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Nutrient cycling in an agroforestry system with runoff irrigation in Northern Kenya

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Abstract. A nutrient balance was determined for sole and alley cropped *Sorghum bicolor* and *Acacia saligna* in a runoff irrigation system in Northern Kenya. Nutrient input including precipitation and runoff, and output through harvest and leaching were measured for N, P, K, Ca and Mg using adsorption resins, tensiometry and suction cups. Various management scenarios are discussed with respect to nutrient return. Nutrient input with rainfall was generally low in comparison to nutrient uptake or leaching losses. The irrigation water, however, constituted an important nutrient input, especially for Ca and Mg. Nutrient export with the harvest was large for N and K, but can effectively be reduced by a nutrient return with mulch. Nutrient leaching losses from the topsoil (0–30 cm) were lower in the sorghum monoculture than in the tree-based systems. In the subsoil (120 cm), however, leaching was effectively reduced by the trees. In the agroforestry system, leaching losses of N under the sorghum were 53% lower than in the sorghum monoculture. This could be attributed to a higher root abundance and a higher ratio of nutrient uptake-to-leaching in the agroforestry system than in the monocultures indicating a higher nutrient efficiency. The lower leaching losses in the agroforestry system compared to the crop monoculture could not compensate for the additional nutrient export in tree biomass. A nutrient return by mulching crop residues and acacia leaves was essential for a positive nutrient balance in the agroforestry system. Combining annual and perennial crops provided a higher internal nutrient cycling than the monocultures.

Introduction

On many tropical soils, nutrient deficiency is one of the severest constraints to crop production (Sanchez, 1976) while the use of commercial fertilisers in tropical land use systems is restricted for various reasons (Mokwunye and Hammond, 1992). Runoff irrigation may enhance the problem of nutrient deficiency by nutrient depletion due to high leaching rates (Lehmann et al., 1998d). An accelerated plant growth as a consequence of a higher water supply can further induce nutrient deficiency under dryland irrigation (Rauschkolb and Hornsby, 1994).

The integration of trees into farmland has been suggested to combat soil nutrient depletion in tropical cropping systems (Sanchez, 1995). Trees are able to mobilise nutrients from the subsoil and then return these nutrients to the topsoil making them available for an annual crop (Buresh and Tian, 1998). This may be especially important for nitrate in deep soils with high anion exchange capacity in the subsoil (e.g. Akonde et al., 1997). Trees may reduce nutrient leaching and form a ‘safety-net’ under the root zone of the annual crop (Van Noordwijk et al., 1996). These processes have largely been hypotheses up to now and very few have been proven for tropical agroforestry systems.

Some evidence exists that trees are able to reduce nutrient leaching in comparison to sole cropped annuals (Seyfried and Rao, 1991), or that they can take up nutrients below the rooting depth of crops (Hartemink et al., 1996). All nutrient fluxes should be considered to evaluate the sustainability of a land use system, but such attempts have rarely been completed for agroforestry systems up to now (e.g. Akonde et al., 1997).

We investigated the nutrient inputs with precipitation and runoff, and the nutrient outputs with leaching and harvest during one cropping season. Sole cropped *Sorghum bicolor* or *Acacia saligna* were compared with an alley cropping combination in a runoff irrigation system in Northern Kenya. The aim of this study was (i) to compare the importance of nutrient inputs and outputs in the nutrient cycle of a runoff agroforestry system, (ii) to investigate the effects of trees on nutrient leaching and nutrient export with the harvest, and (iii) to compare the nutrient budgets of monocultures with the agroforestry system. Different scenarios of nutrient management with and without biomass return will be discussed.

Materials and methods

Study site

This study was carried out in a dry tropical savannah of Northern Kenya near Kakuma (34°51′ E and 3°43′ N, altitude 620 m a.s.l.) between 1994 and 1996. The rainfall distribution is bimodal with two maxima in April to May and September to October and an average annual precipitation of 318 mm (14 year record; W. I. Powell, and Turkana Drought Control Unit, unpubl. data), 330 mm in the whole year of 1996 with 166 mm during the first cropping season (Figure 1). The soils are *Calcareous fluvisols* (FAO, 1995), deep soils with a loamy texture, high pH and a subsoil characterised by high EC, low organic C and N contents (Table 1).

Experimental design and treatments

Prior to the study in 1994, a runoff irrigation system was built using a design of levelled basins in lower slope position with an inclination of less than 2° (Lehmann et al., 1998a). Similar irrigation systems have been used in the Negev (Lövenstein et al., 1991) and were adapted to drylands throughout

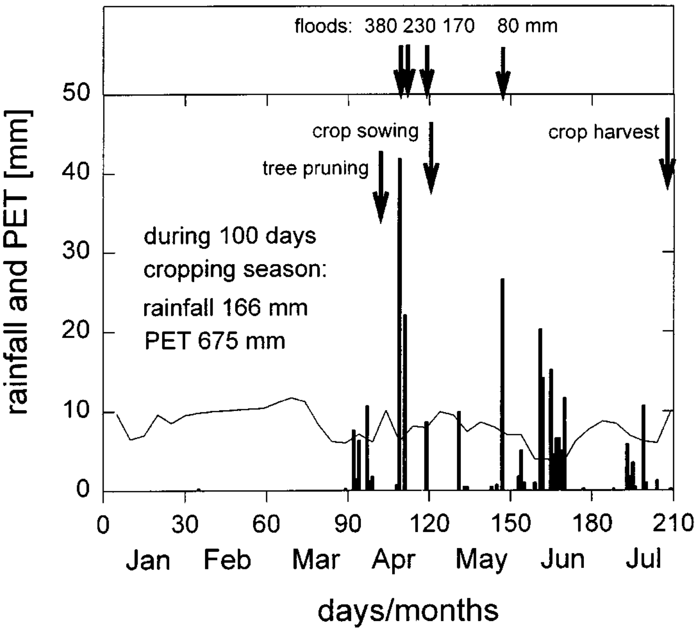

Figure 1. Rainfall (bars), potential evapotranspiration (PET; line), floods (arrows and amount of irrigation per flood) and management techniques in Kakuma, Northern Kenya, from January to July 1996.

Table 1. Chemical characterisation of a representative soil profile and the individual plots ($n = 9$) at the experimental site near Kakuma, Northern Kenya.

Depth (cm)	Horizon	Bulk density (mg m^{-3})	pH H_2O	Organic C (g kg^{-1})	EC (S m^{-1})	Particle size distribution (%)		
						Sand 60–2000	Silt 2–60	Clay < 2 µm
0–7	Ah	1.50	8.6	5.3	0.054	39	49	12
7–14	2A	1.38	8.9	2.5	0.035	77	17	6
14–30	3Ah	1.25	8.6	6.4	0.043	21	61	18
30–60	3Bt	1.34	8.9	5.1	0.056	11	74	15
60–107	3Btn	1.36	9.2	8.0	0.185	5	67	28
107–170	4Btz1	1.44	8.7	5.3	0.581	31	47	22
170+	4Btz2	1.41	8.2	2.3	1.362	19	64	17

Depth (cm)	N (g kg^{-1})	P (mg kg^{-1})	K (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})
0–15	0.26	12.1	242	5208	534
15–30	0.32	16.6	267	5587	596
30–60	0.31	14.2	224	5005	535

$n = 1$.

Africa (cited in Lehmann et al., 1998a), and also in Northern Kenya (NORAD-Kenya, unpubl. report; OXFAM-Kenya, unpubl. report). Four 210 × 30 m basins were laid out in the contour and divided in 13 × 24 m plots. The level of the plots was lowered by 40 cm, and the surrounding walls were built with soil from the excavation and compacted manually. Each of the plots investigated in this study were separated from the adjacent plots by walls 1.5 m wide. The runoff water originated from a nearby mountain range during heavy rainstorms and was guided into the irrigation system. The basins could be filled in April/May, August and November 1994, in May and September 1995 and in April and August 1996 up to a level of about 500 mm. During the cropping season presented here from April to July 1996, a total of 860 mm could be guided into the basins (Figure 1). The water infiltrated into the soil with a rate of 4 to 10 cm day^{-1} depending on the soil texture and the soil water content before the flood. An alley-cropping system with *Acacia saligna* (Labill.) H. L. Wendl, which proved suitable for runoff agroforestry (P. Berliner, pers. comm.; for the similar *Acacia salicina* see Lövenstein et al., 1991) and *Sorghum bicolor* (L.) Moench was compared with monocultures of either acacia or sorghum. At tree planting, the five months old saplings were inoculated with a mixture of nine strains of *Rhizobium* spp. commonly found in the area (Kenya Forestry Research Institute KEFRI). After the November rains in 1994, the trees were planted in 4 m wide alleys and a 1 m distance between trees within the row (2500 trees ha^{-1}). Five tree rows were planted with 14 trees per row, and the central 30 trees were used for biomass determination, leaving a distance of 8 m to the adjacent plots. All other measurements were carried out in this central part of each plot. In 1996, the fourth basin was flooded more often than the other ones; thus, only three replications could be used in this study.

Biomass determinations

In March and August 1996, the trees were pruned to a height of 1.5 m, and the prunings were separated into leaves (phyllodes) and branches (all lignified material) and then weighed. Subsamples were dried at 70 °C for 48 hours and weighed again to correct for the water content. All harvested biomass was taken out of the system.

Sorghum was sown in rows 0.5 m apart with 0.25 m distance between plants in the row in April and September1995, and in May 1996, of which only the latter is presented here (Figure 1). In the agroforestry plots, every 8th crop row was replaced by a tree row. The biomass production was measured at harvest, 90 days after planting. 12 randomly chosen stands per treatment were separated into grain and straw, weighed, dried at 70 °C for 48 hours and weighed again. The yield of the intercropped sorghum (Table 4) was expressed per total area of the cropping system including the area of the tree row.

Plant nutrient analyses

In order to determine plant nutrient uptake, straw and grain samples were obtained from sorghum at harvest. Representative subsamples were taken from acacia prunings in August 1996. The leaves were gently rinsed with de-ionised water to remove adhering particles and dried at 70 °C for 48 hours. Afterwards, they were finely ground with a Retsch mill.

N was determined after dry combustion with an automatic C/N Analyser. For the other nutrients, 200 mg dry leaves were digested in 2 ml concentrated HNO_3 at 170 °C for eight hours, and diluted to 20 ml with de-ionised water. K, Ca and Mg were analysed with an atomic absorption spectrometer, P was measured by colorimetry according to the molybdenum blue method (Olsen and Sommers, 1982).

The nutrient uptake was calculated from biomass production and nutrient concentrations. In the agroforestry system, the uptake was determined for the individual rows and computed for the land use system considering the reduced cropped area of the sorghum. Since the nutrient concentrations of the sorghum in Table 5 are given as mean values of the whole agroforestry system, the uptake in Table 4 cannot be directly deduced from nutrient concentrations and biomass production.

Soil solution 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. Two to three parallel cups were installed in each replicate and analysed separately; in the tree plots, they were inserted under the tree row and in the middle of the alley 2 m from the tree row. The cups were treated with HCl (10% for 48 hours) before installation and remained in the soil for two years prior to this study. Below the soil surface, the hoses which were attached to the cups were bent into a curve and guided a few decimetres further out of the soil to ensure that no preferential flow would contaminate the solution obtained through the cups. Vacuum was applied on individual sampling flasks by a portable electric pump; the suction cups were constructed in a way that the solution was sucked automatically 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 vacuum was manually adjusted to the soil water suction measured by the tensiometers at the same site. Before the vacuum application, the flasks were treated with chloroform to avoid the growth of algae. Soil solution was extracted at one to two weeks intervals as long as it could be obtained from the cups before the soil dried up. Only from May to July could the soil solution be sampled. This was considered to adequately represent the mobile nutrients, since soil water suction at other times of the year was too high to permit relevant water movement in the soil. The collected soil solution was treated with chloroform, deep frozen and transported to Germany for further analyses. NO_3^- and NH_4^+ were analysed by spectroscopy with a Rapid Flow Analyser, K^+, Ca^{2+} and Mg^{2+} with ICP-AES. Organic N could only be detected in small amounts (< 15%) during a preliminary study and was not analysed further.

Determination of the soil water suction dynamics

For the measurements of the soil water suction, gypsum blocks (Eijkelkamp 14.23.03, The Netherlands) with a mobile meter were used in the topsoil, operating also at high soil water suctions in contrast to tensiometers. The gypsum blocks were calibrated at 0.1, 0.3, 1, 5 and 15 bars in pressure chambers to obtain the relationship between meter readings and the soil water suction, and the results were used to adjust 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 put at the same positions. In two replicates per treatment, two parallel instruments were installed, but five and six in the third replicate of the sole cropped and intercropped systems, respectively. The readings were made at weekly intervals, more often during the first week after each flood.

Calculation of nutrient fluxes in the soil from soil solution measurements

For the determination of nutrient fluxes in the soil, three different methods were employed: (1) the resin core method, where only nutrient fluxes from the topsoil (0–30 cm) to the subsoil (> 30 cm) could be measured without considering capillary rise (see next section).

(2) The water fluxes and subsequently the nutrient fluxes were calculated using soil water suction determinations and nutrient concentrations in the soil solution. The saturated hydraulic conductivity was obtained from the infiltration rate after the irrigation, considering evaporation losses by subtracting potential evapotranspiration (PET) calculated after Priestley and Taylor (1972). The unsaturated hydraulic conductivity was computed with an interpolated water retention curve (capillary bundle approach) following the procedure of Millington and Quirk (1960) modified by Jackson (1972). The determination of the water retention curve was made in laboratory experiments using pressure plates, and a field water retention curve was determined with simultaneous tensiometer and neutron probe measurements. Water fluxes were calculated with Darcy’s law using the unsaturated conductivity and weekly determinations of the soil water suction (gradient method). Convective nutrient transport in soil was obtained with the weakly determined water fluxes

and the nutrient contents of the soil solution, which were then calculated on a daily basis by interpolation using cubic splines. At 35 cm depth, only infiltration was determined in order to compare the nutrient fluxes with the results obtained from the resin cores (Table 6). Due to insufficient retrieval of soil solution, Ca, K and Mg fluxes could only be given for two replicates.

(3) With a model simulation, the water fluxes calculated from tensiometer measurements (2) could be verified using a one-dimensional model (WHNSIM; Huwe and Totsche, 1995). The input parameters for the model comprised soil physical properties (see above), PET, rainfall (all taken from K. Droppelmann, unpubl. data), initial soil water suction, irrigation (PET was subtracted; without considering the pressure potential), above-ground vegetation development (from this study) and below-ground vegetation development (root length density from Lehmann et al., 1998b). Only the means for all replicates integrated over the whole plot were used with parameters representative for the entire site, not considering the spatial patterns of the tree systems.

Determination of topsoil nutrient fluxes using resin cores

Resin cores, which were up to now only used in N mineralisation experiments (DiStefano and Gholz, 1986; Hübner et al., 1991; Kolberg et al., 1997) were modified and used in two different ways, for the determination (i) of the nutrient inputs to the soil with the flood and (ii) of the nutrient fluxes from the topsoil into the subsoil. For the measurements of nutrient inputs, PVC cores with a diameter of 7.8 cm and a length of 10 cm were filled with a resin-sand mixture. Mixing the resin with sand was meant (i) to increase the adsorption time of percolating nutrients and (ii) to improve the hydraulic properties (Hagedorn et al., 1997) in comparison to pure resin as used in previous studies (e.g. Kolberg et al., 1997). In contrast to Hagedorn et al. (1997), a combined anion and cation exchange resin (Amberlite MB 20; 0.7 meq H^{+-}; 0.7 meq OH^{-}) was used, 100 ml of which were mixed with 500 ml of acid washed sand. The resin had negligible blank values and recoveries were around 100%. The use of acid washed sand permitted the determination of all desired nutrients. The mixture was slightly wetted to avoid separation of sand and resin, filled into the cores and compacted to give similar bulk densities as the surrounding soil. Preliminary infiltration studies proved that the cores and the undisturbed soil had similar saturated hydraulic conductivity (S. Wulf, unpublished data). A 2 cm extension at the bottom, filled with acid washed sand, ensured a good contact of the core with the soil. At the top, a 2 cm extension was designed to collect soil particles which were carried into the fields with the runoff water; the soil was weighed and analysed for its elemental contents. The three core sections (upper soil collector, resin-sand mixture, sand) were separated by nylon mesh (0.5 mm diameter). One resin core was randomly installed in each plot level to the soil surface in holes with a diameter of 8 cm, nine cores in total. For comparison, the nutrient contents and the total amount of the runoff water were measured in the basins to give an estimate of nutrient input with the irrigation water.

For the determination of the subsurface nutrient flows, additional resin cores were inserted at 35 cm depth, which were constructed as described above with the exception that ash-free filters were used instead of nylon mesh to improve hydraulic properties under unsaturated conditions. One core was put in the tree row and in the centre of the alley (2 m distance from the trees) of each tree monoculture and in the sole cropped *sorghum* in two replicates. The alley cropping system was equipped with two cores in each position. The installation was done with great precision: for the subsurface cores, the undisturbed soil cores from augering the holes were carefully put onto the resin cores ensuring a good contact between soil and resin core; the small gap between resin core or soil core and soil was filled with soil and compacted to reduce preferential flow. All cores were brought into the field at the beginning of April. The infiltration cores to measure the nutrient input to soil were removed after the last flood in June 1996, and the cores for the determination of the subsurface nutrient fluxes at the end of the experiment in August 1996. The use of the combined anion-cation resin-sand mixture allowed to cut the column into three layers, 0–6, 6–8 and 8–10 cm, in order to verify that no nutrients were lost by leaching and that no capillary rise influenced the results; the thickness of the layers was adjusted after preliminary experiments. The total amount of each fraction was weighed, and a subsample was dried and analysed for NO_3^-, NH_4^+, K^+, Ca^{2+} and Mg^{2+} after extraction with 1 N $CaCl_2$ (only for K^+) or 1 N KCl (for all other elements). With the amberlite resin, one extraction was sufficient to obtain a recovery of more than 90%. The storage of the resin may have not affected the nutrient contents as shown in several experiments (e.g. Hübner et al., 1991).

Precipitation analyses

During the flood events and the infiltration of the irrigation water, the nutrient input with the rainfall was contained in the infiltrating water. During this time, nutrient inputs by precipitation were therefore not accounted for. After the flood events and the removal of the resin cores, precipitation solution was obtained from four rainfall collectors which were installed above the tree canopy in each block and combined. The nutrients in the sampled rains were measured with the same procedure as for the soil solution. The total amounts of nutrients in the rainfall were calculated from the analysed nutrient contents and the total amount of rainfall obtained from a meteorological station on the site (automatic recordings checked with field sampling).

Soil nutrient analyses

C and N were measured after dry combustion with an automatic C/N analyser (Elementar). Soil nutrients were extracted according to the Mehlich three procedure (Mehlich, 1984). K, Ca, Mg, Zn, Fe and Mn were analysed with an atomic absorption spectrometer. P was determined by colorimetry in the same extract by the molybdenum blue method (Olsen and Sommers, 1982).

Statistical analyses

All nutrient data were compared by analyses of variance using a *randomised complete block* design. The effects of distance to the tree row were computed as *split plot* designs (Little and Hills, 1978). In case of significant effects or interactions, individual cell means on the respective level were compared using LSD at $P < 0.05$ (Little and Hills, 1978).

Results and discussion

Nutrient input

The nutrient input through precipitation varied between the different elements and was highest for Ca and K, followed by N (Table 2). The amounts were in the range of results from other studies e.g. 5–10 kg N ha^{-1} y^{-1} reported by Aggarwal and Lahiri (1981) in an inland desert system. The input by runoff water was about three times higher for N, P, and K, but five times higher for Ca and Mg than the input by rainfall (Table 2). This reflects well the lower mobility of P and K in soils with high contents of illite (Wild, 1988) and the low soil N and K contents in comparison to Ca and Mg (Table 1). The calculated nutrient input from nutrient concentrations and the amount of irrigation water, however, was lower ($P < 0.05$) than the nutrients captured at the soil surface with the resin cores (Table 2). This can be explained by the nutrient contents of the sediment which was imported by the runoff water (Table 3): the nutrient contents of the sediment were 1.4 times higher for N, 2.7 times higher for K, 4.7 times higher for Ca, 2.5 times higher for Mg, but

Table 2. Nutrient input by precipitation and runoff at Kakuma, Northern Kenya, (a) calculated with the nutrient contents of the runoff and the amount of water in the basins or (b) determined with the nutrients captured in resin cores at the soil surface.

Method	N	P	K	Ca	Mg
Rainfall	3	1	8	9	1
Runoff:					
Runoff water calculation	9	2.3	29	49	5
Resin core measurement	27	3.2	41	388	42
Effect of method	***[a]	**	*	***	***

n = 1 from 4 subsamples.

[a] ANOVA; n = 9 : * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

Nutrient inputs in kg ha^{-1}.

Table 3. Total nutrient input into the runoff irrigation system with a load of 150 Mg ha^{-1} sediment and its nutrient concentrations.

Method	N	P[a]	K	Ca	Mg
Concentration (g kg^{-1})	0.66 ± 0.04	0.012 ± 0.0004	0.66 ± 0.03	24.7 ± 1.4	1.33 ± 0.05
Total amount (kg ha^{-1})	98 ± 7	1.8 ± 0.01	99 ± 10	3600 ± 198	198 ± 17

Means and standard errors (n = 9).

[a] Mehlich (1984).

not higher for P than the topsoil nutrient contents (Table 1). An input of soil bound nutrients is not necessarily a nutrient input which can be used by the crop. But imported sediment had higher plant available nutrient contents than the soil and the irrigation water was enriched when percolating through the sediment resulting in nutrients leached into the soil. The resin core method allowed to assess the total nutrient input from irrigation water, sediment and precipitation with only one measurement with a satisfactory accuracy.

All resin cores adsorbed the majority of nutrients in the upper layer indicating that the nutrients were quantitatively recovered. The mixture of a combined anion-cation resin-sand mixture proved to be useful in excluding systematic errors like nutrient loads exceeding the exchange capacity of the resin. In some resin cores, comparatively large amounts of nutrients were also retrieved from the lowest core layer; this would indicate that capillary rise can obscure the leaching results. The presented resin core design could control these sources of errors. Preferential flow alongside the cores and differences in the hydraulic properties between adjacent soil and resin-sand mixture may still have occurred and could have led to an under- or overestimation of flows; however, the low standard errors of the results from the resin cores in the topsoil (Table 2) and preliminary infiltration studies (S. Wulf, unpublished data) confirmed the reliability of the obtained values.

Nabhan (1984) found slightly lower nutrient contents of the floodwater sediments with 0.02–0.4, 0.2–0.9 and 0.3–0.9 g kg^{-1} for N, K and Mg, respectively, but without indicating how much of these nutrients were mobile or plant available. In our study, the difference between the nutrient concentrations of the sediment and the soil was larger for Ca and Mg than for P and K, N being intermediate. This difference can again be explained by the higher mobility of Ca and Mg and the relatively low total soil N contents as mentioned above.

Plant nutrient uptake of sole and mixed cropping systems

The nutrient uptake of the agroforestry system was higher than that of the sole cropped sorghum ($P < 0.05$) or trees alone ($P < 0.05$ only for K; Table 4).

Table 4. Biomass production and nutrient uptake in above-ground biomass of sole cropped *Acacia saligna* (SCA) and *Sorghum bicolor* (SCS) and of the alley cropping system (AC) at Kakuma, Northern Kenya.

Treatments		Sorghum		Acacia		Total
		Grain	Straw	Leaves	Branches	
SCA	Biomass	–	–	2.7	2.3	5.0 a
SCS	Biomass	0.42	4.9	–	–	5.3 a
AC	Biomass	0.63	6.0	2.1	1.7	10.4 b
SCA	N	–	–	56.9	15.3	72.2 ab
SCS	N	9.0	20.5	–	–	29.5 a
AC	N	9.9	24.5	41.7	11.4	87.5 b
SCA	P	–	–	3.9	4.3	8.2 ab
SCS	P	1.7	4.1	–	–	5.8 a
AC	P	2.3	7.0	2.4	2.7	14.4 b
SCA	K	–	–	14.4	18.9	33.3 a
SCS	K	2.1	67.8	–	–	69.9 b
AC	K	3.2	79.6	12.5	15.2	110.5 c
SCA	Ca	–	–	59.6	21.6	81.2 a
SCS	Ca	0.2	26.4	–	–	26.6 b
AC	Ca	0.2	28.3	44.4	19.9	92.8 a
SCA	Mg	–	–	14.3	3.7	18.0 a
SCS	Mg	0.8	4.4	–	–	5.2 b
AC	Mg	1.0	5.5	9.8	3.5	19.8 a

Biomass production in Mg ha^{-1} (K. Droppelmann, unpubl. data) and nutrient uptake in kg ha^{-1}. Values followed by the same letter are not significantly different at $P < 0.05$ (LSD from ANOVA; $n = 3$), only values within one nutrient were compared.

This was mainly caused by a higher biomass production in the agroforestry system. The total nutrient uptake of sorghum was enhanced by alley cropping due to a higher biomass production (Table 4) but also higher nutrient contents of the sorghum straw (Table 5) in the agroforestry system than in monoculture. Sorghum grain and acacia leaf and branch nutrient concentrations did not change when alley cropped (Table 5).

Relatively small amounts of Ca and K were allocated to the sorghum grain in comparison to the straw, whereas almost half of the N, P and Mg uptake was found in the grain. Comparing uptake of leaves or branches of the acacias, the differences between nutrients were even more pronounced: only 21% of the total N, 23% of the total Mg and 29% of the total Ca uptake, but 53% of the total P and 56% of the total K uptake were found in the branches. This would indicate that for an efficient N, Mg and Ca recycling the leaves have to be returned, but for P and K the branches. Under on-farm conditions, this decision will depend on the preferences of the farmer.

Table 5. Nutrient concentrations in above-ground biomass of sole cropped *Acacia saligna* (SCA) and *Sorghum bicolor* (SCS) and of the alley cropping system (AC) at Kakuma, Northern Kenya.

Treatments		Sorghum		Acacia	
		Grain	Straw	Leaves	Branches
SCA	N	–	–	19.4	6.1
SCS	N	21.3	3.5	–	–
AC	N	18.0	5.3	17.5	6.1
SCA	P	–	–	1.3	1.9
SCS	P	3.9	0.70	–	–
AC	P	3.9	1.49	1.0	1.6
SCA	K	–	–	5.0	7.6
SCS	K	4.9	11.6	–	–
AC	K	5.1	17.7	5.3	8.1
SCA	Ca	–	–	21.1	8.0
SCS	Ca	0.38	4.6	–	–
AC	Ca	0.34	5.9	18.5	10.6
SCA	Mg	–	–	5.0	1.4
SCS	Mg	1.9	0.76	–	–
AC	Mg	1.8	1.14	4.2	1.9

Nutrient concentrations in g kg^{-1} ($n = 3$; means only).

Effects of agroforestry on nutrient leaching

The determination of nutrient fluxes in soils is extremely difficult. The measurements of soil water suctions and nutrient contents in the soil solution are subject to large errors; the difficulties arise from soil heterogeneity, inadequacy of sampling of the mobile soil water by vacuum extraction and the inability to measure macropore fluxes with routine measurement designs. In this study, we used different methods to determine the nutrient fluxes in the soil in order to increase data precision and reliability. It is emphasised, however, that the results have to be regarded with the noted short-comings. The high variability of the measured fluxes can be seen from the standard errors (Tables 6 and 7). The high variability of the results from the resin core measurements were not caused by methodological short-comings of the resin cores themselves as they operated very well at the topsoil but may be caused by macropore fluxes and the installation procedure. Macropore fluxes, which are included in resin core measurements in contrast to the suction cups, may vary within short distances and may explain part of the observed variability. An installation not from the top but from the side in a soil pit, which could not be done in our experiment due to the irrigation, would diminish soil disturbance above the cores and increase the accuracy of the results. In this case, however, a good contact of soil and resin core is a difficulty which may not easily be overcome. Dependencies of the leaching rates on soil texture

Table 6. Nutrient fluxes from the topsoil (0–30 cm) into the subsoil (> 30 cm) in sole cropped *Acacia saligna* (SCA) and *Sorghum bicolor* (SCS) and in the alley cropping system (AC) at Kakuma, Northern Kenya, measured with three different methods using suction cups, resin cores and calculations with flood water input and soil solution nutrient contents.[a]

Method	Nutrient	SCA		SCS	AC	
		Tree row	Alley		Tree row	Alley
Suction cups	N	67ab ± 23	166a ± 87	11b ± 2	32b ± 22	74ab ± 50
Resin cores	N	45 ± 33	88 ± 25	27 ± 8	108 ± 44	169 ± 163
Calculation[a]	N	51 ± 17	65 ± 23	5 ± 2	18 ± 7	55 ± 9
Suction cups	K	90 ± 73	68 ± 41	73 ± 2	85 ± 5	155 ± 135
Suction cups	Ca	182 ± 128	285 ± 139	288 ± 35	155 ± 91	207 ± 94
Suction cups	Mg	69 ± 49	128 ± 83	83 ± 9	120 ± 59	91 ± 48

[a] Only available for N; calculated using the equation L = (I-PET – ΔSW) × NC; with L leaching, I amount of irrigation water, PET potential evapotranspiration, ΔSW soil water changes before vs after the flood, NC soil solution nutrient contents.

Nutrient fluxes in kg ha^{-1} 100 $days^{-1}$.

Values followed by the same letter are not significantly different at $P < 0.05$ (calculated from ANOVA; $n = 3$); only N fluxes were statistically compared; for the other nutrients the standard errors are indicated ($n = 2$).

Table 7. Nutrient leaching below 1.20 m depth in sole cropped *Acacia saligna* (SCA) and *Sorghum bicolor* (SCS) and in the alley cropping system (AC) at Kakuma, Northern Kenya.

Nutrient	SCA		SCS	AC	
	Tree row	Alley		Tree row	Alley
N	6 a ± 2	47 b ± 12	17 b ± 6	10 ab ± 14	8 a ± 2
K	106 ± 93	223 ± 182	14 ± 15	4 ± 1	0 ± 7
Ca	149 ± 99	162 ± 117	50 ± 49	95 ± 51	79 ± 35
Mg	59 ± 56	108 ± 91	2 ± 16	22 ± 9	16 ± 11

Nutrient leaching in kg ha^{-1} 100 $days^{-1}$.

Values followed by the same letter are not significantly different at $P < 0.05$ (calculated only for N from ANOVA; $n = 3$); means and standard errors.

have to be considered especially under unsaturated soil conditions (Arnold, 1996). Higher amounts of coarse soil pores in the undisturbed soil than the resin core can lead to lower fluxes through the core than the adjacent soil at high soil water contents, whereas at low soil water contents it can be opposite. Diffusion does not play a major role under the presented soil water conditions with either high soil water suction (Arnold, 1996) or high flow rates. The determination of nutrient fluxes using suction cups reflected the trend of the resin core measurements only within a given plot comparing tree and alley positions; a good correlation between the two methods could be achieved for the monocultures ($r^2 = 0.89$; $P < 0.05$; $n = 6$). A comparison of the nutrient fluxes determined with flux calculations or resin cores from the topsoil and calculations using the water input with the floods and the soil water nutrient contents showed the same trend (Table 6), considering that the calculations were made only for the flood period in April and did not include the whole cropping period. Diffusion and dispersion was not accounted for in the flux calculations, but was considered to be of minor importance. The soil water suction (Figure 2) and the water fluxes (Table 8) simulated with the WHNSIM model (Huwe and Totsche, 1995) coincided well with the calculated values (gradient method) even without calibrating the model or fitting the gradient method. The simulated soil water suction dynamics (Figure 2) differed from

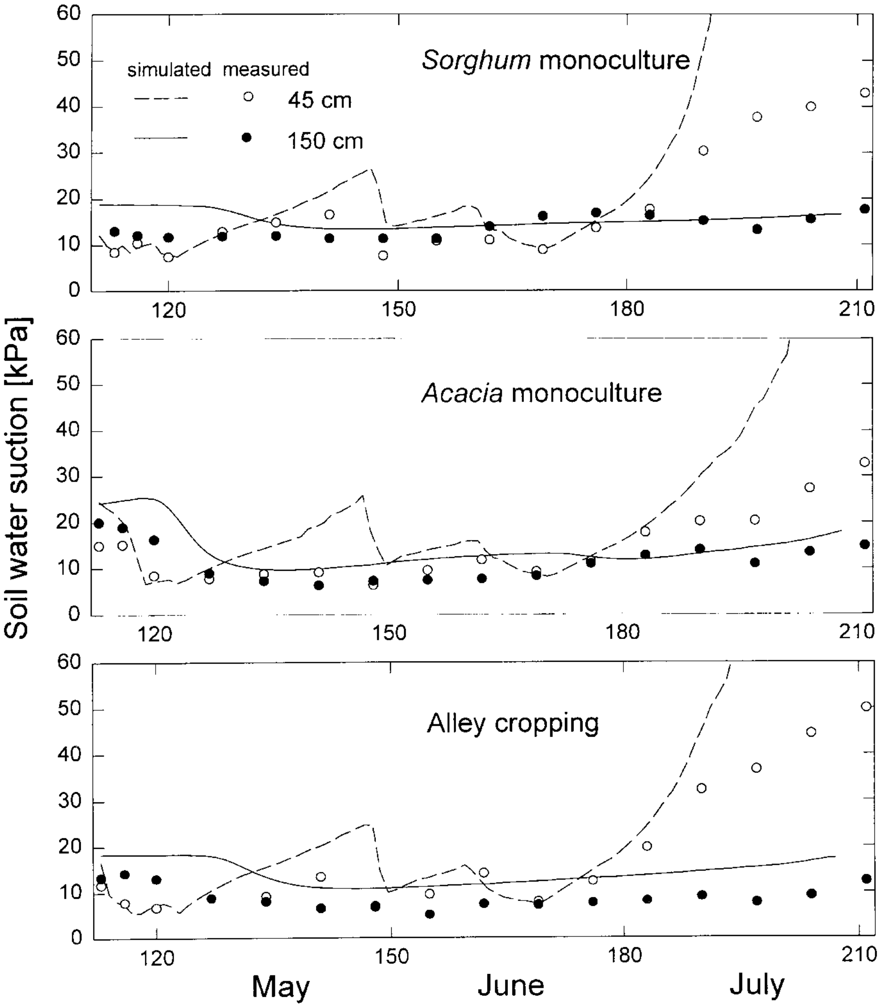

Figure 2. Measured (symbols) and simulated soil water suction using WHNSIM (lines) in sole and alley cropped *Sorghum bicolor* and *Acacia saligna* during the 100 day cropping season in 1996, in Kakuma, Northern Kenya.

Table 8. Water percolation below 1.2 m depth from sole cropped *Acacia saligna* (SCA) and *Sorghum bicolor* (SCS) and from the alley cropping system (AC) at Kakuma, Northern Kenya, calculated from soil water suction measurements (gradient method) and simulated with a model (WHNSIM) during the cropping period from April to July 1996.

Method	SCA		SCS	AC	
	Tree row	Alley		Tree row	Alley
Calculated	39 bc ± 16	58 c ± 7	59 c ± 10	21 a ± 11	31 ab ± 9
Simulated (only plot means)	36		41	31	

Water percolation in cm.
Values followed by the same letter are not significantly different at $P < 0.05$ (from ANOVA, $n = 3$; means and standard errors).

the experimentally determined suctions at the end of the cropping period after day 190. This can be explained by the inability of the tensiometers to operate at high suctions. At these values, however, the soil water movement is very low and does not affect our conclusions. These results encouraged us to discuss the determined nutrient fluxes.

The nutrient fluxes from the topsoil into the subsoil at 35 cm depth were always lower in the sole cropped sorghum than in the tree-based cropping systems, apart from the Ca values (Table 6). This can only be an effect of high nutrient uptake of the sorghum at 0–30 cm depth and export with the biomass. It is confirmed by the lower soil nutrient contents at the topsoil of the sorghum monoculture than the tree systems with the notable exception of Ca which was higher in the sorghum monoculture than in the other two systems (data not shown). For N, the trees were not only taking up fewer nutrients from the topsoil than the sole cropped sorghum, but they were able to increase the N content of the soil under the hedgerows as summarised by Lehmann and Zech (1997). A higher N-mineralisation due to improved soil physical conditions (Torquebiau and Kwesiga, 1996) or root exudates (Grayston et al., 1996) and a higher N input by root turnover (Lehmann and Zech, 1998) can largely be held responsible for this observation. Thus, lower leaching rates under the sorghum monoculture at 35 cm depth can be entirely explained by lower nutrient contents in soil and soil solution, not by lower water percolation (data not shown).

Nutrient leaching measured with the suction cups tended to be higher in the alley than in the tree row for both sole and alley cropped acacias (Table 6). This effect was a result of reduced water percolation, whereas the nutrient contents of the soil solution were equal in both positions (data not shown).

In contrast to 35 cm depth, N and K leaching below 120 cm depth was larger in the sole cropped than in the intercropped sorghum (Table 7), the latter resembling the leaching rates under the tree rows of both sole and alley cropped acacias. Thus, large amounts of N were leached beyond 35 cm depth in the tree systems, but captured by the tree underneath the rooting depth of the sorghum between 35 and 120 cm depth. In the sorghum monoculture, N fluxes were even higher at 120 than at 35 cm depth. Between the tree rows of the sole cropped trees, we found higher N leaching rates than in any other cropping system at both 35 and 120 cm depth. Thus, growing crops between tree rows reduced nutrient leaching and increased nutrient use efficiency compared to tree monocultures.

In humid Costa Rica, Seyfried and Rao (1991) also demonstrated that nutrient leaching losses were lower under multiple cropping systems including trees than under maize monoculture. Hartemink et al. (1996) concluded from soil nitrate measurements and water contents that young Sesbania sesban fallow was able to reduce N leaching compared to maize. For alley cropping with *Leucaena leucocephala* and *Cajanus cajan*, Kühne (1993) reported lower nitrate leaching than under monocropped maize or cassava.

The trees were effectively reducing N leaching by 53% underneath the sorghum in the agroforestry system compared to the sole cropped sorghum ($P < 0.05$). The tree root system may have acted as a ‘safety-net’ (Van Noordwijk et al., 1996) retrieving leached nutrients underneath the root system of the shallow rooted annual crop. The nutrient and water uptake can be related to the root length density (RLD) in the respective soil layer (see e.g. Wiesler and Horst (1994) for different maize cultivars) assuming equal fine root activities of the different plant species. Lehmann et al. (1998b) showed that the sorghum root system was largely restricted to the upper 0.3 m (RLD 3.5 cm cm^{-3}) with only 30% of its root length density below 0.3 m and 12% between 0.6 and 1.5 m depth. The acacia root system, however, was deeper with 62% of its root length density below 0.3 m. In the agroforestry combination, the tree root system was deeper than in both tree and crop monocultures and the total amount of roots in the alley cropping system exceeded the sum of the sole cropped trees and crops (RLD 6.6 cm cm^{-3} under the tree row at 0–0.3 m depth; Lehmann et al. (1998b)). This high subsoil root abundance resulted in low N leaching, which could be explained by low water fluxes (Table 8) and N contents in the soil solution (data not shown). The total amount of N leached was significantly correlated with live root abundance at sorghum flowering for a depth of 0.3–1.2 m ($r = 0.64$; $P < 0.01$) but not for a depth of 0–1.2 m ($r = 0.33$; $P > 0.05$). Not only the spatial distribution but also the temporal root development may have played an important role in reducing nutrient leaching. The acacias exhibited a high root abundance throughout the whole year without a visible reduction of the root production even during the dry season (Lehmann and Zech, 1998). Thus, an extensive and perennial subsoil root system reduced nutrient leaching.

The other elements K, Ca and Mg did not show these effects as clearly as N due to their higher soil contents which were not limiting plant growth in contrast to N at this site (Lehmann et al., 1998d). P fluxes could not be determined with the suction cups, because PO_4^{3-} adsorbs to the ceramic cups and cannot be measured in the extracted soil solution.

Relationship of nutrient fluxes

Nutrient input with rainfall was generally low compared to other nutrient fluxes, also in comparison to the nutrient input with the irrigation water (Table 2). The highest proportions (> 0.1) of nutrient input by rainfall to output by harvest were found for Ca, P and K, whereas N and Mg showed lower proportions. Nutrient input with rainfall does not play an important role for the nutrient budget at this site.

On the contrary, the runoff irrigation water formed an important part of nutrient input into the land use system. This was less pronounced for the relatively immobile nutrients P and K, but very important for Ca, Mg and N. The N input with the irrigation water was in the range of the N output with the sorghum harvest. The Ca input even exceeded the output of both leaching and biomass harvest. This result was probably caused by the specific situation of the experimental site and land use system using runoff irrigation, and cannot be extrapolated to other agroforestry systems. But it gives valuable information on the potential of fertility improvement in irrigated agriculture.

The nutrient output by leaching may not entirely capture the real output, because it cannot be excluded that the tree roots could recover nutrients below 1.2 m depth. However, at this stage of tree development, the acacias had most of their roots above 1.2 m depth (Lehmann et al., 1998b). For the tree based systems, the leaching rates in Table 9 are shown as means of the tree row and alley position assuming a linear relationship of leaching rates and distance to the hedgerow; this may be a valid assumption for the short distance of two meters between the sampling points.

Nutrient uptake was lower than leaching in the acacia monocultures (apart from N), but higher in the agroforestry system, the sole cropped sorghum being intermediate. This can be interpreted as a higher resource use efficiency of the agroforestry system compared to the monocultures, as a larger amount of nutrients is utilised for biomass production than lost by leaching. The nutrient uptake-to-leaching ratio is a measure of the nutrient use efficiency in the nutrient cycle and ranged from 0.4 to 2.8 and 0.7 to 5.6 for the sole cropped acacias and sorghum, respectively, but 1.6 to 52 for the agroforestry combination.

However, the extent of nutrient uptake did not exclusively control nutrient leaching in the investigated land use systems. A negative correlation between nutrient uptake and leaching could not be found ($P > 0.05$). Equally important were the dynamics of root development and the root distribution as outlined in a previous section.

The nutrient balance – impact of different mulching scenarios

The nutrient balance with all inputs and outputs is shown in Table 9 (balance A). Different scenarios were calculated, depending on whether the tree leaves (balance B), the sorghum straw (balance C) or both (balance D) were returned

Table 9. Nutrient balance during one cropping season of sole cropped *Acacia saligna* (SCA) and *Sorghum bicolor* (SCS) and of the alley cropping system (AC) at Kakuma, Northern Kenya, with different nutrient output scenarios: balance A with output of all above-ground biomass; balance B with return of acacia leaves and exporting only the branches; balance C with return of sorghum straw and harvesting only the grain; balance D with return of both tree leaves and sorghum straw and exporting only tree branches and sorghum grains yield.

Nutrient fluxes	N			P			K			Ca			Mg		
	SCA	SCS	AC	SCA	SCS	AC	SCA	SCS	AC	SCA	SCS	AC	SCA	SCS	AC
Input															
Rainfall + irrigation	30	30	30	4	4	4	49	49	49	397	397	397	43	43	43
Output															
Tree harvest (A, C)	72		53	8		5	33		28	81		64	18		13
Sorghum harvest (A, B)		30	34		6	9		70	83		27	29		5	7
Leaching (A, B, C, D)	27	17	9	nd	nd	nd	165	14	3	156	50	87	84	2	19
Balance A	**–69**	**–17**	**–66**	**–4**	**–2**	**–10**	**–149**	**–35**	**–64**	**+160**	**+320**	**+217**	**–59**	**+36**	**+4**
Tree harvest (returning the leaves; B, D)	15		11	4		3	19		15	22		20	4		4
Balance B (returning tree leaves)	**–12**	**–17**	**–24**	**0**	**–2**	**–8**	**–135**	**–35**	**–51**	**+219**	**+320**	**+261**	**–45**	**+36**	**+13**
Sorghum harvest (returning the straw; C, D)		9	10		2	2		2	3		0.2	0.2		1	1
Balance C (returning sorghum straw)	**–69**	**+4**	**–42**	**–4**	**+2**	**–3**	**–149**	**+33**	**+16**	**+166**	**+347**	**+246**	**–59**	**+40**	**+10**
Balance D (returning tree leaves and sorghum straw)	**–12**	**+4**	**+0**	**0**	**+2**	**–1**	**–135**	**+33**	**+29**	**+219**	**+347**	**+290**	**–45**	**+40**	**+19**

Nutrient balance in kg ha^{-1} 100 days^{-1}.

as mulch. The P cycle was not fully determined because P leaching could not be measured due to its sorption on the ceramic cups; it can be assumed, however, that P leaching was small due to fixation of PO_4^{3-} to iron oxides (Wild, 1988), but the results of the calculation of the P balance should still be viewed with caution. A relevant gaseous loss of N was unlikely: at the same site, N_2O evolution was found to be below 0.1 kg ha^{-1} in one cropping period and NH_3 volatilisation could not be detected (Wulf et al., 1999).

If all above-ground biomass was exported, the nutrient balance was negative for N, P and K, and positive for Ca and Mg (balance A). With a nutrient return of mulched acacia leaf or sorghum straw, the nutrient budget could be improved, but largely depending on the cropping system.

The sorghum monoculture exhibited the lowest nutrient losses and highest gains, when the whole above-ground biomass was harvested (balance A). Apart from P, the sole cropped acacias lost more nutrients than the other two cropping systems. With a nutrient return by mulching the acacia leaves, the tree-based systems still showed negative nutrient balances for N, P and K. Positive balances could be achieved for K, if the sorghum straw was not exported in both the sorghum monoculture and the tree-crop combination, for P in the sorghum monoculture only (balance C). It should be noted that the nutrient balance was better in the sorghum monoculture than the agroforestry system if the straw was returned. When both the sorghum straw and the acacia leaves were returned as mulch in the agroforestry system, the N balance was still negative (balance D). Only when the biological N_2 fixation was considered in the calculation with 15 kg N ha^{-1} 100 $days^{-1}$ (Lehmann, unpubl. data) could the N balance become positive in the agroforestry system, but not in the tree monoculture (26 kg N ha^{-1} 100 $days^{-1}$). Salazar et al. (1993) also reported positive balances for N, K and Ca but in contrast to our work negative ones for Mg in an alley cropping system with *Inga edulis, Erythrina* or *Leucaena leucocephala* in Peru. At our site, however, it is not clear whether the additional nutrients from mulching leaves and straw can be completely retrieved by the trees as presumed in the nutrient balance, because mulching increases potentially leachable nutrients (Hagedorn et al., 1997).

Despite encouraging results of a positive nutrient balance in the agroforestry system when mulching both tree leaves and sorghum straw, the short-term effect on the amount of plant available nutrients may not be satisfactory, as the soil nutrient content is very low. An important question for the nutrient cycle is how much of the recycled nutrients are released from above- and below-ground biomass and if they can be used by the intercropped annuals. The nutrient use efficiency of leaf mulch applications seems to be very low according to Palm (1995). Haggar et al. (1993) hypothesised that the below-ground input of N from *Gliricidia sepium* contributed more to the N nutrition of alley cropped maize than the leaf mulch. The nutrient release from roots is generally lower than from leaves as seen from three tree legumes in West Africa (Lehmann et al., 1995). Short-term increases of N in particle size fractions after root amendments could not be found in contrast to an incubation with leaves (Lehmann et al., 1998c). A rapid and large improvement of nutrient stocks available for the crop may not be feasible by nutrient recycling through alley cropping with the amounts of recycled nutrients shown in this study. Maintaining high yields on a long-term is only feasible when the nutrient export with the harvest can be replenished by external inputs. A higher nutrient use efficiency will then be ensured by integrating trees into cropland.

Conclusions

Trees were shown to decrease nutrient leaching under runoff irrigation. Furthermore, the incorporation of trees into cropland was able to diminish nutrient leaching compared to monocropped sorghum. The agroforestry system exhibited a higher nutrient use efficiency as shown by the relationship between nutrient uptake and leaching. A relation between spatial and temporal rooting patterns and nutrient leaching could be identified, but not between leaching and nutrient uptake alone. The spatial and temporal nutrient uptake patterns of trees seem to be the key factor for an effective nutrient recycling. The concept of nutrient retrieval and reduction of nutrient leaching with trees seems to be feasible. For a positive balance of N, P and K, a nutrient return through mulching of at least part of the harvested biomass is necessary. Whether additional mobile nutrients can be effectively recycled by the trees is unclear and should be investigated in the future. Biological N_2 fixation could relevantly improve the N budget, but seems not to be sufficient to increase the production at our site; improving this N source is an important issue in agroforestry. On nutrient poor soils, initial fertiliser applications may not be avoided for specific nutrients, as for N in this study. It may be questioned whether this agroforestry system may cope with higher nutrient inputs from fertilisation and improved N_2 fixation and still guarantee a lower leaching rate and an efficient recycling of larger stocks of nutrients. Further studies on this aspect are needed.

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