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Nitrogen uptake of sorghum (*Sorghum bicolor* L.) from tree mulch and mineral fertilizer under high leaching conditions estimated by nitrogen-15 enrichment

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Abstract The effects of applying either inorganic fertilizer or leaf mulch of *Acacia saligna* (Labill.) H.L. Wend. on yields of *Sorghum bicolor* (L.) were compared with an unfertilized control under the high leaching conditions of runoff irrigation in a dry tropical environment. The N use efficiency and transfer from ^{15}N-labelled $(NH_4)_2SO_4$ or acacia leaves to the sorghum differed in quantity and quality. Only 6% of the applied mulch N was retrieved in the crop, in contrast to 21% of the fertilizer N. The proportions of N in the crop derived from the fertilizers were small, amounting to 7% and 28%, respectively, in the mineral fertilizer and mulch treatments. However, the application of inorganic fertilizer and mulch significantly increased crop grain yield ($P<0.05$ and $P<0.1$, respectively), biomass production and foliar N contents ($P<0.05$). The inorganic fertilizer improved crop yields to a larger extent than mulching. At the same time, more N was lost by applying $(NH_4)_2$ SO_4 than leaf mulch: only 37% of the N of applied $(NH_4)_2$ SO_4 was found in the crop and the soil (0–0.3 m), but 99% of the mulched N. High NO_3^- contents in the topsoil of the inorganic fertilized sorghum treatments indicated the risk of N leaching. However, more important may have been gaseous N losses of surface-applied NH_4^+. From a nutrient conservation point of view, mulches should be given preferance to inorganic fertilizers under high soil pH and leaching conditions, but larger improvements of crop yields could be achieved with mineral fertilizers.

Key words Agroforestry · Mulch · Nitrogen fertilizer · Runoff irrigation · *Sorghum bicolor*

Introduction

Improving the nutrient management of soils is important in subsistence farming in the tropics as they are very often depleted of nutrients, especially in sub-saharan Africa (Sanchez et al. 1997). By using locally available organic fertilizers, nutrient deficiencies of crops can be remedied when farmers are not able to afford commercial fertilizers. In agroforestry systems, mulching with tree prunings is expected to return recycled nutrients from the subsoil or nutrients which were leached beyond the root zone of the crop (Young 1989). The efficiency of this nutrient return through mulching is low, as seen from several studies undertaken throughout the tropics (see Palm 1995), and inorganic fertilizer applications may be unavoidable in many situations (Buresh and Tian 1998). However, there may be an advantage of mulching over inorganic fertilizers in addition to the lower costs incurred. When water fluxes into the subsoil are extremely high as often observed in the humid tropics (e.g. Klinge 1998) or under flood irrigation (Lehmann et al. 1999), nutrient leaching may pose a problem with respect to easily available and mobile nutrients, such as those supplied by inorganic N fertilizers. Also gaseous losses by denitrification (Tiedje 1988) or NH_3 volatilization (Kumar et al. 1994) may be high with elevated soil water saturation and inorganic N contents. A source of slowly released nutrients like leaf mulch may be an alternative when the release rates can be controlled by the quality of the mulch material (e.g. Lehmann et al. 1995). But even with leaf mulch, nutrient availability and leaching from the mulch highly depend on the rainfall regime and hence water percolation (Hagedorn et al. 1997).

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The possibility of reducing nutrient losses and increasing nutrient-use efficiency through mulching may be of great importance when designing sustainable land-use systems.

In this study, we tested whether N can be more effectively supplied with mulch than with inorganic fertilizer under the high leaching conditions of runoff irrigation. We studied the effects of leaf mulch of *Acacia saligna* (Labill.) H.L. Wend and of $(NH_4)_2\ SO_4$ on crop yields of *Sorghum bicolor* (L.), nutrient uptake and soil mineral N contents during one cropping season.

Materials and methods

The present study was carried out on a calcareous fluvisol (FAO 1990) in the dry tropical savanna of northern Kenya from April to August 1996. The soils were sandy to clayey loams with high pH (8.5), low organic C (5.3 g kg^{-1}) and N contents (0.42 g kg^{-1}). Mean annual precipitation was 318 mm (calculated over 14 years; W.I. Powell, and Turkana Drought Control Unit, unpublished data), 330 mm in 1996 and 166 mm during the cropping season from April to August 1996. The experiments were conducted in a runoff irrigation system as described by Lehmann et al. (1998a), and the layout is only briefly outlined here. Runoff water from a nearby mountain range was guided into the irrigation system, which could be filled during a series of floods in April 1996 with about 860 mm. The water infiltrated within approximately 8–10 days.

Before the first flood in March 1996, either mineral fertilizer or mulch was applied to microplots (2 × 2 m) and the results compared to those of a control without added nutrients in three replicates using a randomized complete block design. The chemical fertilizer was applied as $(NH_4)_2SO_4$ with 0.96 atom % excess ^{15}N at a rate of 100 kg N ha^{-1}. Leaf mulch of *A. saligna*, which had been labelled with ^{15}N prior to the experiment, was applied with 0.078 atom % excess ^{15}N at a rate of 94 kg N ha^{-1} (Table 1).

In May 1996, *S. bicolor* was sown in rows 0.5 m apart with 0.25 m distances between plants in the row. Two weeks after emergence, the stands were thinned to 1 plant $stand^{-1}$. The biomass production and grain yield was measured at harvest 90 days after planting. The central eight stands (leaving 0.75 m and at least one sorghum row to either side of the microplot) per treatment were weighed, separated into grain and stover, dried at 70 °C for 48 h and reweighed.

Soil samples were taken from 0–0.3 m depth at sorghum flowering in July 1996. Four samples were taken, combined and a subsample was air-dried. Plant and soil samples were finely ground and N isotopes were analysed using an Elemental analyser (Carlo Erba NA 1500) for Dumas combustion connected to an isotope ratio mass spectrometer (Finnigan Mat delta E) via a split interface. S was measured with an automatic CNS analyser (Elementar). For the determination of foliar P and Zn contents, 200 mg dry leaves were digested in 2 ml concentrated HNO_3 at 170 °C for 8 h, and diluted to 20 ml with deionised water. Zn was analysed with an atomic absorption spectrometer (Varian), and P was measured colorimetrically according to the molybdenum blue method (Olsen and Sommers 1982). Polyphenols in acacia leaves were determined colorimetrically after King and Heath (1967). Lignin was measured using the acid-detergent fiber method of Van Soest and Wine (1968).

Mineral soil N was measured at 0–0.15, 0.15–0.3, 0.3–0.6 and 0.6–0.9 m depths in a combined sample from four subsamples, before the flood in April (only control), after the flood had infiltrated in May and at sorghum flowering in July. 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 proportion of crop N derived from inorganic and organic fertilizers (%Ndff) or soil (%Ndfs) was calculated as follows in Eqs. 1 and 2:

$$\%\mathrm{Ndff} = \frac{\text{atom \% }^{15}\mathrm{N\ excess}_{\mathrm{sorghum}}}{\text{atom \% }^{15}\mathrm{N\ excess}_{\mathrm{applied}}} \times 100 \qquad (1)$$

$$\%\mathrm{Ndfs} = \left(1 - \frac{\text{atom \% }^{15}\mathrm{N\ excess}_{\mathrm{sorghum}}}{\text{atom \% }^{15}\mathrm{N\ excess}_{\mathrm{applied}}}\right) \times 100 \qquad (2)$$

The fertilizer use efficiency (%FUE) and the proportion of fertilized N in the soil (%Nis) were computed according to Eqs. 3 and 4:

$$\%\mathrm{FUE} = \frac{\text{atom \% }^{15}\mathrm{N\ excess}_{\mathrm{sorghum}} \times \mathrm{N}_{\mathrm{sorghum}}}{\text{atom \% }^{15}\mathrm{N\ excess}_{\mathrm{applied}} \times \mathrm{N}_{\mathrm{applied}}} \times 100 \qquad (3)$$

$$\%\mathrm{Nis} = \frac{\text{atom \% }^{15}\mathrm{N\ excess}_{\mathrm{soil}} \times \mathrm{N}_{\mathrm{soil}}}{\text{atom \% }^{15}\mathrm{N\ excess}_{\mathrm{applied}} \times \mathrm{N}_{\mathrm{applied}}} \times 100 \qquad (4)$$

Statistical analyses were performed using ANOVA. If effects were significant, means were compared with the least significant difference method at $P < 0.05$ (Little and Hills 1978). The soil mineral N contents were compared for each depth among treatments.

Results

Grain yield, biomass production and thousand grain weight were higher when sorghum was fertilized with $(NH_4)_2\ SO_4$ than with acacia leaf mulch or without additions (Table 2). Fertilized sorghum had a significantly higher ($P < 0.05$) grain yield than the other two systems, but biomass production was not significantly higher than when leaf mulch was applied. Biomass production was significantly ($P < 0.05$) enhanced by both the mineral fertilizer and the mulch compared to the control. At the same time, the foliar N contents of the sorghum were higher after both the application of mineral fertilizer and mulch, but not the P, S or Zn contents (Table 3).

The total ^{15}N uptake and the %FUE were significantly higher when mineral fertilizer was added (21%) than when N was applied as mulch (6%, $P < 0.05$; Table 4). The mineral fertilizer led to a higher %Ndff (28%) than mulch (7%). %Nis, however, was higher after mulching (93%) than after fertilization with inor-

Table 1 Amounts of nutrients applied in mineral fertilizer $[(NH_4)_2\ SO_4]$ and leaf mulch of *Acacia saligna* (5 Mg ha^{-1}) and foliar nutrient contents of *A. saligna* (means, $n = 3$). *PP* Polyphenols

Applied nutrients	N (kg ha^{-1})	P (kg ha^{-1})	S (kg ha^{-1})	Zn (kg ha^{-1})	Foliar contents	N (g kg^{-1})	P (g kg^{-1})	S (g kg^{-1})	Zn (g kg^{-1})	PP (g kg^{-1})	PP/N	Lignin (g kg^{-1})	Lignin/N	(PP + lignin)/N
Fertilizer	100	0	114	0										
Mulch	94	6	88	0.07	Mulch	19.5	1.2	17.6	0.014	41	2.1	112	5.7	7.9

Table 2 Grain yield, biomass production and thousand grain weight (*TGW*) of *S. bicolor* with applications of mineral fertilizer, and leaf mulch of *A. saligna*, and in the control, in a runoff irrigation system. Values within one column followed by the *same letter* are not significantly different at $P<0.05$ ($n=3$). Data are means ±SE

Treatment	Grain yield (Mg ha^{-1})	Biomass production (Mg ha^{-1})	TGW
Fertilizer	2.05±0.74 a	9.80±1.54 a	19.4±3.1 a
Mulch	1.03±0.34 b	8.68±1.11 a	17.9±3.6 a
Control	0.45±0.10 b	5.14±0.68 b	15.0±3.3 a

Table 3 Foliar nutrient contents of *S. bicolor* following the application of mineral fertilizer, leaf mulch of *A. saligna*, and in the control, in a runoff irrigation system. Values within one column followed by the *same letter* are not significantly different at $P<0.05$ ($n=3$). Data are means ±SE

Treatment	N (g kg^{-1})	P (g kg^{-1})	S (g kg^{-1})	Zn (mg kg^{-1})
Fertilizer	33.4±1.4 a	4.13±0.3 a	1.50±0.14 a	24.1±4.9 a
Mulch	31.7±2.9 a	3.97±0.5 a	1.50±0.06 a	17.2±4.1 a
Control	22.3±0.7 b	3.65±0.6 a	1.28±0.13 a	22.4±8.5 a

Table 4 Applied amounts of ^{15}N with mineral fertilizer or with leaf mulch of *A. saligna*, ^{15}N and N uptake of *S. bicolor*, total uptake of applied N (*Ndff*) and soil N (*Ndfs*), the proportion of sorghum N derived from applied N (%*Ndff*) or from soil (%*Ndfs*), the fertilizer use efficiency (%*FUE*), the proportion of soil N derived from applied N (%*Nis*) and the proportion of N recovered (%*Recovery*=%FUE+%Nis). Values within one row followed by the *same letter* are not significantly different at $P<0.05$ ($n=3$). Data are means ±SE

		Fertilizer	Mulch	Control
^{15}N applied	(g ha^{-1})	964	74	0
^{15}N uptake	(g ha^{-1})	202±62 a	5±2 b	–
N uptake	(kg ha^{-1})	110±33 a	86±24 a	41±15 b
Ndff	(kg ha^{-1})	31±7 a	6±2 b	0
Ndfs	(kg ha^{-1})	79±19 a	80±14 a	41±15 b
%Ndff	(% of crop N)	28±6 a	7±4 b	–
%Ndfs	(% of crop N)	72±6 a	93±4 b	100
%FUE	(% of applied N)	21±7 a	6±3 b	–
%Nis	(% of applied N)	16±2 a	93±9 b	–
%Recovery^{1}	(% of applied N)	37±5 a	99±12 b	–

ganic N (16%). The total ^{15}N recovery in plant and soil from mulching reached 99%, whereas the recovery from fertilization with inorganic N was only 37% (Table 4).

After flooding and before crop emergence, larger amounts of mineral N were found in the topsoil with mineral fertilizer than with mulch application or in the control (Fig. 1). At sorghum flowering, topsoil N contents were still significantly higher in mineral fertilizer amended soils than in the other two treatments. In the subsoil, however, no significant differences were found, and fertilized soils showed only slightly higher N contents below 0.6 m than mulched soils or the control.

Discussion

Effects of fertilization and mulching on crop production

Without nutrient additions, biomass production and especially grain yield were very low compared to other studies using runoff irrigation, but with mineral fertilization the grain yield was similar to results from Niger (2.8 Mg ha^{-1}; Klemm 1989) and Mali (1.9 Mg ha^{-1}; Tabor 1995). Thus, the soils at the experimental site were poor in available N, which could be compensated for by the mineral fertilizer and mulch applications. Irrigation alone was not able to elevate crop production to an acceptable level, as available soil water was considered to be sufficient during the cropping season studied (Lehmann et al. 1998b).

Effects of fertilization and mulching on crop nutrition

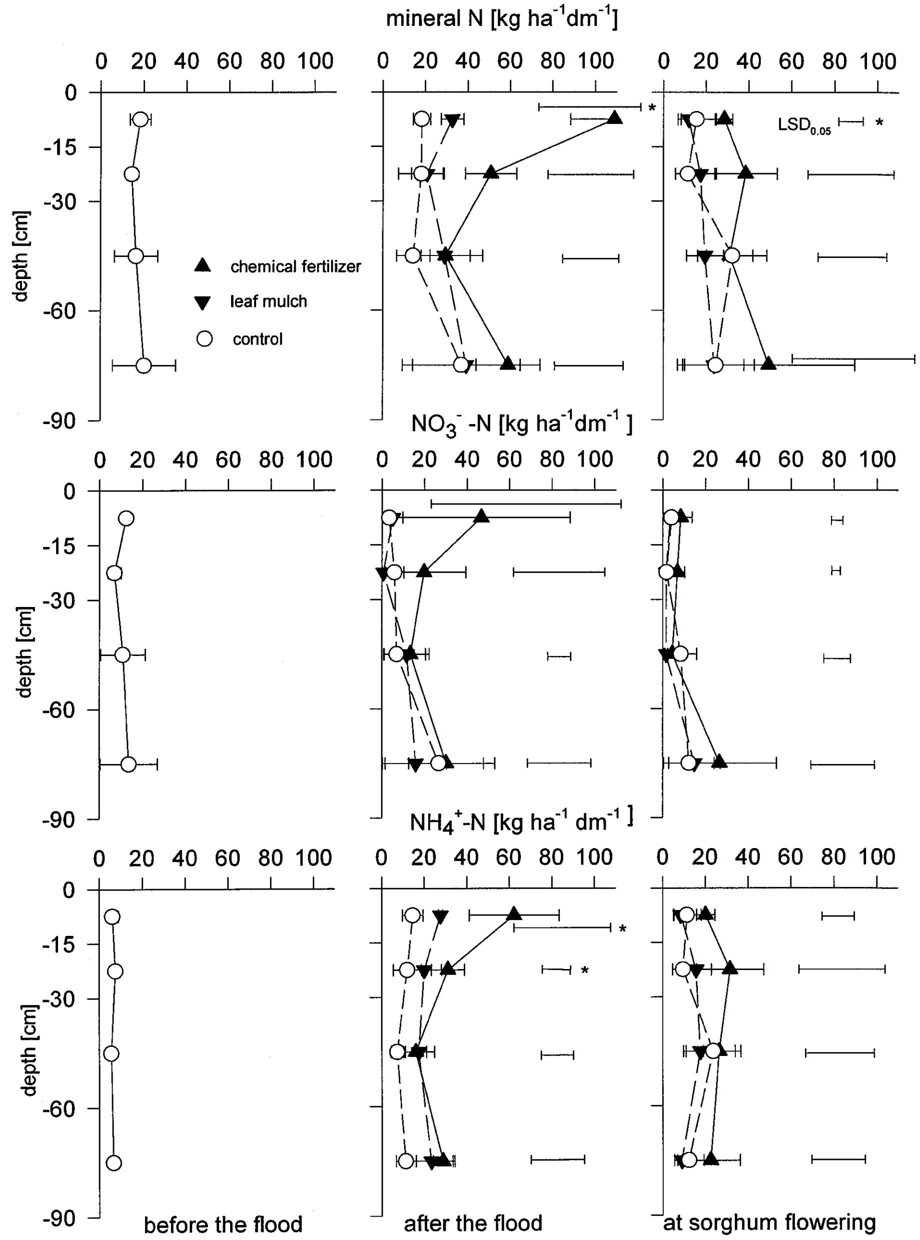
The N applications led to an increase in the foliar N contents of the sorghum in spite of its higher biomass production. Higher P contents were not found after mulching, but P benefits were not expected with the small amounts of applied P, and are unlikely to be of importance in tropical agroforestry systems (Buresh and Tian 1998). P seemed not to be limiting plant growth in the soils of the experimental site, as crop production increased at similar foliar P contents without relevant P applications. This agreed with earlier results from this site (Von Willert 1997).

The amounts of S applied with the leaf mulch were considerable and in the range of the amounts of N applied, because the acacia had unusually high S concentrations, exceeding values normally reported for acacias (Drechsel and Zech 1991). The high S uptake may be explained by the high SO_4^{2-} contents, especially in the subsoil (Lehmann et al. 1998a). These high soil S contents were also the reason for the lack of response to the S applications. On the other hand, the low Zn applications did not improve crop Zn nutrition, even though Zn was earlier identified as the most important nutrient limiting plant production, apart from N, at the experimental site (Von Willert 1997). It can be concluded that the effects of adding nutrients to the soil by mineral fertilizer and mulch were solely due to the applied N.

Fate of applied N

The low uptake of the mulched N may be explained by the poor synchronization of N release from the leaves

Fig. 1 Mineral N, NO_3^--N and NH_4^+-N (kg N ha^{-1} dm^{-1}) following applications of mineral (*chemical*) fertilizer, and leaf mulch of *Acacia saligna*, and in the control, at 0–0.15, 0.15–0.3, 0.3–0.6 and 0.6–0.9 m depths before the flood, after the flood and at sorghum flowering in a runoff irrigation system. The data are means, and the *bars* on data points indicate SEs. The *vertical bars* above each data point indicate least significant differences ($n = 3$, $P < 0.05$). The *asterices* indicate significant effects of N application (ANOVA, $P < 0.05$)



and N uptake of the sorghum (Palm 1995). Nutrient release was insufficient to meet plant requirements and most of the N was retained in the soil. The large portion of mulch N in the soil may have been held by undecomposed leaf material. The high polyphenol contents, polyphenol-N and polyphenol plus lignin-N ratio of the acacia leaves (Table 1) indicated low rates of decomposition and nutrient release, as shown by Lehmann et al. (1995) for *Gliricidia sepium*, *Senna siamea* and *Calliandra calothyrsus* in central Togo. Several authors have reported low recoveries of applied nutrients, e.g. by maize from mulch of *Erythrina poeppigiana* and *Gliricidia sepium* in humid Costa Rica (12% and 9%, respectively; Haggar et al. 1993), mulch of *Leucaena leucocephala* in semiarid Australia (10%; Xu et al. 1993), and from *Leucaena leucocephala* and *Dactyladenia barteri* muches in subhumid Nigeria (9% and 5%, respectively; Vanlauwe et al. 1998a). A large portion of the mulched N may have been incorporated into soil organic matter fractions, as shown for several tree legumes in Togo (Lehmann et al. 1998c) or into the microbial biomass. Shortly after mulching, Vanlauwe et al. (1998b) found applied N from leucaena or dactyladenia mulch in coarse particle sizes, while towards the end of their experiment most of the recovered N was found in smaller separates. Haggar et al. (1993) suggested that this N fraction is only successively available.

The markedly positive effect of mulching on crop yield and N nutrition was surprising considering the low recovery and the low proportion of mulched N that contributed to sorghum nutrition. Apart from the known beneficial effects of adding N, mulching may also have reduced evaporation from the soil surface (Wallace 1996). However, the %Ndff was not high enough to explain the pronounced yield increases. The significant improvement of sorghum N nutrition in spite of low recoveries suggested that even low N benefits to the sorghum may have stimulated crop productivity in the soils of the experimental site which were poor in N.

A large proportion amounting to 63%, of the applied N from the mineral fertilizer disappeared from the investigated soil-plant system up to 0.3 m depth. Nutrients below 0.3 m had to be considered as unavailable to sorghum, as more than 80% of its root length density was in the upper 0.3 m of soil (Lehmann et al. 1998b). It cannot be excluded that fertilized N may have been leached beyond 0.3 m depth. The leached N may have passed 0.9 m depth by the time of sorghum flowering, and thus would not have been measured in the soil extracts (Fig. 1), although direct evidence for this cannot be presented. The high NO_3^- contents in the soil after fertilizing with $(NH_4)_2\ SO_4$ in contrast to mulching, where no differences to the control could be seen, indicated the risk of N leaching when applying mineral N fertilizer. Using mulch instead of mineral fertilizer could reduce these risks. Denitrification was shown to be minimal at this site (Wulf et al. 1999) and also NH_3 volatilization could not be detected in unfertilized plots (S. Wulf, unpublished data). With $(NH_4)_2\ SO_4$ applications, however, large amounts of mobile inorganic N were present at the soil surface in contrast to leaf applications. Large quantities of NH_4^+ in the topsoil may have caused considerable volatilization of NH_3, especially in the studied soils with high pH (Kumar et al. 1994). An application of *Sesbania aculeata* leaves, however, was shown to decrease NH_3 losses in rice systems (Kumar et al. 1994).

The different amounts of mineral N in the topsoil reflected well the biomass production and grain yield between treatments. With the inorganic fertilizer, however, the biomass production and grain yield increased less than expected from the increase in soil mineral N. When deducting the respective values of the control, the biomass production and grain yield of the mulch-amended sorghum were 76% and 36% of the fertilized sorghum, respectively. The total mineral N, NO_3^- and NH_4^+ contents of the mulched sorghum plots amounted to only 16%, 4% and 27% of the fertilized sorghum plots, respectively, at crop emergence. This may indicate that the N which was mineralized and released from the leaf mulch was more efficiently taken up by the crop than the mineral fertilizer N. Thus, nutrient preservation was better when using mulch than inorganic fertilizer. On the other hand, the large amounts of mineral soil N present after mineral fertilizer applications led to higher yields than after mulch applications. These results may not hold for all mulch materials. Hagedorn et al. (1997) found a strong positive relationship between rainfall and nutrient leaching from prunings. This influence of rainfall on nutrient leaching is not only controlled by the amount of percolating water but also by the effect of soil water on decomposition and nutrient release, depending on substrate quality (Seneviratne et al. 1998).

The conclusions from the presented results are ambivalent: on the one hand the N transfer from applied N sources, as well as crop yields and N nutrition, were higher with mineral fertilizer than with mulch. On the other hand, the losses of applied N were also higher in the former treatment. Despite the low N use efficiency of mineral fertilizer N and mulch N, the yield increases were satisfactory. A large portion of the applied mineral fertilizer N was lost from the main root zone of the crop whereas the majority of the mulched N was retained in the topsoil but was not available to the crop during the experimental period. Neither result is desirable for efficient nutrient cycling. More rapid decomposition and nutrient release would probably increase the rate of nutrient transfer from mulch to crop, but inevitably also increase the risk of gaseous losses or leaching. Nutrient preservation, however, within undecomposed leaf mulch or soil organic matter seems more favourable than nutrient loss. For an immediate and large improvement of crop yields, mineral fertilizer was superior to mulching in our study. In the long-term, mulching with low quality organic material led to better nutrient conservation with acceptable increases in crop production.

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