Nitrogen retention and plant uptake on a highly weathered central Amazonian Ferralsol amended with compost and charcoal

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Abstract

Leaching losses of N are a major limitation of crop production on permeable soils and under heavy rainfalls as in the humid tropics. We established a field trial in the central Amazon (near Manaus, Brazil) in order to study the influence of charcoal and compost on the retention of N. Fifteen months after organic-matter admixing (0–0.1 m soil depth), we added ^{15}N-labeled $(NH_4)_2SO_4$ (27.5 kg N ha^{-1} at 10 atom% excess). The tracer was measured in top soil (0–0.1 m) and plant samples taken at two successive sorghum (*Sorghum bicolor* L. Moench) harvests. The N recovery in biomass was significantly higher when the soil contained compost (14.7% of applied N) in comparison to only mineral-fertilized plots (5.7%) due to significantly higher crop production during the first growth period. After the second harvest, the retention in soil was significantly higher in the charcoal-amended plots (15.6%) in comparison to only mineral-fertilized plots (9.7%) due to higher retention in soil. The total N recovery in soil, crop residues, and grains was significantly ($p < 0.05$) higher on compost (16.5%), charcoal (18.1%), and charcoal-plus-compost treatments (17.4%) in comparison to only mineral-fertilized plots (10.9%). Organic amendments increased the retention of applied fertilizer N. One process in this retention was found to be the recycling of N taken up by the crop. The relevance of immobilization, reduced N leaching, and gaseous losses as well as other potential processes for increasing N retention should be unraveled in future studies.

Key words: biochar Brazil / carbon / nitrogen cycling / slash-and-burn / soil organic matter / Terra Preta

1 Introduction

The fertility of highly weathered Ferralsols in the tropics is low, and soil organic matter (SOM) plays a major role in sustaining soil productivity. Thus, long-term intensive use is not sustainable without nutrient inputs where SOM stocks are depleted (*Tiessen* et al., 1994). Due to low nutrient-retention capacity and high permeability of these soils, strong tropical rainfalls cause rapid leaching of mobile nutrients such as those applied with mineral N fertilizers (*Hölscher* et al., 1997a; *Giardina* et al., 2000; *Renck* and *Lehmann*, 2004).

To overcome these limitations of poor soil, low nutrient-retention capacity and accelerated SOM decay require alternatives to slash-and-burn (the prevalent agricultural practice in the tropics) and alternative fertilization methods (*Ross*, 1993; *Fernandes* et al., 1997). Instead of burning, involving a quick release of nutrients (*Kuhlbusch* et al., 1991; *Hölscher* et al., 1997b; *Giardina* et al., 2000; *Hughes* et al., 2000) and CO_2 (*Fearnside*, 1997), fallow vegetation could be applied as mulch (*Sommer* et al., 2004), compost, or charcoal (*Lehmann* et al., 2002). Depending on the mineralization rate, organic fertilizers such as compost, mulch, or manure applications release nutrients in a gradual manner (*Burger* and *Jackson*, 2003). This may be different for very recalcitrant organic addi-

tions such as charcoal. According to *Duxbury* et al. (1989) and *Sombroek* et al. (1993), it is important to separate effects due to OM *per se* (maintenance and improvement of water infiltration, water-holding capacity, structure stability, CEC, healthy soil-biological activity) from those due to its decomposition (source of nutrients).

Only relatively small amounts of charcoal are produced by the traditional slash-and-burn technique. Charcoal represents only 1.7% of the preburn biomass if a forest is converted into cattle pasture (*Fearnside* et al., 2001). Producing charcoal for soil amelioration from aboveground biomass instead of converting it to CO_2 through burning might be an alternative to slash-and-burn (*Lehmann* et al., 2002; *Steiner* et al., 2004b; *Lehmann* et al., 2006).

The existence of so-called "Terra Preta de Índio" (Indian black earth) suggests that a human-induced accumulation of SOM can be maintained over centuries (*Sombroek* et al., 1993). These soils are exceptionally fertile, and their productivity is most likely linked to an anthropogenic accumulation of P and Ca associated with bone apatite (*Lima* et al., 2002) and black C (BC) as charcoal (*Glaser* et al., 2001).

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The sustained fertility of charcoal-containing Terra Preta and the frequent use of charcoal as a soil conditioner (*Steiner* et al., 2004b) in Brazil provided the incentive to study the effects of charcoal application on N cycling. Charcoal acted as an adsorber which reduced N leaching in previous pot experiments (*Lehmann* et al., 2002, 2003), and charcoal additions proved to sustain fertility if an additional nutrient source is given in a field trial (*Steiner* et al., 2007). Charcoal *plus* fertilizer improved plant growth and doubled grain production in comparison to the fertilizer without charcoal. Plant biomass production sharply decreased within 1 y when only mineral fertilizer was applied, but could be maintained for a longer period of time when OM was added. The authors proposed that charcoal can improve soil chemical, biological, and physical properties, but could not completely discern the mechanisms of fertility enhancement (*Steiner* et al., 2007).

Stable isotopes such as ^{15}N can serve as valuable tracers to study plant resource acquisition and as a means to understand how plants interact with their abiotic and biotic environments (*Dawson* et al., 2002). Therefore, our objective was to compare the effect of organic amendments such as charcoal and compost on retention of ^{15}N-labeled mineral fertilizer in a highly weathered Ferralsol under humid tropical field conditions.

2 Materials and methods

2.1 Study location and experimental setup

The experiment was conducted within a larger field trial established 30 km N of Manaus, Amazonas, Brasil (3°8′ S, 59°52′ W, 40–50 m asl) at the Embrapa-Amazônia Ocidental (Empresa Brasileira de Pesquisa Agropecuaria) experimental research station. The natural vegetation is evergreen tropical rainforest with a mean annual precipitation of 2530 mm (1971–1997) having its seasonal maximum between December and May, a mean annual temperature of 25.8°C (1987–1997), and relative humidity of 85% (*Correia* and *Lieberei*, 1998). The soil was classified as a highly weathered Xanthic Ferralsol (*FAO*, 1990), fine-textured with high clay content. It is strongly aggregated and has medium contents of organic C (24 g kg^{-1}), low pH values of 4.7 (in H_2O), low CEC of 1.6 cmol$_c$ kg $^{-1}$, and low base saturation (BS) of 11% (*Steiner* et al., 2007).

This experiment is part of a long-term field trial established in January 2001 (*Steiner* et al., 2007). The main objective was to study different organic-amendment combinations based on equal amounts of C additions. Fifteen different treatments were established in five repetitions after clearing of approx. 3600 m^2 secondary forest and removing the aboveground biomass. The treatments were applied on 4 m^2 plots (2 m × 2 m) forming an entire field area of 1600 m^2 (45 m × 35 m) with a minimum distance to the surrounding vegetation of 10 m. For this study, five mineral-fertilized (F) treatments were chosen, four of them with compost (CO + F) and/or charcoal (CC + F) application (Tab. 1). The treatment receiving compost only (CO) served to provide a reference value for N isotope composition in soil and plants. This treatment was used as a control for all treatments as δ^{15}N did not differ between the treatments without tracer application [(NH$_4$)$_2$SO$_4$ fertilized or not].

The charcoal derived from secondary forest wood and was considered rather as soil conditioner than fertilizer due to the charcoal's low nutrient contents (Tab. 1). It was manually crushed to particle sizes <2 mm. The applied 11 Mg ha^{-1} corresponded to the amount of charcoal-C which could be produced by a single slash-and-char event of a tropical secondary forest on Xanthic Ferralsols in central Amazonia (*Lehmann* et al., 2002). The amount of C added with charcoal was chosen as a reference value for adding the compost. Compost was prepared from biomass of a secondary forest, fruit residues, manure, and kitchen waste. On February 3, 2001, organic materials were mixed with hand hoes into the top soil (0–0.1 m) of the plots, and the first mineral fertilization was done on March 19, 2001 [30 N kg ha^{-1} as (NH$_4$)$_2$SO$_4$, 35 kg P ha^{-1} as simple superphosphate, 50 kg K ha^{-1} as KCl, and 2100 kg lime ha^{-1}]. The fields were cropped twice (rice *Oryza sativa* L. and sorghum *Sorghum bicolor* L. Moench) prior the second fertilization on April 16 (see Tab. 1 for treatment description). All crop residues remained on the field, and only grains were removed. Sorghum was planted again on April 18, 2002 in a density of 25 plants m^{-2} producing two harvests by ratooning (July 21 and October 16, 2002). Only these two harvests are subject of the present paper and designated as 1st (HI) and 2nd (HII) harvest.

Table 1: Treatments, organic amendments, and harvest remnants (from previous harvests remained in the field). Mineral fertilization (F) was applied after the second harvest in April 2002, ^{15}N-labeled N (55), P (40), K (50), lime (430) [kg ha^{-1}].

Token	Organic matter	1st harvest (HI) remnants[a]	2nd harvest (HII) remnants[a]	Total
		[Mg dry matter ha^{-1}]		
CO[b]	compost (67)	5.13	1.11	6.24
F		1.98	0.27	2.25
CO + F	compost (67)	6.24	1.51	7.75
CC + F	charcoal (11)	2.55	0.72	3.27
½CC + ½CO + F	charcoal (5,5), compost (33,5)	4.74	1.10	5.85
CC + ½CO + F	charcoal (11), compost (33,5)	4.28	1.10	5.38

F = mineral fertilizer; CO = compost; CC = charcoal
[a] previous harvests July 7, 2001 and February 6, 2002
[b] unfertilized control treatment, reference value for ^{15}N natural abundance;
previous mineral fertilization: March 2001 [kg ha^{-1}] N (30), P (35), K (50), lime (2100);
compost contained 10.1, 0.73, 2.85, 3.27, and 1.51 g kg^{-1} N, P, K, Ca, and Mg, respectively;
charcoal contained 5.39, 0.03, 0.23, 0.82, and 0.17 g kg^{-1} N, P, K, Ca, and Mg, respectively.

2.2 Tracer application, sampling, and calculations

The chosen treatments (F, CC + F, CO + F, ½CC + ½CO + F, and CC + ½CO + F) received ^{15}N isotope enrichment using ^{15}N-labeled (NH$_4$)$_2$SO$_4$ with 10 atom% ^{15}N excess. The tracer was mixed in a ratio 1:1 with conventional (NH$_4$)$_2$SO$_4$ and

applied at a rate of 55 kg N ha^{-1} in April 2002 (second fertilization). Additionally, 40 kg P ha^{-1}, 50 kg K ha^{-1}, and 430 kg ha^{-1} of lime was applied. Soil and plant samples were taken at each harvest and analyzed for δ^{15}N. Only the top 0.1 m of soil was sampled, this was also the depth down to which the organic amendments were mixed. Two soil samples were taken per plot to form one composite sample. Soils were air-dried and ground before isotope analysis. Representative plant samples were taken from the entire crop by using the center 1.4 × 1.4 m (49 plants) of each plot. Plant samples were dried at 70°C for 48 h and ground.

The remaining fertilizer N in soil or plant biomass was calculated after Eq. 1 (*Boutton*, 1996).

$$N_f \cdot \delta^{15}N_f = N_f \cdot \delta^{15}N_c + Y \cdot \delta^{15}N_{NPK}, \tag{1}$$

N_f = nitrogen content of biomass or soil in N-fertilized treatment,

$\delta^{15}N_f$ = measured δ^{15}N value of biomass or soil in N-fertilized treatment,

$\delta^{15}N_c$ = measured δ^{15}N value of biomass or soil in unfertilized control treatment (only CO served as valid control treatment as δ^{15}N did not differ between treatments without tracer application),

$\delta^{15}N_{NPK}$ = δ^{15}N of $(NH_4)_2SO_4$ 10 atom% ^{15}N excess (= 29330.3‰).

The amount of ^{15}N remaining in soil or in plant biomass (Y) was calculated according to Eq. 2. The subtraction of $\delta^{15}N_c$ in the denominator was neglected because it is small (approx. 10 and 20 for soil and biomass, respectively) in comparison to $\delta^{15}N_{NPK}$.

$$Y = \frac{N_f \cdot \delta^{15}N_f - N_f \cdot \delta^{15}N_c}{\delta^{15}N_{NPK}}. \tag{2}$$

The percentage of N taken up by biomass or remaining in the soil was calculated according to Eq. 3:

$$N\% = \frac{Y}{N_{(NH_4)_2SO_4}} \cdot 100, \tag{3}$$

where $N_{(NH4)2SO4}$ = amount of tracer fertilized [27.5 kg ha^{-1} $(NH_4)_2SO_4$ 10 atom% ^{15}N excess].

2.3 Analyses of soil and plant samples

Soil and plant samples were analyzed for their C and N contents by dry combustion with an automatic C/N-Analyzer (Elementar, Hanau, Germay). Total N isotope composition in soil and plants was determined using an Elemental Analyzer (Carlo Erba NA 1500, Carlo Erba Reagenti, Rodano, Italy; for Dumas combustion) connected to an isotope-mass spectrometer (FINNIGAN MAT delta E; Thermo Finnigan, San Jose CA) *via* a split interface.

2.4 Statistical analyses

Treatment effects were analyzed by one-way analysis of variance (ANOVA). Significant treatment effects were detected using the Fisher's LSD (last significant difference) test. Statistical analyses and figures were performed using SPSS 12.0 (SPSS Inc.) and SigmaPlot 7.0.

3 Results and discussion

While the soil C contents were significantly increased by the organic amendments (CO and CC), the N values were only significantly enhanced in comparison to the F plots if CO was applied (Fig. 1). After the second harvest (HII), the N and C contents on solely compost-amended plots (CO) did not differ from those receiving only mineral fertilizer. The OM-amended and N-fertilized plots had significantly higher C and N contents than the F plots. All organic amendments significantly increased the C : N ratio after the first harvest. This difference was even more distinct after the second harvest but only on charcoal-containing plots (Fig. 1).

Neither the N concentrations in the biomass nor the measured δ^{15}N values differed significantly (data not shown). The significantly higher mineral N uptake by plants growing on the compost-amended plots (CO + F) was due to a significantly higher plant biomass production (Tab. 2).

Wardle et al. (1998) found greater tree-seedling growth, N uptake, and enhanced efficiency of nutrient uptake in boreal forest soils when charcoal was added. The authors assumed that adsorption of phenolics by the charcoal diminished adverse effects on plant growth, both as allelopathic agents, and through complexing N, thus reducing its availability to plants. In our case, soil analyses indicate that other nutrients than N were more important to enhance plant growth leading to N sequestration in biomass (*Steiner* et al., 2007). This assumption is corroborated by the study of *Alfaia* et al. (2000) who found only a 16% rice grain-yield increase due to $(NH_4)_2SO_4$ fertilization, but significant losses of fertilized N.

In the soil, the situation was rather different. After the second harvest (HII), significantly more fertilizer N remained in the soil amended with charcoal (15.6% of applied N) than on plots without organic amendment (9.7%). The compost treatment showed intermediate values (12.6%) (Fig. 2). In the soil, the increased retrieval of N rather than higher total soil N contents caused the significantly enhanced N recovery. Only remaining crop residues could have caused the increase in encountered ^{15}N from HI to HII. However, the treatment ½CC + ½CO + F showed a much larger increase in soil ^{15}N encountered from HI to HII than the F treatment but had slightly less crop-residue input (Tab. 2). Only the compost treatment (CO + F) generated significantly more crop residue ^{15}N than the control group but this additional residue return did not significantly affect the soil ^{15}N at HII.

At least to some extent the accrued crop residues after HII added to the soil's N pool as shown by the shift in isotope values (data not shown) because soil sampling was done 7–14 d after the harvest. Belowground biomass was not
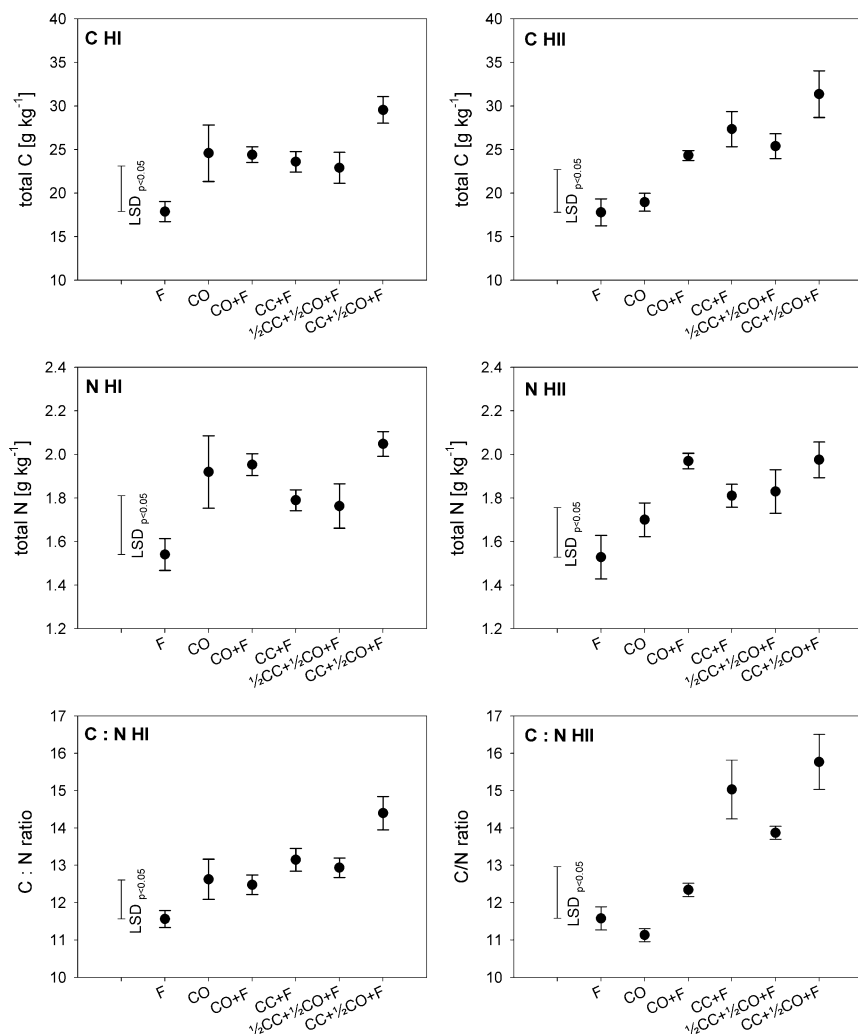
Figure 1: Contents of C and N in of the soil at the first (HI) and second harvest (HII). The error bars show the mean ± standard error. The Fisher's LSD (least significant difference) value is plotted to scale significant mean separation ($p < 0.05$).

assessed and can contribute significantly to N cycling as the root biomass pool can be assumed to be at least half as large as the aboveground biomass pool (*Lacerda* et al., 2004; *Hattori* et al., 2005). *Lehmann* and *Zech* (1998) found 30% of sorghum roots in Kenya below 0.3 m. We sampled only the upper 0.1 m, thus N could have been recycled from deeper soil layers.

The significantly increased uptake of applied N by plants on plots with additional compost and the significantly higher N retention in the soil due to charcoal additions may be explained by either reduced N leaching (*Lehmann* et al., 2003) or reduced gaseous N losses (*Yanai* et al., 2007). Reduced N leaching may be a result (1) of either improved retention of the applied NH_4^+ by electrostatic adsorption to exchange sites provided by the com-

Table 2: Biomass production, N uptake, and withdrawal (grains) at the first (HI) and second harvest (HII). Different letters in the same column indicate significant differences ($p < 0.05$) between treatments (Fisher's LSD test, $n = 5$).

Treatment	HI crop residues	grains	HII crop residues	grains	HI N residues	N grains	HII N residues	N grains
	[Mg dry matter ha⁻¹]				[kg ha⁻¹]			
F	1.38 b	0.28 c	0.50 c	0.14 c	11.3 c	4.7 c	4.9 b	2.3 c
CO	1.50 b	0.28 c	0.56 c	0.16 bc	19.8 b	5.8 c	7.5 b	3.2 bc
CO + F	2.69 a	0.96 a	1.17 a	0.80 a	29.8 a	15.5 a	13.1 a	12.6 a
CC + F	1.85 b	0.42 bc	0.72 bc	0.28 bc	17.3 bc	7.1 c	7.0 b	4.6 bc
½CC + ½CO + F	1.76 b	0.65 b	0.80 abc	0.33 bc	18.9 bc	11.8 ab	8.7 b	6.1 bc
CC + ½CO + F	2.08 ab	0.49 bc	0.97 ab	0.49 ab	19.7 b	8.1 bc	9.1 ab	8.5 ab

F = mineral fertilizer; CO = compost; CC = charcoal
Crop residues remained in the field; mean C 44.8, N 9.97 g kg⁻¹, C : N = 44.16; mean N content of grains = 16.9 g kg⁻¹
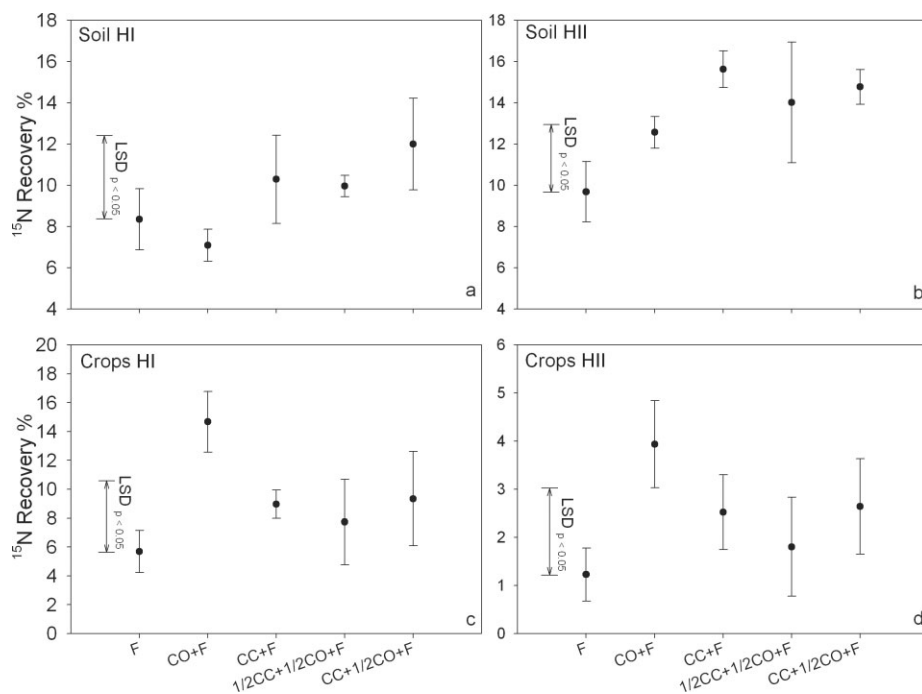
Figure 2: Amount of mineral N fertilizer remaining in the soil (Ferralsol, a and b) and in the crop (sorghum, c and d) after the first (HI, a and c) and second harvest (HII, b and d) as a percentage. Means and standard errors ($p < 0.05$, Fisher's LSD test, $n = 5$).

post or charcoal or (2) of immobilization of N by microbial biomass. *Lehmann* et al. (2003) made microbial immobilization responsible for decreases in foliar N contents and total N uptake as a response to charcoal additions due to their higher C : N ratio. However, their pot experiment used larger amounts of applied charcoal (67.6 and 135.2 Mg C ha^{-1}) than our study. The C : N ratio in the soil studied here was found to be significantly higher in the charcoal treatments at both harvest times (Fig. 1) in comparison to the control. Decomposition of a portion of newly applied charcoal and concurrent N immobilization is most likely a transient phenomenon as charcoal is much more stable than other organic additions (*Baldock* and *Smernik*, 2002). In the studied permeable soils under high-rainfall conditions, temporary immobilization of mobile nutrients might be desirable. The results of the ^{15}N experiments by *Burger* and *Jackson* (2003) suggest a very dynamic role of microbially bound N and highlight the importance of N immobilization that is taking place simultaneously with inorganic-N production by mineralization. They concluded that greater C availability stimulates microbial activity resulting in greater N demand, promoting immobilization and recycling of NO_3^-. The resilience of soil C in charcoal-amended plots shows the refractory nature of charcoal (*Kuhlbusch* and *Crutzen*, 1995). While the stability of charcoal leads to low C losses, nutrient release by mineralization is most likely lower than from other organic materials. As charcoal is expected to be an extremely recalcitrant form of OM, it is unknown to what extent charcoal C favors N immobilization. In previous studies, the same plots showed significantly increased plant growth and potential for microbial-population growth in mineral-fertilized soils amended with charcoal and in Terra Preta, but lower microbial respiration in the absence of an easily degradable C source (glucose) compared to soils without charcoal (*Steiner* et al., 2004a, 2007). It has been shown that charcoal amendments can significantly enhance nitrification in pine-forest soils (*DeLuca* et al., 2006). The authors suggest that charcoal alters

the activity of the nitrifying community and removes inhibiting phenols. We could not elucidate alterations in nitrification and its possible consequences for leaching and denitrification, although *Birk* (2005) found evidence that the organic amendments increased the presence of anaerobic bacteria which possibly are denitrifiers. *Dinkelmeyer* et al. (2003) found a rapidly decreasing total recovery (in plants and soil) of ^{15}N (87% to 54% to 24% at 1, 3, and 12 months after N application, respectively), but they assessed a complex and deep-rooting agroforestry system to a soil depth of 5 m. They found a minimum of 13% N-fertilizer efficiency when applied to peach palm (*Bactris gasipaes*) and a maximum of 38% if applied to cupuassu (*Theobroma grandiflorum*). *Alfaia* et al. (2000) assessed N utilization of a rice crop grown in central Amazona and found a N-fertilizer efficiency of only 7.8%, 10.0%, and 1% in shoot, grain, and root biomass, respectively. We found a maximum recovery in plant biomass of 15% and total recovery of 22% 3 months after N application at HI. Already after 4 d, *Renck* and *Lehmann* (2004) found applied ^{15}N in the soil solution to a depth of 0.6 m and to a depth of 5 m after 1 week at the same study site. They found that the largest part of applied ^{15}N in the top soil was leached as organic N. The total fluxes of organic N were similar to those of NO_3^- in the topsoil. According to *Lehmann* et al. (2002), the NH_4^+ adsorbability of charcoal is largely dependent on soluble OM, as an addition of DOC from a manure extract increased NH_4^+ adsorption. Therefore charcoal might have reduced leaching of organic N in addition to the inorganic forms. The organic amendments might likewise have altered denitrification but leaching is most likely the predominant N loss in the studied soil and the relative proportion could not be clarified in this study.

The charcoal's low biodegradability (*Kuhlbusch* and *Crutzen*, 1995), low nutrient content (*Ogawa*, 1994; *Antal* and *Grønli*, 2003), and high porosity and specific surface area (*Braida* et al., 2003) makes charcoal a rather exceptional SOM con-

stituent. Terra Preta research has shown that oxidation on the edges of the aromatic backbone and adsorption of other OM to charcoal is responsible for the increased CEC, though the relative importance of these two processes remains unclear (*Liang* et al., 2006).

4 Conclusion

We conclude that both the higher retention of N in the soil and the increased uptake by biomass are responsible for the significantly enhanced N cycling in plots that received charcoal. Soil charcoal amendments improve the efficiency of mineral N fertilizer.

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