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Carbon and nitrogen mineralization in cultivated and natural savanna soils of Northern Tanzania

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Abstract In the present study, soil C and N mineralization and nutrient availability were compared: (1) in savanna woodland soils under natural acacia vegetation; (2) at termite sites; (3) in degraded woodland where acacias were selective logged for charcoal production; (4) in agricultural fields which were cultivated for 3 and 15 years, and (5) in traditional homestead fields which regularly received animal manure for about 10 years. Soil C and N mineralization dynamics were measured by incubation under controlled conditions for 120 days. Labile and stable soil C and N pools were determined by fitting double-exponential models to the measured cumulative mineralization. Selective removal of acacias from the woodland and short-term cultivation for 3 years did not affect available nutrient contents but significantly decreased total C and N contents and mineralization ($P<0.05$). Mainly the labile soil N pool decreased during the first 3 years of continuous cropping, whereas after 15 years the stable N pool, total S, available Ca and Zn contents were also depleted. Even after 15 years, however, the decrease of nutrient availability (apart from N) was less severe than that of soil organic matter stability. Additionally, not only the labile but also the more stable soil C and N pools decreased and controlled total mineralization as determined by the incubation experiments. Homestead fields with manure additions were shown to have elevated soil nutrient and organic matter contents. However, the manure should be mixed into the soil to improve organic matter stabilization. Soil regeneration in degraded savannas and recently cultivated fields might rapidly be achieved, whereas the 15-years-cultivated fields may require longer fallows to restore soil fertility.

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Introduction

The savanna woodland of Northern Tanzania is increasingly deforested for charcoal (Kahurananga 1995) and agricultural production. Agricultural soils usually have lower aggregate stability (Kandeler and Murer 1993) and soil N availability (Mengel 1996) than soils under natural vegetation. However, the impact of land-use conversion on soil fertility in the semiarid tropics, such as on the chromic Luvisols of Northern Tanzania, and its temporal dynamics are largely unknown. Whereas some information exists about total organic C and N contents of African savanna soils (Birch and Friend 1956; Jones 1973), little is known about the stability of the soil organic matter (SOM). This knowledge is necessary, however, to evaluate the long-term effect of land-use conversion in tropical savannas.

High losses of SOM can only be replenished in the short-term by application of organic matter such as manure. In the traditional homesteads of the indigenous Masai population in Northern Tanzania, large amounts of animal manure are usually accumulating. In a temperate climate, manure applications usually lead to increased soil C and N contents (Christensen 1988). The degree to which applications of animal manure are sufficient for replenishing soil fertility is not known for semiarid tropical agroecosystems such as in Northern Tanzania. Furthermore, the effects of manure additions on SOM stability under semiarid tropical conditions have not studied up to now.

Within the savanna ecosystem, termites impose an important change on the soil environment and can occupy a large portion of the land (Lee and Wood 1971). Knowledge about the impact of termites on soil fertility is not only important for understanding the ecology of tropical savannas, but also for evaluating the potential and constraints for agricultural production, since they are very abundant on farmers' fields in Northern Tanzania. Therefore, their impact has to be considered when evaluating soil productivity. In addition, no information is available about SOM stability as affected by termites in savanna soils. This contribution should help to fill this gap.

Soil fertility and nutrient availability are closely connected to the SOM content and its mineralization (Zech et al. 1997a). The extent of C mineralization determines soil nutrient release and therefore nutrient availability (Zaman et al. 1999). Since N is incorporated into soil microbial biomass to a higher extent than C, both C and N mineralization have to be determined to evaluate N availability and soil fertility (Nadelhoffer 1990; Gaiser et al. 1994). As agriculture has mostly been undertaken without fertilizer inputs in the Northern Tanzanian savanna, crop productivity relied on nutrient release from SOM.

Forest clearing and land-use changes have important consequences not only for nutrient availability but also for SOM stability. Using radioisotopes, Jenkinson (1971) distinguished five soil C pools differing in their turnover times. The assessment of such soil C pools was useful to evaluate soil changes in a wide variety of soils (Christensen 1996). This information cannot be obtained from measurements of bulk soil C contents. Different soil organic matter pools can also be determined from mathematical fitting of models to measured mineralization dynamics. Double-exponential models have been used frequently to distinguish labile and stable soil pools (Deans et al. 1986; Gregorich et al. 1989; Cabrera 1993). The separate determination of stable and labile organic matter pools is important for estimating the recalcitrance of SOM. This will allow us to study the extent of soil degradation after land-use changes and estimate the possibilities of replenishing soil fertility in low-input, tropical agriculture such as in Northern Tanzania.

The objectives of this study were to examine (1) soil fertility and organic matter stability of savanna soils under native acacia vegetation and at termite sites, (2) the impact of selective logging of acacias for charcoal production as well as continuous cropping for different time periods, and (3) the effects of manure in homestead fields on organic C and N mineralization in Northern Tanzania.

Materials and methods

Study site

The present study was carried out in the semiarid savanna region of Northern Tanzania between 1,200–1,400 m above sea level (a.s.l.). The vegetation types of the Northern Tanzanian savanna range from *Digitaria macroblephara/Panicum coloratum* grassland to *Acacia tortilis/Commiphora schimperi* woodland and *A. stuhlmannii/A. drepanolobium/A. mellifera/Pennisetum mezianum* bushland (Kahurananga 1979). Mean annual precipitation in the area was between 500–600 mm with a maximum between December and April and a mean annual temperature of 25°C. The soils are classified as Chromic Luvisols (FAO 1988) with a sandy-loam texture. The clay contents of the soils at the different sites were not significantly different (P>0.05) and ranged between 180 and 295 g kg^{-1} soil with a bulk density between 1.20 and 1.45 Mg m^{-3}. The soils have neutral to alkaline pH values, medium to low levels of organic C and N, moderately high cation exchange capacity and high base saturation (Table 1). More detailed

Table 1 Chemical characterization of the topsoils (0–0.1 m) in cultivated and natural savanna of Northern Tanzania. Values in one row followed by the same letter are not significantly different at P<0.05 (*Woodland Nativ*. soil from a native tropical woodland; *Woodland Degr*. soil from a degraded woodland; *Woodland Term*. soil from the base of termite mounds; *Cultiv. 3 yr.* soil from 3-years-cultivated fields; *Cultiv. 15 yr.* soil from 15-years-cultivated fields; *Manured* soil from homestead fields which received manure and were left bare fallow for 7 years; *CEC* cation excange capacity; C_{org} organic carbon; *BS* base saturation; n=5 for all soil types except Cultiv. 3 yr. and Manure where n=4)

		Woodland Nativ.	Woodland Degr.	Woodland Term.	Cultiv. 3 yr.	Cultiv. 15 yr.	Manured
pH	($CaCl_2$)	6.0 b	6.1 b	6.1 b	6.2 b	5.9 b	8.0 a
pH	(H_2O)	6.6 cd	6.9 bc	6.6 d	7.0 b	6.7 bd	9.1 a
C_{org}	(g kg^{-1})	21.3 a	13.1 bc	6.2 d	9.3 cd	7.6 d	16.9 ab
N	(g kg^{-1})	2.04 a	1.19 b	0.90 b	1.03 b	0.86 b	1.82 a
C-to-N		10.4 ab	11.0 a	6.9 d	9.1 c	8.8 c	9.2 bc
S	(g kg^{-1})	0.28 b	0.20 bc	0.20 bc	0.19 bc	0.17 c	0.52 a
CEC	(mmol$_c$ kg^{-1})	168 ab	157 bc	147 bc	141 bc	117 c	211 a
BS	(%)	85.0 b	75.8 b	87.1 b	87.4 b	77.5 b	173.0 a
K[a]	(g kg^{-1})	0.66 b	0.62 b	0.45 b	0.65 b	0.50 b	7.21 a
Ca[a]	(g kg^{-1})	1.76 ab	1.30 bc	1.39 bc	1.36 bc	0.93 c	2.55 a
Mg[a]	(g kg^{-1})	0.47	0.44	0.50	0.44	0.35	0.38
Na[a]	(mg kg^{-1})	5.1 c	9.2 bc	14.2 b	0.4 c	2.8 c	35.0 a
K[b]	(g kg^{-1})	0.79 b	0.62 b	0.48 b	0.63 b	0.56 b	5.35 a
Ca[b]	(g kg^{-1})	1.63 b	1.19 bc	1.58 b	1.09 bc	0.81 c	2.71 a
Mg[b]	(g kg^{-1})	0.41 ab	0.34 ab	0.48 a	0.32 b	0.30 b	0.44 ab
Mn[b]	(mg kg^{-1})	316 ab	312 ab	304 ab	368 a	317 ab	264 b
Cu[b]	(mg kg^{-1})	6.6 ab	5.1 bc	6.3 ab	7.3 a	7.0 ab	4.0 c
Zn[b]	(mg kg^{-1})	3.4 ab	2.9 abc	0.6 d	2.1 bcd	1.4 cd	4.3 a

[a] Bases exchangeable with ammonium acetate
[b] Extraction according to Mehlich (1984)

information about basic physical and chemical properties have been reported by Solomon et al. (2000a).

The following investigations were conducted in the acacia woodland, which was partly cleared for agricultural and charcoal production by the native population. Some fields, originally woodland under acacia vegetation (Woodland Natv.), had been manually cleared and cultivated for 3 years (Cultiv. 3 yr.) and for 15 years (Cultiv. 15 yr.). The size of the cultivated fields varied from 1 to 10 ha. The sites were adjacent to each other and the distance between replicates was larger than the distance between treatments ensuring that the soils resembled each other before land clearing. In addition, in traditionally managed homestead fields (0.25–0.5 ha) animal manure had accumulated for about 10 years. These sites had been abandoned for about 5 years. As these sites reflected traditional homesteads of the native Masai population, the applied amounts of manure were unknown but it was clear from the huge organic horizons (between 0.1 and 0.2 m) that tremendous amounts of manure had accumulated (Manured). Additionally, soils at termite mounds (Woodland Term.; taken at the base of the mounds) and in a degraded woodland, where the acacia trees had been selectively deforested for charcoal production for 15 years (Woodland degr.), were investigated. The homestead fields had not yet been cultivated at the time of our study and were burned. The cultivated fields were not fertilized and beans (*Phaseolus vulgaris*) and maize (*Zea mays*) were grown. The termite mounds were inhabited by *Macrothermes* sp. and were a representative average of the termite mounds in the area rather than one species. It could not be determined whether the termites were humus or litter consumers.

Soil samples each comprised ten subsamples of an area of about 0.25 ha from the upper 0–0.1 m in four (Cultiv. 3 yr. and Manure sites) or five (all other sites) replicates taken in March 1997, using a completely randomized design. The samples were air-dried and sieved (<2 mm) prior to chemical analysis and incubation.

Soil chemical analyses

C, N and S contents of the ground soils were analyzed by dry combustion with a C/N/H/S analyzer (Elementar, Vario EL; Hanaus, Germany). The pH was determined in water and 0.01 M $CaCl_2$ with a soil:solution ratio of 1:2.5 (w:v). The cation exchange capacity was measured after ammonium acetate extraction (Soil Survey Staff 1997) and the cations were analyzed using an atomic absorption spectrometer (AAS Varian, SpectrAA 400). Plant available nutrients (K, Ca, Mg, Mn, Zn, Cu) were determined in a Mehlich 3 extract (Mehlich 1984) by atomic absorption spectrometry.

Carbon mineralization

Carbon mineralization was determined after Isermeyer (1952) in closed chambers and under controlled conditions. Dry soil (10 g) was wetted to field capacity and incubated in 1-L jars at 25±1°C for 120 days. The moisture content was kept constant by weighing at each sampling date. The analyses of each field replicate were done in three parallel incubations. The evolved CO_2-C was trapped in 0.05 N NaOH and titrated with 0.05 N HCl against a phenolphthalein indicator after precipitation with 0.5 N $BaCl_2$. It was measured daily during the 1st week and every 3–4 days in the following 2 weeks. The next five measurements were done at weekly intervals, then 3 times at 2-week intervals, and after another 3 weeks, at the end of the incubation period. At each sampling date, the water content was controlled and the containers were randomly distributed in the incubator.

Nitrogen mineralization

For the determination of aerobic N mineralization (changed after Stanford and Smith 1972), dry soil (15 g) was mixed with 15 g quartz sand and put in a microlysimeter, which was open at the lower end and attached to a vacuum pump. This ensured that the samples were optimally aerated and no denitrification occurred (Allison et al. 1960). Above and below the soil sample a glass fiber filter (Whitman GF/C) was placed to reduce soil losses and mixture during percolation, and to decrease evaporation. Additionally, the microlysimeters were covered with Parafilm to keep the moisture content at field capacity, which was checked weekly or at each sampling date and corrected if necessary. The incubations were done at 35±1°C for 120 days in three parallel incubations per field replicate. The temperatures for both mineralization experiments were chosen according to the temperature optimum for microbial activity in order to obtain the potential mineralization.

The samples were extracted with 30 mL of 0.01 N $CaCl_2$ (Smith et al. 1980) by adding the solution to the microlysimeter and applying a vacuum of 0.8 hPa. This was done daily during the 1st week, at weekly intervals for the following 3 weeks and every 2 weeks thereafter apart from the last sampling which was done after 28 days. After each extraction, 25 mL N-free nutrient solution (4 mM $CaCl_2$; 2 mM KH_2PO_4; 1 mM K_2SO_4; 1 mM $MgSO_4$; 25 µM H_3BO_4; 2 µM $MnSO_4$; 2 µM $ZnSO_4$; 0.5 µM $CuSO_4$; 0.5 µM Na_2MoO_4) was added to the soil to replenish the extracted nutrients (Nadelhoffer 1990). The water content was adjusted by applying a vacuum of 0.8 hPa.

The mineral N was analyzed colorimetrically as NO_3^- and NH_4^+ with a rapid flow analyzer (RFA-300, Alpkem, Clackamas, Ore.). Irregular, random tests did not detect any NO_2^-, which was therefore not determined. Organic N was supposed to have a negligible effect on treatment differences of N mineralization (Smith et al. 1980; Lindemann et al. 1989) and was not analyzed.

Modeling of mineralization dynamics and pool sizes

For both C and N mineralizations, a double exponential model was used to determine the potentially mineralizable C and N, the sizes of labile and stable soil C and N pools and their mineralization rates (Deans et al. 1986; Gregorich et al. 1989):

$$X_t = X_1(1 - e^{-k_1 t}) + X_2(1 - e^{-k_2 t})$$

where X_t=mineralizable C or N (mg g^{-1} soil), X_1=labile C or N pool (mg g^{-1} soil), X_2=stable C or N (mg g^{-1} soil), k_1, k_2=mineralization rates of the labile and stable pools, respectively (day^{-1}) and t=time of incubation (days).

Statistical analyses

The analyses of variance were computed using a completely randomized design (STATISTICA Version 5), after testing for normal distribution with the Kolmogorov-Smirnov test and for homogeneity of variances with the Levene test. The requirements for conducting an ANOVA (analysis of variance) were met. In case of significant effects, means were compared using least significant difference (LSD) at $P<0.05$ (Little and Hills 1978). The regressions were computed with the least square fittings method (Quasi-Newton).

Results

Soil chemical properties

The pH values significantly increased where manure was applied ($P<0.05$), but remained constant at all other sites (Table 1). Organic C and total N contents were significantly higher ($P<0.05$) in the soils of the native savanna woodland than at any other site apart from the soils amended with manure. Conversion of native acacia

Table 2 Cumulative C mineralization ($C_{min120\ days}$), potentially mineralizable C ($C_{potential}$), mineralization rates (k_1, k_2), and C pool sizes (C_1, C_2) of cultivated and natural savanna soils in Northern Tanzania. Values in one column followed by the same letter are not significantly different at P<0.05

Sites [a]	$C_{min(120\ days)}$		Cpotential	k_1	k_2	C_1	C_2	$t_{1/2}C_1$ [b]	$t_{1/2}C_2$	R [c]
	g kg^{-1} (%)			days^{-1}		g kg^{-1} soil		days		
Woodland Nativ.	5.2 a	(26 b)[d]	6.6 (31)[d]	0.308	0.011	1.21	5.43	2.25	63.0	0.99
Woodland Degr.	1.4 c	(11 c)	1.5 (12)	0.269	0.187	0.73	0.74	2.58	3.7	0.99
Woodland Term.	2.8 b	(47 a)	3.9 (63)	0.265	0.008	1.15	2.75	2.62	86.6	0.99
Cultiv. 3 yr.	1.8 bc	(19 bc)	1.5 (16)	0.294	0.025	0.71	0.82	2.36	27.7	0.99
Cultiv. 15 yr.	2.7 b	(38 a)	3.3 (43)	0.319	0.126	0.83	2.46	2.17	5.5	0.99
Manure	2.5 b	(16 bc)	2.1 (12)	0.288	0.014	1.07	1.44	2.41	49.5	0.99

[a] For an explanation of abbreviations, see Table 1
[b] Half-life of labile (C_1) and stable (C_2) soil pools
[c] All regression coefficients significant at P<0.001
[d] As percentage of total organic C

woodland savanna soils into agricultural land decreased the soil organic carbon content by 56% within 3 years. Fifteen years of continuous cropping caused a further C loss of 18%. Calculated C loss rates were higher for the 15-years-cultivated fields (0.07 days^{-1}; 64% C loss) than for the degraded savanna during the same 15-year time period (0.03 days^{-1}; 39% C loss). Soil N loss rates (0.04 days^{-1}) were larger than C loss rates (0.03 days^{-1}) in the degraded woodland, whereas it was the other way round for the cultivated fields (0.23 N; 0.28 C days^{-1} for 3-years-cultivated fields). The lowest soil C contents and the lowest C-to-N ratios were found in the soils of termite mounds. The highest cation exchange capacities (CEC), S, K, Ca, Na and Zn contents were registered in the soils of the homestead fields, whereas Mn and Cu availability were reduced. The long-term cultivated fields had significantly lower CEC, S, Ca and Zn contents (P<0.05), and showed trends towards lower K and Mg contents (not significant) than the native savanna soils. The Mn and Cu contents did not decrease upon cultivation. The recently cleared fields showed intermediate values which were not significantly different from either the native savanna soils or the old fields (P>0.05). Similarly, the degraded savanna soils did not show a large loss of nutrients apart from N. The termite sites in the woodland, however, had lower Zn but higher Na contents than the native and degraded savanna soils (P<0.05). The results showed that site effects among the savanna woodland soils in comparison to the cultivated fields were most pronounced in the soil organic C and total N contents. The soils of the homesteads, however, were enriched in basic cations (apart from Mg) and S and had higher pH values but lower Zn and Cu concentrations compared to the other investigated ecosystems.

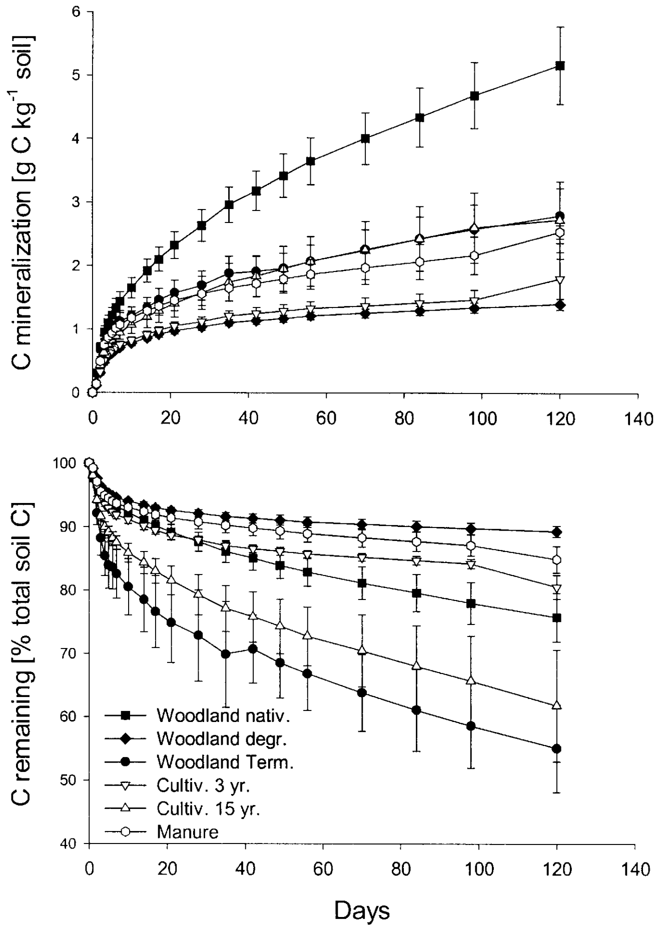

Fig. 1 C mineralization and remaining C during laboratory incubation of soils from cultivated and natural savanna in Northern Tanzania (means and standard errors; n=5 but n=4 for Cultiv. 3 yr. and Manure)

Carbon mineralization

The largest increase of mineralized C was observed during the first days of incubation with highest values in soils of the native savanna, followed by termite sites, long-term cultivated and homestead fields (Fig. 1). During the last 9 weeks of incubation, the native savanna soils had a significantly higher daily CO_2 evolution than all other investigated soils (P<0.05; data not shown). The lowest total C mineralization was noted for the soils of the degraded savanna and the recently cultivated fields (Table 2).

There was only a weak correlation between the soil organic C contents and the cumulative C mineralization

Table 3 Cumulative N mineralization, potentially mineralizable N ($N_{min120\ days}$), mineralization rates and N pool sizes of cultivated and natural savanna soils in Northern Tanzania. Values in one column followed by the same letter are not significantly different at $P<0.05$

Sites[a]	$N_{min(120\ days)}$		$N_{potential}$	k_1	k_2	N_1	N_2	$t_{1/2}N_1$[b]	$t_{1/2}N_2$	R[c]
	mg kg⁻¹ (%)			days⁻¹		mg kg⁻¹ soil		days		
Woodland Nativ.	228 a	(11 a)[d]	335 (16)	45.3	0.009	18.2	317	0.02	77.0	0.99
Woodland Degr.	97 b	(8 b)	139 (12)	1.0	0.008	8.1	131	0.67	86.6	0.99
Woodland Term.	49 b	(6 c)	73 (8)	0.6	0.008	8.5	64	1.23	86.6	0.99
Cultiv. 3 yr.	83 b	(8 b)	124 (12)	0.6	0.008	7.9	116	1.09	86.6	0.99
Cultiv. 15 yr.	66 b	(7 bc)	82 (10)	1.5	0.012	5.4	77	0.47	57.8	0.99
Manure	87 b	(5 c)	90 (5)	0.1	0.010	32.1	58	7.97	69.3	0.98

[a] For an explanation of abbreviations, see Table 1
[b] Half-life of labile (N_1) and stable (N_2) soil pools
[c] All regression coefficients significant at $P<0.001$
[d] As percentage of total N

(r=0.50; P<0.05). Consequently, the calculated remaining soil C as a proportion of total soil C gave a different picture than the C mineralization in relation to bulk soil (Fig. 1). The soils of the fields cultivated for 15 years and the termite sites mineralized 40% and 50% more of their total organic C than the soils of the other sites, respectively. The lowest C mineralization proportion was found in the degraded savanna, the homestead and the 3-years-cultivated soils. Only for the 15-years-cultivated and termite soils, did the high mineralization correspond with the low remaining soil C. The savanna and homestead soils, however, had a high mineralization but relatively little soil C reduction (Table 2).

The model fittings for both the C and the N mineralization were satisfactory with a double-exponential model as seen from the high regression coefficients (Tables 2, 3). The differences of mineralization rates, half-lives and sizes between soils were low when looking at labile soil pools as defined in this publication (Table 2). The differences in stable soil pools, however, were much larger. The largest stable soil pool was noted in the native savanna. The half-life was higher in soils affected by termites than even in the savanna woodland. The soils of the homestead fields and the recently cleared and cultivated fields also had long turnover times of the stable C fraction, but relatively low pool sizes. The fastest C turnover of the stable soil pool and the lowest pool size were found in soils from the degraded savanna despite their low mineralization and high remaining soil C (Fig. 1). The 15-years-cultivated fields had a large stable pool but a rapid mineralization. The stable pool sizes were significantly related to the cumulative C mineralization (r=0.98; P<0.05).

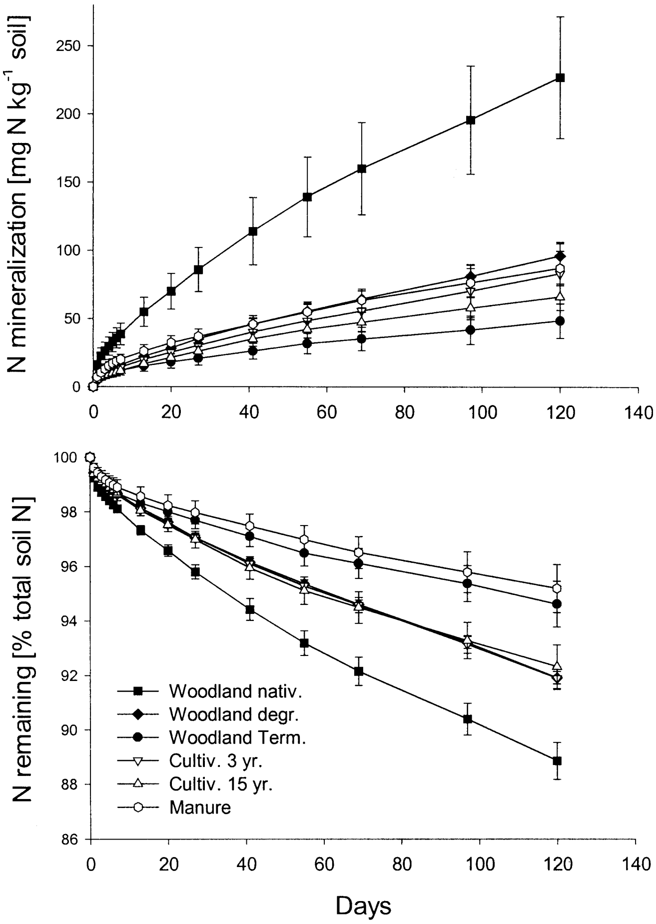

Fig. 2 N mineralization and remaining N during aerobic incubation of soils from cultivated and natural savanna in Northern Tanzania (means and standard errors; n=5 but n=4 for Cultiv. 3 yr. and Manure)

Nitrogen mineralization

Whereas the C mineralization was highest on the second day, N mineralization peaked at the first sampling and decreased thereafter. The soils of the native savanna had an initial mineralization maximum of 15.6 mg kg⁻¹, which was significantly higher than those of the other investigated soils with 4.4–7.1 mg kg⁻¹ (P<0.05; data not shown). Both the daily and cumulative N mineralization of the native savanna soils were 50–80% higher than those of the other soils throughout the whole incubation experiment (Fig. 2,Table 3). The soils from the termite sites had the lowest N mineralization. The N mineralization in relation to the total soil N content was highest in the soils of the native savanna (P<0.05; Fig. 2). The remaining N was highest in soils of the homestead fields followed by the termite sites ($P<0.05$).

The initial mineral N content was not related to N mineralization. The soils showed, however, a close correlation between the total N contents and the cumulative N mineralization ($r=0.87$; without homestead soils $r=0.97$; $P<0.05$).

The sizes and mineralization rates of the labile and stable pools were more than one order of magnitude different for N (Table 3), whereas the two C pools had similar properties between sites (Table 2). The soils of the native savanna showed the fastest N mineralization rate of the labile N pool and the largest stable N pool. The slowest turnover of the labile N pool was observed for the homestead fields, which also had the largest labile N pool. The turnover times of the stable N pool did not differ between the investigated sites.

Discussion

Soil fertility and organic matter stability of natural and disturbed savanna soils

The studied chromic Luvisols of the Northern Tanzanian savanna woodland have comparatively low C and N contents. Birch and Friend (1956) analyzed 570 topsoil samples from East Africa of which only 25% had lower C contents than 20 g kg^{-1}. The N values in the cited work, however, resembled the contents found at our sites. Jones (1973) found C contents of 1.9–110 g kg^{-1} and N contents of 0.19–9.5 g kg^{-1} from 191 soils in West African savannas. The measured rapid mineralization of C and N after rewetting resembled the commonly shown flash of mineralization during dry-wet cycles (Cabrera 1993) as observed in savanna ecosystems. The mineralized compounds comprise easily decomposable SOM and dead microbial biomass, which contributes 35–75% to the initial N mineralization in agricultural fields according to Morumoto et al. (1982). Desorption of organic matter and organic N from soil particles may also contribute to the easy initial accessibility of soil C and N for microbial decay (Cabrera 1993).

The total mineralized N after 120 days accounted for 11% of total soil N (Npot 16%) and it was higher than the 6% reported from laboratory incubations of Cambisols from a West African savanna ecosystem (Bernhard-Reversat 1982), which may be explained by the lower C and N contents in the cited study. However, comparisons of calculated mineralizable N between soil types have limited value without knowing the decomposition rates (Dendooven et al. 1995). The assessment of the mineralization dynamics of the investigated soils allowed us to compare N mineralization between different sites. Bernhard-Reversat (1982) found a similar relationship between total N content and N mineralization as in the present study. This could not be verified for C in our soils, and also Liang et al. (1996) reported that C mineralization was related to the amount of soil microbial biomass rather than total C. The extent of both the N and C mineralizations depended on the size of the stable soil N and C pools in our study, respectively. Mineralization experiments quantifying immediately mineralizable organic C and N may indicate soil differences more sensitively than bulk soil analyses, because labile soil pools are changing rapidly upon land-use changes. However, the stable soil C and N pools analyzed here determined the relevant differences of mineralization between sites. Since only two different pools were studied, it could not be verified whether more stable soil pools behaved differently than the stable pools isolated here.

In contrast to our results, termites have usually been shown to increase soil carbon contents and rarely to decrease them (Lee and Wood 1971). In the Brazilian Cerrados, soil C stabilization was higher in termite mounds demonstrated by higher C contents in silt size separates which led to higher levels of soil organic C (Zech et al. 1997b). For the Northern Tanzanian savanna, Hesse (1955) stated that termites preferred coarser soil material for building the mounds, which would explain the lower C contents observed in our study. The low C-to-N ratios of the soils at termite mounds (Table 1) could be due to N_2 fixation by the termite gut fauna producing about 0.1 kg N_2 ha^{-1} year^{-1} (Martius 1994). In relation to the C contents, the soils at the termite mounds were enriched in all nutrients. The high C mineralization and rapid C turnover as well as the large decrease of soil C can be explained by the higher microbial biomass and especially the more efficient microflora which was frequently found in termite mounds in comparison to adjacent soil (Pathak and Lehri 1959; Meiklejohn 1965). The apparently high microbial activity and mineralization of labile C led to an immobilization of N. Therefore, the outer areas of termite mounds as investigated in this study differed distinctly from the surrounding soil, not only in elemental contents but also in microbial processes. A higher soil fertility was not observed.

The reduced soil N and C contents after the selective removal of acacias for charcoal production (Woodland degr.) can be explained by lower N inputs from biological N_2 fixation and by the generally lower input of organic matter from litter. Mazzarino et al. (1991) also found lower N mineralization under non-leguminous trees than *Prosopis flexuosa* in a semi-arid grassland of Argentina. The 42% lower N content led to a 58% lower mineralization, emphasizing the N limitation for microbial growth in the studied soils. However, the organic C and N contents stabilized in clay fractions were not decreased in the degraded woodland described here (Solomon et al. 2000). Additionally, the stable soil N pool of the degraded woodland as determined by the N mineralization experiments shown here was still high compared to the one of the intensively cropped soils. Therefore, soil fertility replenishment can succeed in these ecosystems if current land-use practices are stopped and re-establishment of the acacia woodland is supported.

Dynamics of soil fertility decline after cultivation

The soil C and nutrient decrease as well as the low total N mineralization in the recently cleared fields (Cultiv. 3 yr.) resembled those in the degraded woodland, and were probably caused by a lack of organic matter input. The observed beneficial effects of trees on soil N mineralization and decreases of soil N after land clearing and cultivation have also been shown for other tropical soils (Bernhard-Reversat 1982; Mazzarino et al. 1991; Saikh et al. 1998). The majority of C and N losses may have occurred during the cropping period investigated which were reported to reach steady-state values 15 years after land-use conversion in India (Saikh et al. 1998). The soil degradation at our site was severe (56% C and 50% N decrease in 3 years) compared to unfertilized Acrisols and Vertisols in West Africa with reductions of 8% and 16% C and 18% N over 2 years (Gaiser et al. 1994). Also, the amino-sugar contents of the organic matter decreased upon cultivation (Solomon et al. in press) indicating lower availability of the remaining N compounds. Apart from N, soil nutrient contents were still high at our site in comparison to long-term cultivated and unfertilized Chromic Luvisols from Kenya with around 1,000 mm annual precipitation, which had 0.30 g K kg^{-1}, 0.65 g Ca kg^{-1} and 0.18 g Mg kg^{-1} (Onchere et al. 1989). The long-term cultivated soils (Cultiv. 15 yr.) were more severely degraded than the recently cleared fields as seen from the lower nutrient and organic C contents. Moreover, the soil structure in the old fields was destroyed and led to mineralization of the stable soil C pool determined by C mineralization. The reason for the increasing value of the stable C in 15-years-cultivated fields probably was a change of pools: the destruction of soil aggregation made the stable C available for decomposition and created an intermediary C pool with high decomposition rates.

Whereas the labile N pools rapidly decreased upon land clearing and cultivation after 3 years, the stable N pool remained high. Only in the 15-years-cultivated soils, did the stable N pool also decrease as a result of continuous cropping. Solomon et al. (2000) also showed that the stable soil N and C bound to clay-size fractions still decreased after 15 years, whereas the organic matter in the sand-size separates was depleted after 3 years. The low N mineralization in the 15-years-cultivated fields was a result of the low pool sizes and generally low total N contents, since decomposition rates were higher in the 15- than 3-years-cultivated soils. Increases in N mineralization rates, however, did not match the increases in C mineralization rates, which can be explained by immobilization of N caused by the high C mineralization. This is in contrast to findings of Ruess and Seagle (1994) that the natural savanna soils of Northern Tanzania are more C than N limited. In cultivated soils (as in our study), however, the N removal by harvest and the intensive disturbance of soil preparation led to a higher depletion of N than in grassland soils.

Therefore, 3 years of cultivation did not destroy but only decreased soil fertility, and soil recuperation may succeed with fallow periods or sufficient organic input under continuous cropping. With the current agricultural practice at the investigated site, 15 years of continuous cropping had a much more severe impact on soil functions and soil rehabilitation may only be successful after prolonged fallow periods.

Manure effects on soil nutrient availability and mineralization

The large increase of pH in the homestead fields was caused by the input of cations from the manure. A portion of the cations was also present as soluble salts since the base saturation was well above 100%. A higher soil enrichment with K than with other cations was also observed after 3 years of animal manure applications in California (Clark et al. 1998). Furthermore, burning enriches the soil with Na (Nye and Greenland 1960). As a result of burning and a high pH, Cu and Zn availability was low in homestead fields (Sims 1986). The Cu and Zn concentrations were generally too low (<7 mg kg^{-1}) for efficient crop production on all land-use systems. The manure was not mixed with the soil, and only mineralized N or dissolved organic C and N entered the soil. This organic C input was stable organic matter as seen from the larger C increases in clay than in sand-size fractions of the same soil (Solomon et al. 2000). The high soil C stability was also confirmed by the low turnover of organic C of homestead fields observed in the present study. This was also concluded from low turnover times of the labile C after animal manure additions to soil under temperate climate (Rochette and Gregorich 1998). The low mineralization of soil C and N in homestead fields was partially caused by the high soil pH (Olness 1999). In addition, burning may have caused the formation of highly recalcitrant aromatic compounds as shown by Haumaier and Zech (1995).

A high stabilization of C and N in clay-size fractions from manure input was also found in Calcaric Fluvisols of semiarid Kenya (Lehmann et al. 1997), where less manure accumulated than in the present study. A better mixture of the manure with the topsoil may improve soil fertility and organic matter stabilization in the soils studied here.

Conclusions

Nutrient availability (apart from N) after land-use conversion was less of a problem than the organic matter stability in the investigated soils. Additionally, the stable soil C and N pools obtained from the mineralization experiments determined the amount of C and N mineralization, not the labile ones. Consequently, the degraded woodland and the recently cleared fields showed comparatively high N mineralization due to large stable N pools despite strong reductions of the labile N pools.

Soils at termite mounds did not have a high fertility in the savanna of Northern Tanzania. Therefore, fields with a very high abundance of termite mounds should be avoided for agricultural production or additional organic matter and nutrients have to be provided. The removal of acacias from the native savanna should be stopped, and already degraded sites should be left for natural regeneration. Additional re-naturation may not be necessary. Soil organic matter degradation of the recently cleared fields also did not affect stable C and N pools, and nutrient availability (apart from N) was not significantly reduced. Organic farm management will be able to replenish soil fertility in 3-year-old fields. In the long-term cultivated fields a drastic change in soil management, however, has to happen to regenerate soil fertility and short-term recuperation may not be expected. Manuring, as in traditional homesteads, was a suitable method to increase soil nutrient and organic matter contents. However, soil fertility was not improved by the common practice of manure accumulation and little mixing with the underlying soil. A better incorporation into the soil will be a favorable technique for improving crop production in the Northern Tanzanian savanna.

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References

Allison FE, Carter JN, Sterling LD (1960) The effect of partial pressure of oxygen on denitrification in soil. Soil Sci Soc Am Proc 24:283–285

Bernhard-Reversat F (1982) Biogeochemical cycle of nitrogen in a semi-arid savanna. Oikos 38:321–332

Birch HF, Friend MT (1956) The organic matter and nitrogen status of East African soils. J Soil Sci 7:156–167

Cabrera ML (1993) Modeling the flush of nitrogen mineralization caused by drying and rewetting soils. Soil Sci Soc Am J 57: 63–66

Christensen BT (1988) Effects of animal manure and mineral fertilizer on the total carbon and nitrogen contents of soil size fractions. Biol Fertil Soils 5:304–307

Christensen BT (1996) Carbon in primary and secondary organomineral complexes. In: Carter MR, Stewart BA (eds) Advances in Soil Science: structure and organic matter in agricultural soils. CPR Press, New York, pp 97–165

Clark MS, Horwath WR, Shennan C, Scow KM (1998) Changes in soil chemical properties resulting from organic and low-input farming practices. Agron J 90:662–671

Deans JR, Molina JAE, Clapp CE (1986) Models for predicting potentially mineralizable nitrogen and decomposition rate constants. Soil Sci Soc Am J 50:323–326

Dendooven L, Merckx R, Vlaasak K (1995) Limitations of a calculated N mineralization potential in studies of the N mineralization process. Plant Soil 177:175–181

FAO (1988) FAO/Unesco soil map of the World, revised legend, with corrections and updates. (World Soil Resources Report 60) FAO, Rome (reprinted with updates as Technical Paper 20, ISRIC, Wageningen, 1997)

Gaiser T, Bernard M, Stahr K (1994) Nitrogen and carbon mineralization in cultivated Acrisols and Vertisols in a sub-humid tropical climate. Z Pflanzenernähr Bodenkd 157:375–381

Gregorich EG, Kachanoski RG, Voroney RP (1989) Carbon mineralization in soil size fractions after various amounts of aggregate disruption. J Soil Sci 40:649–659

Haumaier L, Zech W (1995) Black carbon – possible source of highly aromatic components of soil humic acids. Org Geochem 23:191–196

Hesse PR (1955) A chemical and physical study of the soils of termite mounds in East Africa. J Ecol 43:449–461

Isermeyer H (1952) Eine einfache Methode zur Bestimmung der Bodenatmung und der Karbonate im Boden. Z Pflanzenernaehr Dueng Bodenkd 56:26–38

Jenkinson DS (1971) Studies on the decomposition of C^{14} labelled organic matter in soil. Soil Sci 111:64–70

Jones MJ (1973) The organic matter content of the savanna soils of West Africa. J Soil Sci 24: 42–53

Kahurananga J (1979) The vegetation of the Simanjiro Plains, Northern Tanzania. Afr J Ecol 17:65–83

Kahurananga J (1995) Mission report to Kiteto and Simanjiro Districts for preparation of terms of reference for land husbandry and soil erosion study. In: ORGUT Support Office Babati (ed) Tanzania and Regional Soil Conservation Unit, SIDA, Nairobi, pp 3–24

Kandeler E, Murer E (1993) Aggregate stability and soil microbial processes in a soil with different cultivation. Geoderma 56: 503–513

Lee KE, Wood TG (1971) Termites and soils. Academic Press, London

Lehmann J, Küper U, Zech W (1997) Organic matter properties of soils with varying land use in a semiarid tropical environment. In: Drozd J, Gonet SS, Senesi N, Weber J (eds) The role of humic substances in the ecosystems and in environmental protection. PTSH, Wroclaw, pp 399–406

Liang BC, Gregorich EG, Schnitzer M, Voroney RP (1996) Carbon mineralization in soils of different textures as affected by water-soluble organic carbon extracted from composted dairy manure. Biol Fertil Soils 21:10–16

Lindemann WC, Fresquez PR, Cardenas M (1989) Nitrogen mineralization in coal mine spoil and topsoil. Biol Fertil Soils 7:318–324

Little TM, Hills FJ (1978) Agricultural experimentation. Wiley, New York

Martius C (1994) Diversity and ecology of termites in Amazonian forests. Pedobiologia 38: 407–428

Mazzarino MJ, Oliva L, Nuñez A, Nuñez G, Buffa E (1991) Nitrogen mineralization and soil fertility in the dry Chaco ecosystem (Argentina). Soil Sci Soc Am J 55:515–522

Mehlich A (1984) Mehlich 3 soil test extractant: a modification of Mehlich 2 extractant. Comm Soil Sci Plant Anal 15:1409–1416

Meiklejohn J (1965) Microbiological studies on large termite mounds. Rhod Zambia Malawi J Agric Res 3:67–79

Mengel K (1996) Turnover of organic nitrogen in soils and its availability to crops. Plant Soil 181:83–93

Morumoto T, Anderson JPE, Domsch K-H (1982) Mineralization of nutrients from soil microbial biomass. Soil Biol Biochem 14:469–475

Nadelhoffer KJ (1990) Microlysimeter for measuring nitrogen mineralization and microbial respiration in aerobic soil incubations. Soil Sci Soc Am J 54:411–415

Nye PH, Greenland DJ (1960) The soil under shifting cultivation. Technical Communication No 51, Commonwealth Bureau of Soils, Harpenden

Olness A (1999) A description of the general effect of pH on formation of nitrate in soils. Z Pflanzenernaehr Bodenkd 162:549–556

Onchere J, Goulding KWT, Wood IG, Catt JA (1989) Potassium and magnesium in some Kenyan soils: their mineral sources and release to Ca-resin. J Soil Sci 40:621–634

Pathak AN, Lehri LK (1959) Studies on termite nests. 1. Chemical, physical and biological characteristics of a termitarium in relation to its surroundings. J Indian Soc Sci 7:87–90

Penzlin H (1996) Lehrbuch der Tierphysiologie. Fischer, Jena

Rochette P, Gregorich EG (1998) Dynamics of soil microbial biomass C, soluble organic C and CO_2 evolution after three years of manure application. Can J Soil Sci 78:283–290

Ruess RW, Seagle SW (1994) Landscape patterns in soil microbial processes in the Serengeti National Park, Tanzania. Ecology 75:892–904

Saikh H, Varadachari C, Ghosh K (1998) Changes in carbon, nitrogen and phosphorus levels due to deforestation and cultivation: a case study in Simlipal National Park, India. Plant Soil 198:137–145

Sims JT (1986) Soil pH effects on the distribution and plant availability of manganese, copper and zinc. Soil Sci Soc Am J 50:367–373

Smith JL, Schnabel RR, McNeal BL, Campbell GS (1980) Potential errors in the first-order model for estimating soil nitrogen mineralization potentials. Soil Sci Soc Am J 44:996–1000

Soil Survey Staff (1997) Keys to soil taxonomy, 7th edn. Pocahontas Press, Blacksburg

Solomon D, Lehmann J, Zech W (2000) Land use effects on soil organic matter properties of chromic Luvisols in the semiarid tropics: Carbon, nitrogen, lignin and carbohydrates. Agric Ecosyst Environ 78:203–213

Solomon D, Lehmann J, Zech W (in press) Land use effects on amino sugar signatures of chromic Luvisols in the semi-arid part of Northern Tanzania. Biol Fertil Soils

Stanford G, Smith SJ (1972) Nitrogen mineralization potentials of soils. Soil Sci Soc Am Proc 36:465–472

Zaman M, Di HJ, Cameron KC (1999) A field study of gross rates of N mineralization and nitrification and their relationships to microbial biomass and enzyme activities in soils treated with dairy effluent and ammonium fertilizer. Soil Use Manage 15:188–194

Zech W, Senesi N, Guggenberger G, Kaiser K, Lehmann J, Miano TM, Miltner A, Schroth G (1997a) Factors controlling humification and mineralization of soil organic matter in the tropics. Geoderma 79:117–161

Zech W, Amelung W, Neufeldt H (1997b) Organic matter in termite mounds of the cerrados, Brazil. In: Drozd J, Gonet SS, Senesi N, Weber J (eds) The role of humic substances in the ecosystems and in environmental protection. PTSH, Wroclaw, pp 263–268