in the topsoil decreased in soils at the center of the alley and in the sole cropped sorghum. At the topsoil under the tree rows of both sole cropped and intercropped trees, however, the N contents increased (Figure 3). Also the net-N-mineralisation was higher in the soils under the tree row than in the center of the alley (Table 5). The high percentage of N

in the resin compared to soil mineral N inside the cores (Table 5) indicates the danger of leaching of mineralised N.

At sorghum flowering, the mineral N contents decreased under the row of both sole cropped and alley cropped trees and in the topsoil of the sole cropped sorghum, where the highest nutrient uptake can be expected. In the subsoil of the sole cropped annual, however, the N contents increased throughout the experiment and were higher than in the other two cropping systems. This finding cannot easily be interpreted, as the standard error was very high at this particular depth. Whereas soil N depletion by the trees was uniform from all depths up to 90 cm, the crop did not deplete relevant amounts of N below 30 cm depth. N leached below this depth must be considered as lost for crop nutrition. When the trees were cropped alone, mineral N contents increased especially in the topsoil between the hedgerows, the highest proportion being NO_3^-. Thus, crop and tree monocultures took up N complementarily: crops were not able to utilize much of the mineral N in the subsoil, whereas the trees did not not taken up relevant amounts of topsoil N between the rows. In the alley cropping system, soil N depletion occured simultaneously in top- and subsoil under the tree row and in the alley. The agroforestry system seemed to make better use of the available N resources than the monocultures.

Other soil nutrient contents were also affected by the cropping systems: the soil Ca content increased in the sole and alley cropped sorghum, whereas it decreased under acacia monoculture (significant interaction time×treatment) and was significantly lower under the sole cropped trees than when intercropped for two years (treatment (2); Table 6). Soil P, Mg and Zn contents significantly decreased in all treatments. While Mg and Zn decreased uniformly throughout the whole sampling depth (non-significant interaction time×depth (1)), P increased in the topsoil but decreased below 15 cm depth (significant interaction time×depth (1); Table 6). The decrease of the soil Ca, Mg and Zn contents may be the reason for the low foliar nutrient contents and explain why intercropping further reduced crop and tree nutrition of these nutrients described in the preceding section. The soil K, Fe and Mn contents did not relevantly change with time or between cropping systems.
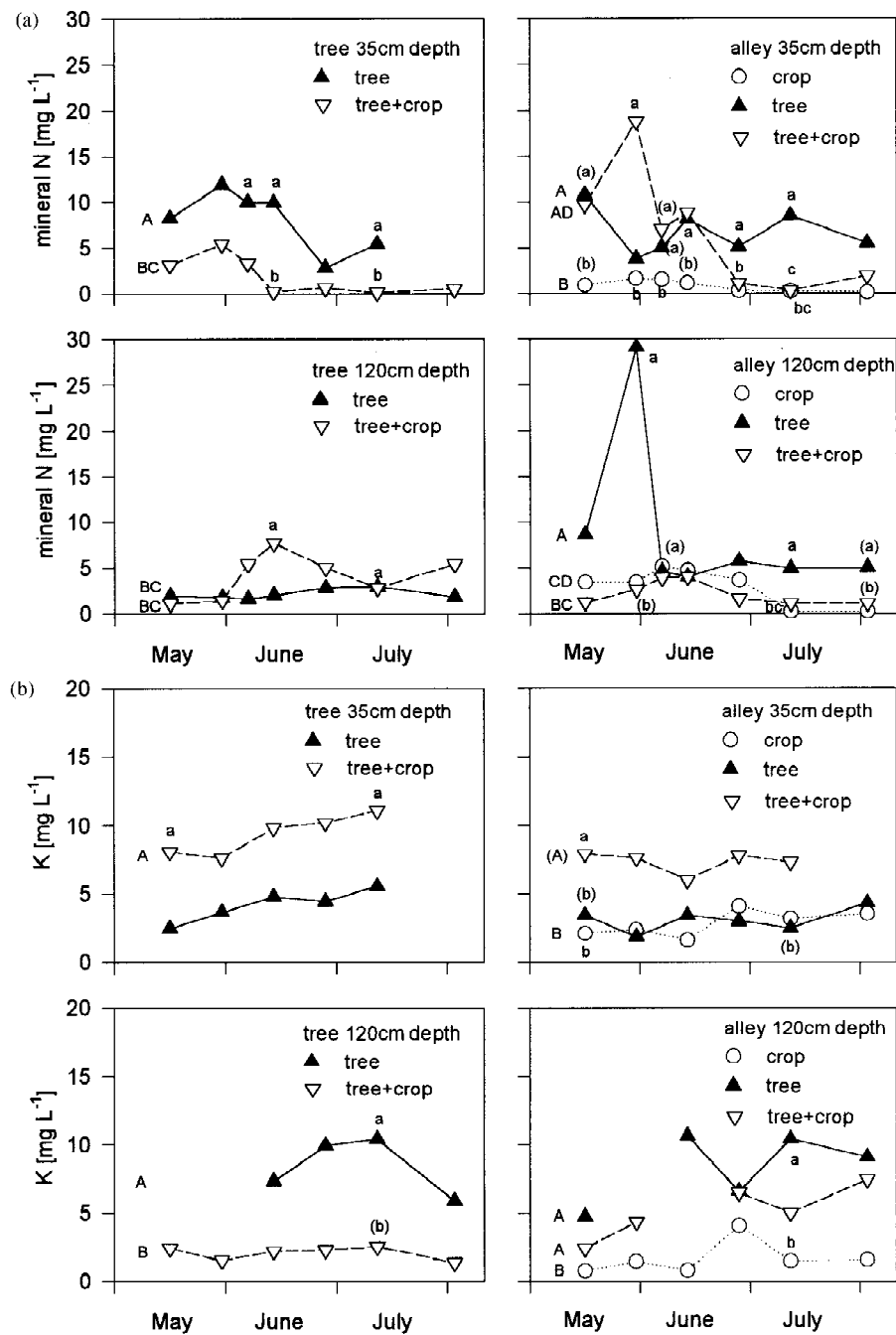
Figure 4. Total mineral nitrogen, potassium, calcium and magnesium in the soil solution at 35 and 120 cm depth under the tree row and in the alley of sole and intercropped *Sorghum bicolor* and *Acacia saligna* from May to July 1996; symbols with the same letter are not significantly different at $p < 0.05$ (in brackets $p < 0.1$), small letters refer to one sampling date, capital letters to the whole experimental period; mean values.
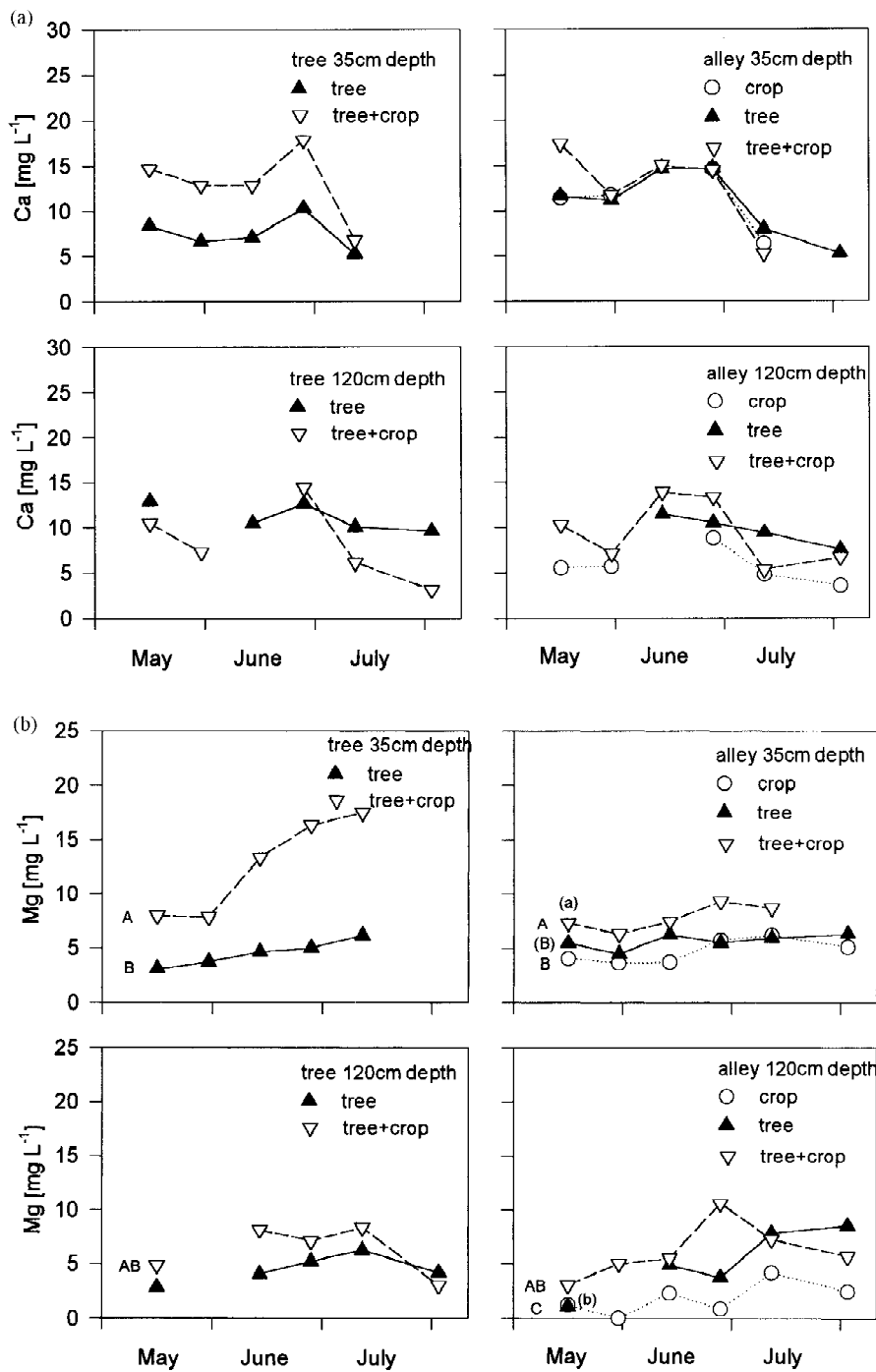
Figure 4. Continued.

Table 6. Changes of the soil nutrient contents in monocultures of *Sorghum bicolor* (C) and *Acacia saligna* (T) and in the alley cropping system (T + C) at two positions within the alley (A) and under the hedgerow (R) in July 1996 compared to the contents before the experiment in June 1994 (Table 2); effects (1) of treatment, time and depth, and (2) of treatment and depth on soil nutrient changes computed with ANOVA (*n*=3)

Treatment	depth [cm]	P	K	Ca	Mg	Fe	Mn	Zn
		[% of initial contents]						
C	0–15	+56	+20	+9	−19	+31	+5	+17
	15–30	−36	+5	+19	−6	+20	+4	−27
	30–60	−11	+7	−13	−37	+16	+18	−21
T + CR	0–15	+66	+11	+7	−11	+17	+5	−26
	15–30	−37	−6	+3	−10	−0	+6	−37
	30–60	−11	+4	+10	+5	+11	+7	−34
T + CA	0–15	−9	+2	+6	−20	+3	+8	−53
	15–30	−43	−13	+8	−9	−2	+12	+9
	30–60	−11	+17	+23	+11	+18	+31	−33
TR	0–15	+9	+22	−10	−16	+14	−6	−48
	15–30	−18	−2	−22	−24	+10	−0	−43
	30–60	−30	+8	−5	−14	+17	+13	−22
TA	0–15	+14	+21	−9	−10	+7	−6	−39
	15–30	−23	−19	−24	−27	−3	−5	−64
	30–60	−22	+16	−4	−6	+7	+10	−55
(1) Time		*	ns	ns	*	ns	ns	*
(1) Time × treatment		ns	ns	**	ns	ns	ns	ns
(1) Time × depth		**	*	ns	ns	*	ns	ns
(2) Treatment		ns	ns	**	ns	ns	ns	ns
(2) Depth		**	*	ns	ns	ns	*	ns
(2) Depth × treatment		ns	ns	ns	ns	ns	ns	ns

Soil solution nutrient dynamics

The soil solution contains the most mobile and readily plant-available fraction of soil nutrients. The mineral N dynamics in the soil solution confirmed the results shown for the soil extractable N. The N contents in the topsoil were higher within alleys of sole cropped trees than for alleys intercropped with sorghum or in the crop monoculture (Figure 4). This finding gives strong evidence that the available N in the topsoil between the hedgerows was not efficiently used by the sole cropped trees. The analysis of the soil solution revealed the dynamics of available nutrients more sensitively than N extraction from the bulk soil: not only at the topsoil between the tree rows were the N concentrations of the soil solution higher in sole cropped than intercropped trees but also at 120 cm depth and in the topsoil under the tree row. Moreover, the topsoil N availability was higher in the tree plots than in the crop monoculture. The N concentrations in the subsoil solution of the sole cropped sorghum were low compared to the results of the soil N extraction.

These results showed that integrating a crop between tree rows improved the efficiency of using topsoil N. On the other hand, integrating trees into the farming system seemed to have improved the content of available topsoil N. A difference of 1 mg L^{-1} in the soil solution (Figure 4) corresponds to 1 kg ha^{-1} dm^{-1} at pF1 with 20% volumetric water content. Therefore, N contents in the soil solution of the agroforestry system were about 9 kg ha^{-1} dm^{-1} higher than in the crop monoculture in May. The same amount was calculated from relative changes of the soil mineral N at 0–15 cm depth (Figure 3). This seemed to be a relevant improvement of the N availability through agroforestry. The effects of the different cropping systems on K,
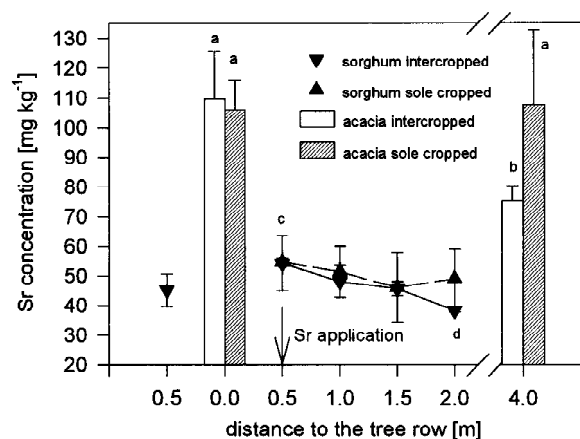
Figure 5. Foliar strontium content of sole and intercropped *Sorghum bicolor* and *Acacia saligna* one month after a strontium application; symbols and bars with the same letter are not significantly different at $p < 0.05$ ($n = 3$); means and standard errors.
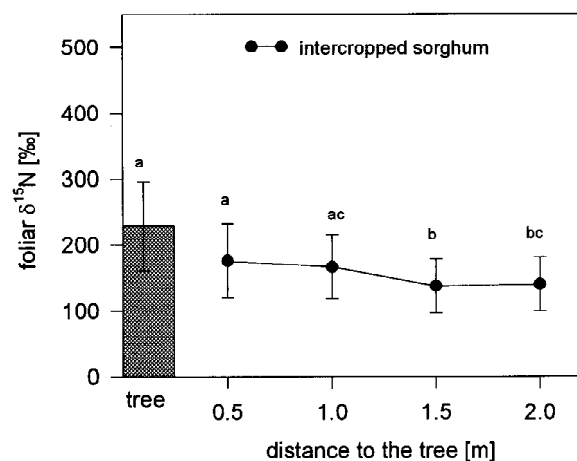

Figure 6. Biomass $\delta^{15}N$ values of intercropped *Sorghum bicolor* and *Acacia saligna* at crop harvest in August 1996; symbols and bars with the same letter are not significantly different at $p < 0.05$ ($n = 3$); means and standard errors.

Ca and Mg dynamics in the soil solution were less pronounced and less clear than on N contents.

Areas of nutrient uptake in hedgerow intercropping

The foliar Sr content of the sorghum decreased with increasing distance to the place of application irrespectively of the cropping system (Figure 5; $r = 0.98$ and $r = 0.55$ for tree+crop and crop monoculture; $p < 0.05$). In the alley cropping system also the crop row next to the hedge in the adjacent alley without a Sr application showed similar Sr contents as the sorghum at the same distance to the Sr application but within the

same alley. The close relationship between distance to the Sr application and the foliar Sr contents were also observed including this sorghum row ($r = 0.98$; $p < 0.05$). Thus, the trees did not affect the Sr uptake of the crop. However, the Sr uptake of the trees themselves was affected by intercropping: the hedgerow Sr content near the application showed no effect of intercropping, but foliar Sr contents in the tree row opposite to the application were significantly reduced when alley cropped. The sorghum was more competitive than the acacia in taking up the Sr tracer. On the other hand, the trees were taking up a higher proportion of ^{15}N, which was applied at the installation of the experiment, than the intercrop (Figure 6). As foliar $\delta^{15}N$ values of sorghum decreased with increasing distance to the tree row, it is suggested that ^{15}N has partly been taken up by the trees, was then recycled and once again mineralized for plant uptake. The trees may have exploited sources of ^{15}N from the applied tracer, which the crop did not utilize. One explanation is that the trees were taking up ^{15}N at times when no sorghum was planted as between cropping cycles. The trees may also have utilized ^{15}N from below the root zone of the crop. This would well coincide with the observation of the subsoil mineral N content being less utilized by the crop monoculture than by trees (Figure 2).

Nutrient interactions of associated tree and crop

Nutrient competition and complementary use of soil nutrients can occur between associated trees and crops, either simultaneously or with spatial and temporal differentation. In our study, we observed complex interactions of the above mentioned processes. Acacia and sorghum were competing for nutrient sources as seen from changes of the foliar Zn contents. On the other hand, the N contents of the sorghum were not lower when intercropped, but rather higher than in the monoculture. The same was observed for the mineral and soil solution N contents in the topsoil. The increasing mineral N content of the soil could be a direct N input from tree to soil but also a stimulation of the mineralisation of soil N. Litterfall did not play an important role since the trees were pruned. Root turnover of the tree is another process of direct N input, which could increase soil N, as hypothesized by Haggar et al. (1993) for an alley cropping experiment in Costa Rica. The determined fine root turnover of 0.9 kg N ha^{-1} dm^{-1} a^{-1} in a study at our site (Lehmann and Zech, 1998), however, could not explain the 9

kg ha^{-1} dm^{-1} of mineral N which were mobilized in the tree plots compared to the crop monoculture at the beginning of the cropping season (see above). N may also have been released by live acacia roots, or root exudates could have stimulated mineralisation of soil N (Grayston et al., 1996). The higher abundance of live fine roots could have induced a higher microbial activity and subsequently a higher mineralisation of N from organic residues, as shown with labelled biomass by Cheng and Coleman (1990).

Apart from the described competition and soil nutrient improvement, tree and crop N uptake was complementary: subsoil mineral N contents were higher in sorghum monoculture than when alley cropped, whereas N reserves were found in the topsoil between the tree rows which were not utilized by the sole cropped acacia. This also gave evidence for deeper capture of nutrients by the trees than by the crops. Similar observations were made by Hartemink et al. (1996) who found a higher NO$_3$ uptake by *Sesbania sesban* at 0.5–2 m depth compared to unfertilized maize at two locations in Kenya.

Conclusions

Nitrogen was the nutrient which was limiting plant growth the most at the experimental site. However, a pronounced competition for N could not be verified. Trees and crops were competing for Zn, and trees had lower foliar Ca contents when intercropped. The acacias caused an increase of available soil N in the agroforestry system, which was beneficial for crop N nutrition. N sparing was found in the topsoil between the hedges, which could be utilized by the sorghum when intercropped. The pathways of N at the tree–crop interface could not be fully clarified. Since the above-ground biomass did not recycle nutrients via mulching or litterfall, the tree roots were supposed to have caused the increase of the N availability. Root turnover could not be the entire reason for soil mineral N improvement, though it has certainly contributed. The investigation of nutrient fluxes at the root–soil interface in mixed cropping systems needs more attention and should be looked at in the future.

Acknowledgements

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