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Article *in* Plant and Soil · February 2003

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Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments

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Received 27 February 2002. Accepted in revised form 4 October 2002

Key words: charcoal, nutrient leaching, organic fertilizer, Terra Preta de Indio

Abstract

Soil fertility and leaching losses of nutrients were compared between a Fimic Anthrosol and a Xanthic Ferralsol from Central Amazônia. The Anthrosol was a relict soil from pre-Columbian settlements with high organic C containing large proportions of black carbon. It was further tested whether charcoal additions among other organic and inorganic applications could produce similarly fertile soils as these archaeological Anthrosols. In the first experiment, cowpea (*Vigna unguiculata* (L.) Walp.) was planted in pots, while in the second experiment lysimeters were used to quantify water and nutrient leaching from soil cropped to rice (*Oryza sativa* L.). The Anthrosol showed significantly higher P, Ca, Mn, and Zn availability than the Ferralsol increasing biomass production of both cowpea and rice by 38–45% without fertilization ($P < 0.05$). The soil N contents were also higher in the Anthrosol but the wide C-to-N ratios due to high soil C contents led to immobilization of N. Despite the generally high nutrient availability, nutrient leaching was minimal in the Anthrosol, providing an explanation for their sustainable fertility. However, when inorganic nutrients were applied to the Anthrosol, nutrient leaching exceeded the one found in the fertilized Ferralsol. Charcoal additions significantly increased plant growth and nutrition. While N availability in the Ferralsol decreased similar to the Anthrosol, uptake of P, K, Ca, Zn, and Cu by the plants increased with higher charcoal additions. Leaching of applied fertilizer N was significantly reduced by charcoal, and Ca and Mg leaching was delayed. In both the Ferralsol with added charcoal and the Anthrosol, nutrient availability was elevated with the exception of N while nutrient leaching was comparatively low.

Introduction

Upland soils in the humid tropics such as the Amazon basin are often highly weathered and therefore possess low plant-available nutrient contents (van Wambeke, 1992). This is a result of both high rainfall and low nutrient retention capacity. In these soils the cation exchange capacity is very low due to the dominance of iron and aluminum oxides and kaolinite as well as generally low soil organic matter contents and pH values. Applied nutrients are rapidly leached below the root zone of annual crops (Cahn et al., 1993; Melgar et al., 1992) and large amounts of nitrate (NO_3^-) were found to accumulate in acid subsoils (Cahn et al., 1992). In order to increase nutrient use efficiency, techniques must be developed to keep applied nutrients in the topsoil and therefore in the main root zone of the crop.

Two basic approaches can be used to reduce nutrient leaching; applying slow-release nutrient forms such as organic fertilizers and increasing adsorption

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sites thereby retaining applied inorganic nutrients. Animal manures and composts have shown in several trials to increase nutrient availability and to partly substitute mineral fertilizers (Goyal et al., 1999). How well organic amendments are effective for supplying sufficient nutrients for plant growth and for reducing leaching of applied mineral nutrients under high leaching conditions is far less clear. Additionally, organic fertilizers may mineralize rapidly and therefore have to be applied repeatedly to maintain sufficient available nutrients and exchange capacity.

In Central Amazônia, soils have been found with high organic matter contents of up to 150 g kg^{-1} which were created by pre-Columbian populations from 500 to 2500 years B.P. (Petersen et al., 2001; Smith, 1980; Woods et al., 2000). Their distribution stretches mainly along waterways from Eastern Amazônia to the central Amazon basin with sizes ranging from less than 1 ha to more than 100 ha (Smith, 1980). It is presently not entirely clear which types of organic applications are responsible for the observed increase in soil organic matter. These relict Anthrosols (so-called 'Terra Preta de Indio') have persisted over many centuries despite the prevailing humid tropical conditions and rapid mineralization rates. They are highly valued by farmers for their sustainable fertility and production potential. Despite the observed high cation exchange capacity and nutrient availability of the Anthrosols (Kern and Kämpf, 1989; Kern et al., 1999; Smith, 1980; Sombroek, 1966) no systematic research has been conducted to quantify crop nutrient uptake, production potential or nutrient movement in these soils. The question also remains how these soils maintain their fertility over long periods of time.

Applications of organic matter may be a feasible way to create sustainably fertile soils similar to the prehistoric Anthrosols. An additional option to manure and composts could be the application of charcoal to soil. Testing the addition of charred organic matter was stimulated by the fact that the described relict anthropogenic soils in the Amazon contain large amounts of pyrogenic C (Glaser et al., 2001) and charcoal may have been one of the amendments used by Amerindian populations. Burning is a common practice in tropical smallholder agriculture, and the main land use system in the Amazon region is shifting cultivation often following logging (Laurance, 1998). The aboveground biomass is usually slashed and afterwards burned to clear the agricultural field but also to add nutrients to soil resulting in increased nutrient availability during the first cropping seasons (Sanchez et al., 1983). The same land-clearing technique may be used to produce charcoal instead of largely burning the woody biomass.

In laboratory experiments, charcoal was shown to increase the cation exchange capacity of sandy soils from temperate regions (Tryon, 1948). The effect of charcoal additions on nutrient availability is not entirely clear and both increasing (Iswaran et al., 1980) as well as decreasing (Kishimoto and Sugiura, 1985) nutrient uptake and biomass production have been reported. No information is available about the effect of charcoal applications on nutrient retention and soil fertility of highly weathered soils in the humid tropics, and whether charcoal additions among other organic applications could produce similarly fertile soils as the relict Anthrosols found in the Amazon basin.

Therefore, we addressed the following objectives: (i) compare the fertility of an archaeological Anthrosol to a typical upland Ferralsol of the central Amazon basin; (ii) assess how these Anthrosols maintain their high nutrient availability; (iii) compare the effect of inorganic and organic amendments such as charcoal and manure on fertility and nutrient retention of a Ferralsol with those of an archaeological Anthrosol.

Materials and methods

The present study was carried out in greenhouse facilities of the Embrapa Amazônia Ocidental near Manaus, Brazil. We used two different soils for our experiments: (1) a Xanthic Ferralsol taken from a secondary forest (approximately 15 years old) with high clay contents (65%), medium organic C (39 g kg^{-1}) and N contents (31.7 g kg^{-1}); (2) a Fimic Anthrosol obtained from a farmers field under fallow with low clay (5%) and high sand contents (85%), high organic C (84.7 g kg^{-1}), available P (318 mg kg^{-1}) and Ca contents (656 mg kg^{-1}), but low to medium total N (49.6 g kg^{-1}), available K (4.0 mg kg^{-1}) and Mg contents (57 mg kg^{-1}). Both soils have not been fertilized before they were collected. We conducted two different experiments (i) using pots which did not allow leaching of solutes and which were amended only with triple super phosphate ('pot experiment'), and (ii) using lysimeters which were free-draining and which received full fertilization ('lysimeter experiment').

Pot experiment

A bioassay was done using cowpea (*Vigna unguiculata* (L.) Walp.) as a test plant. The pots had a diameter of 0.2 m and were filled with 3 kg of either the Ferralsol or the Anthrosol. The soils received different inorganic and organic amendments with and without prior charcoal additions totaling to 19 treatments (Table 1). Only the Ferralsol received 10 and 20% (w/w) charcoal (67.6 and 135.2 Mg C ha^{-1}, respectively), which was produced by local farmers and originated from secondary forests. The charcoal was ground by hand to a grain size of about 1 mm. Additionally, amendments of 20% of charcoal pieces were tested which had a diameter of approximately 20 mm. The applied amounts of charcoal at 10% were in the range of projected charcoal yields from the aboveground woody biomass of Amazonian forests which calculate to 57–66 Mg C ha^{-1} (Table 2) for the topsoil (0–0.1 m) with an estimated mass loss of 46% C during charcoal production (Lehmann et al., 2002). Further studies are needed to show how much charcoal can be produced for secondary forests on site. The present study is designed to investigate if soil fertility can in principle be increased by charcoal additions in highly weathered tropical soil, and charcoal amounts were selected which reflected the higher range of possible amendments. The charcoal contained a total amount of 708 g C kg^{-1} and 10.9 g N kg^{-1}, 6.8 g P kg^{-1}, 0.32 g Mg kg^{-1}, 1.3 g Ca kg^{-1}, 0.89 g K kg^{-1}. Phosphorus fertilizer was added as triple super phosphate (TSP) at 135 kg P_2O_5 ha^{-1} (59 kg P ha^{-1}; recommendation for cowpea; Araujo et al., 1984, Embrapa Amazônia Ocidental, Manaus) at planting. Other elements were not supplied, since soil test levels were higher than the threshold values of applications for cowpea (Araujo et al., 1984, Embrapa Amazônia Ocidental, Manaus). The cattle and chicken manures were applied at 13 and 3.2 Mg ha^{-1}, respectively, to give the same amount of P than the mineral fertilizer. The chicken manure contained a total amount of 342 g C kg^{-1}, 27.9 g N kg^{-1}, 18.7 g P kg^{-1}, 5.4 g Mg kg^{-1}, 25.4 g Ca kg^{-1}, 6.2 g K kg^{-1}; the cattle manure 314 g C kg^{-1}, 16.2 g N kg^{-1}, 4.5 g P kg^{-1}, 6.5 g Mg kg^{-1}, 27.0 g Ca kg^{-1}, 4.8 g K kg^{-1} (total amounts of amendments determined by dry combustion or wet digestion).

Cowpea was sown in five planting holes per pot with three seeds per hole and thinned to one plant per hole after emergence. Soil water contents were kept at approximately 60% water holding capacity and were corrected daily. After 45 days, aboveground biomass was cut and the belowground biomass was hand-sorted from the soil. The biomass was dried at 70 °C for 48 h and weighed.

Lysimeter experiment

Free-draining lysimeters were constructed with a diameter of 0.2 m and a height of 0.1 m which were filled with either the Ferralsol or the Anthrosol. The effect of soil type, manure, mineral fertilizer and charcoal (Table 1) on growth, nutrient uptake and leaching was tested using rice (*Oryza sativa* L.) as a test plant. The amounts and composition of manure and charcoal (20%) were identical to those in the pot experiment described above. Fertilizer was applied at 30, 21.8, and 49.8 kg ha^{-1} for N, P, and K using ammonium sulfate, TSP, and KCl, respectively. Lime was applied at 2.1 Mg ha^{-1} (all recommendations for rice from Araujo et al., 1984, Embrapa Amazônia Ocidental, Manaus).

After the soil was filled into the lysimeters, water was gently poured on the soil at a daily rate of 6.85 mm (2500 mm year^{-1}) avoiding saturation at the soil surface. After 4 days the electrolyte content in the leachate had stabilized and fertilizer was added and the rice was planted similar to the cowpea. The water was applied and collected daily, but only selected samples were analyzed. Nutrient contents were determined daily for the first week, twice a week for 3 weeks and after 5 and 10 days. The sampling was stopped when the rice was cut at 37 days after planting. The amount of leachate was determined by weight and a subsample was retained for further analyses and frozen. Cumulative leaching for the entire experimental period was calculated from the measured leachates and amounts were interpolated linearly. Plant samples were dried at 70 °C for 48 h and weighed. Soil samples were taken after plant harvest, sieved to 2 mm and air-dried.

Chemical analyses

The aboveground biomass of both cowpea and rice was ground with a ball mill and analyzed for nutrients and organic C. Carbon and N analyses were performed with an automatic CN analyzer (Elementar, Hanau, Germany). The K, Ca, Mg, Fe, Zn, Cu contents in the plant biomass were determined after wet digestion with sulfuric acid using atomic absorption spectrometry (AA-400, Varian Associates, Inc., Palo Alto, CA). The P contents were measured photometrically

Table 1. Description of experimental treatments for the pot experiment (P) and the lysimeter experiment (L)

Treatment	No amendment	Mineral fertilizer	Cattle manure	Chicken manure	Mineral fertilizer+ chicken manure
Ferralsol	P, L	P, L	P, L	P, L	P, L
Ferralsol + 10% Charcoal	P	P		P	P
Ferralsol + 20% Charcoal	P, L	P, L		P, L	P, L
Ferralsol + 20% Charcoal (pieces)	P	P			
Anthrosol	P, L	P, L		P	P

in the same extract with the molybdenum blue method (Olsen and Sommers, 1982).

Total K, Ca, and Mg contents in soil were extracted with 5 M HNO_3 and concentrated $HClO_4$ at 200 °C. Plant available P and exchangeable cations were extracted using the Mehlich 1 extraction for P and K and 1 N KCl for Ca, Mg, and acidity according to Brazilian national recommendations (Embrapa, 1979). The effective cation exchange capacity was calculated as the sum of exchangeable cations and acidity (Embrapa, 1979). The K, Ca, and Mg contents in the leachate and in the extracts were measured using atomic absorption spectrometry. Nitrate (NO_3^-) and ammonium (NH_4^+) concentrations in the leachate were determined photometrically with a continuous flow analyzer (RFA-300, Alpkem Corp., Clackamas, OR and Scan Plus analyzer, Skalar Analytical B.V., Breda, The Netherlands) after reduction with Cd and reaction with salicylate, respectively.

Statistical analyses

Treatment effects were analyzed by analysis of variance (ANOVA) with a randomized complete block design (Little and Hills, 1978). Mean separation was done using the least significant difference test (LSD) (Little and Hills, 1978).

Results

Crop nutrition and biomass production

The mineral P fertilizer and equivalent amounts of manure did not result in higher above- or belowground biomass and nutrition of cowpea in comparison to the unfertilized control (Figure 1 and Table 3). Cattle manure had a similar effect on plant growth and nutrition as chicken manure ($P > 0.05$) and was therefore not shown. In contrast, a significant growth improvement was found for the Anthrosol and after charcoal amendments in the Ferralsol. Phosphorus fertilization increased foliar P contents, but not total P uptake (Table 3 and Figure 1). Nitrogen uptake of cowpea was significantly ($P < 0.05$) decreased by charcoal additions and in the Anthrosol (Figure 1), which was an effect of poor N nutrition (Table 3). Phosphorus nutrition and uptake increased when charcoal was added to the Ferralsol and for the Anthrosol. Charcoal amendments improved foliar K nutrition and uptake in contrast to the Anthrosol, whereas K nutrition was even significantly ($P < 0.05$) reduced in comparison to the control (Table 3). In contrast, Ca contents and uptake were higher for cowpea grown on the Anthrosol than with charcoal applications, which did not increase compared to the unamended control. The Mg contents and uptake of cowpea were reduced in both the charcoal amended soils and Anthrosols. Foliar Zn and Mn contents were improved in the Anthrosol ($P < 0.05$), whereas foliar Zn contents did not change and Mn contents decreased after charcoal application (Table 3). The effects on foliar Cu contents were variable and may indicate a slight increase in charcoal amended soils. Charcoal additions and Anthrosol had no effect on foliar Fe contents of cowpea. The differences between fertilizer and manure treatments within charcoal or Anthrosols were not significant ($P > 0.05$).

Increasing the amount of charcoal further increased above- and belowground biomass production (Figure 2). Similarly, P, K, Ca, Zn, and Cu uptake by cowpea increased. The N, Mg, and Mn nutrition did not decrease further when 20% instead of 10% charcoal were added to soil. Using charcoal pieces instead of ground charcoal did not affect the results with the exception of Mn uptake which improved significantly (Figure 2).

Table 2. Aboveground live biomass of secondary and primary forests in Amazonia and potential charcoal yield from woody biomass

Region	Type	Age	Total biomass ($Mg\ ha^{-1}$)	Woody biomass ($Mg\ ha^{-1}$)	Wood C content[1] (%)	Charcoal yield[2] ($Mg\ C\ ha^{-1}$)	Source
Rondonia, Pará, Brazil	2nd regrowth	4	134.2	119.6	49.6	31.7	Hughes et al. (2000)
Rondonia, Pará, Brazil	3rd regrowth	4	90.6	72.7	49.6	19.3	Hughes et al. (2000)
San Carlos,	SF	5	40.1	35.2	nd	8.5	Uhl and Jordan (1984)
Pará, Brazil	SF[3]	3.5	16.3	12.9	nd	3.1	Buschbacher et al. (1988)
Pará, Brazil	SF[3]	8	35.0	30.4	nd	7.3	Buschbacher et al. (1988)
Pará, Brazil	SF[4]	8	86.5	81.8	nd	19.7	Buschbacher et al. (1988)
Pará, Brazil	SF	2.3	22.2	16.5	nd	4.0	Gehring et al. (1999)
Pará, Brazil	SF	4	20	15	nd	3.6	Kato et al. (1999)
Pará, Brazil	SF	10	52	44	nd	10.6	Kato et al. (1999)
Pará, Brazil	SF	10	54.9	49.8	47.3	12.6	Johnson et al. (2001)
Pará, Brazil	SF	20	65.5	59.2	47.9	15.2	Johnson et al. (2001)
Pará, Brazil	SF	40	128.8	119.8	47.6	30.5	Johnson et al. (2001)
San Carlos, Venezuela	PF	–	261.0	252.3	nd	60.7	Uhl and Jordan (1984)
Manaus, Brazil	PF	–	264.6	251.2	48.9	65.7	Fearnside et al. (1993)
Pará, Brazil	PF	–	262.5	222.3	49.1	58.3	Fearnside et al. (1999)
Rondonia, Brazil	PF	–	272.2	260.0	44.4	63.5	Graça et al. (1999)
Pará, Brazil	PF	–	256.7	247.6	48.8	59.9	Mackensen et al. (2000)
Pará, Brazil	PF	–	229.6	225.1	47.3	57.0	Johnson et al. (2001)

[1]Where no information was available, C contents were estimated at 45%.
[2]Calculated using 53.5% as conversion of wood biomass C to charcoal C from Lehmann et al. (2002).
[3]With previous pasture use of moderate intensity.
[4]With previous pasture use of low intensity.
SF – secondary forest; PF – primary forest; nd – not determined.

The effect of charcoal amendments and Anthrosol on N, P, K, Mg, Fe, Mn, and Cu were similar for rice (data not shown) and for cowpea. However, foliar Ca and Zn contents of rice were not higher when grown in the Anthrosol compared to the control ($P > 0.05$). Ammonium sulfate and lime did not improve rice N, Ca or Mg nutrition irrespective of charcoal amendments or soil type. Foliar P, S, and K contents were, however, significantly ($P < 0.05$) improved by fertilization (data not shown).

Soil chemical properties

The Anthrosol contained twice as much soil C compared to the Ferralsol (Table 4). Charcoal amendments to the Ferralsol, however, resulted in the highest soil C contents which were doubled compared to the Anthrosol. In contrast, total N contents did not increase in the same order of magnitude, which is reflected by higher C-to-N ratios in charcoal-amended Ferralsols (41.6) than the Anthrosol (17.2) than the Ferralsol without charcoal (12.7). The Anthrosol had a higher ($P < 0.05$) pH value than the Ferralsol. Fertilization and liming significantly ($P < 0.05$) increased the pH, similar to the amendment with charcoal. However, soil available P contents were not significantly higher after fertilization. The Anthrosol showed a significantly higher P availability by one order of magnitude. Extractable K contents were higher in fertilized than unfertilized soil and even higher in Ferralsols amended with charcoal ($P < 0.05$). Potassium and Mg availabilities were lower and Ca availability was higher in the Anthrosol than in the Ferralsol ($P < 0.05$). Neither P, Ca, nor Mg contents were higher when charcoal was added to soil. The extractable Al contents were effectively reduced by both liming and charcoal additions. Manuring had no significant effect on soil chemical properties apart from a reduction of exchangeable Al.

Table 3. Above and below ground biomass production and foliar nutrient contents of cowpea (*Vigna unguiculata*) grown with applications of mineral and organic fertilizers and charcoal in pots without leaching using a Xanthic Ferralsol and a Fimic Anthrosol in the central Amazon; values in one column followed by the same letter are not significantly different at $P < 0.05$ ($N = 5$)

Treatment	Shoot biomass (g pot^{-1})	Root biomass (g pot^{-1})	N (g kg^{-1})	P (g kg^{-1})	K (g kg^{-1})	Ca (g kg^{-1})	Mg (g kg^{-1})	Fe (mg kg^{-1})	Zn (mg kg^{-1})	Mn (mg kg^{-1})	Cu (mg kg^{-1})
F	2.3 c	0.44 cd	51.9 a	2.00 cd	23.6 b	9.02 cd	7.56 ab	167	41.6 bc	176 c	2.6 d
F + Fert	2.2 d	0.46 cd	55.2 a	2.53 ab	25.3 b	9.04 cd	7.72 a	165	40.6 c	176 c	5.2 abc
F + Manure	1.9 d	0.48 cd	52.9 a	2.03 cd	25.8 b	9.01 cd	7.50 ab	162	43.0 bc	184 c	5.8 abc
F + Manure + Fert	2.6 bcd	0.36 d	52.5 a	2.85 a	24.3 b	9.38 c	7.18 b	337	44.6 b	205 abc	4.2 bcd
F + Charcoal	3.3 ab	0.42 d	23.9 b	1.96 d	33.1 a	8.17 cd	3.67 cd	116	41.2 bc	73.6 d	5.6 abc
F + Charcoal + Fert	2.9 bc	0.48 cd	24.9 b	2.27 bcd	34.8 a	7.88 cd	3.40 d	148	38.4 c	76.4 d	5.6 abc
F + Charcoal + Manure	3.5 ab	0.44 cd	23.4 b	2.32 bcd	35.7 a	7.45 d	3.32 d	77.8	39.8 c	69.6 d	7.0 a
F + Charcoal + Fert + Manure	3.7 a	0.44 cd	24.6 b	2.36 bcd	36.4 a	7.66 d	3.48 d	142	40.8 bc	77.8 d	4.6 ab
A	3.7 a	0.84 a	21.9 b	2.42 abc	17.3 c	13.2 ab	3.96 c	139	51.8 a	205 abc	6.8 ab
A + Fert	3.3 ab	0.62 b	24.1 b	2.65 ab	14.6 c	14.2 ab	3.92 c	168	55.0 a	244 a	3.2 cd
A + Manure	3.4 ab	0.68 b	22.5 b	2.33 bcd	16.9 c	12.7 b	3.72 cd	190	53.2 a	191 bc	2.2 d
A + Fert + Manure	2.9 bc	0.60 bc	23.5 b	2.52 ab	12.7 c	14.5 a	4.00 c	125	54.4 a	226 ab	2.8 d

F – Ferralsol; A – Anthrosol; Fert – fertilized with TSP; Manure – additions of chicken manure; Charcoal – applications at 10% weight.

Table 4. Soil carbon and nutrient contents, pH, acidity and cation exchange capacity of a Xanthic Ferralsol and a Fimic Anthrosol amended with inorganic and organic fertilizers and charcoal (only Ferralsol) after rice (*Oryza sativa*) ($N = 4$)

Treatment	C ($g\ kg^{-1}$)	N ($g\ kg^{-1}$)	C/N	pH (H_20)	P ($mg\ kg^{-1}$)	K ($mmol_c\ kg^{-1}$)	Ca ($mmol_c\ kg^{-1}$)	Mg ($mmol_c\ kg^{-1}$)	Al ($mmol_c\ kg^{-1}$)	CEC ($mmol_c\ kg^{-1}$)
Ferralsol	39.7 d	3.17 c	12.6 c	5.14 e	8.1 c	28.1 e	14.8 e	8.8 de	2.3 a	54.0 e
F+Fert	39.2 d	3.03 c	12.9 c	5.93 b	16.9 c	168.8 d	32.1 c	20.1 b	0.2 de	221.1 d
F+Manure	37.8 d	3.02 c	12.5 c	5.16 e	8.1 c	35.8 e	15.0 e	9.8 d	1.7 c	62.3 e
F+Manure+Fert	39.5 d	3.09 c	12.8 c	5.80 cd	21.0 c	189.3 cd	36.1 b	22.5 a	0.0 e	247.8 bcd
F+Charcoal	159.4 b	3.95 b	40.4 b	5.89 bc	10.5 c	258.3 ab	17.1 e	9.7 d	0.4 d	285.5 bc
F+Charcoal+Fert	156.2 ab	3.92 b	39.8 b	6.29 a	24.1 c	296.7 a	27.5 d	15.3 c	0.0 e	339.4 a
F+Charcoal+ Manure	169.0 a	3.88 b	43.6 a	5.80 cd	9.5 c	220.0 bc	13.9	7.4 e	0.5 d	241.7 cd
F+Charcoal+Fert +Manure	171.1 a	4.00 b	42.7 a	6.22 a	20.0 c	258.3 ab	27.9 d	15.8 c	0.0 e	301.9 ab
Anthrosol	84.7 c	4.96 a	17.1 d	5.71 d	318.4 b	10.2 e	32.8 c	4.7 f	2.0 b	49.7 e
A+Fert	85.0 c	4.93 a	17.2 d	5.93 b	386.1 a	173.9 d	50.6 a	22.2 a	0.0 e	246.7 bcd

F – Ferralsol; Fert – fertilized with TSP, KCl and lime; Manure – additions of chicken manure; Charcoal – applications at 20% weight; A – Anthrosol.

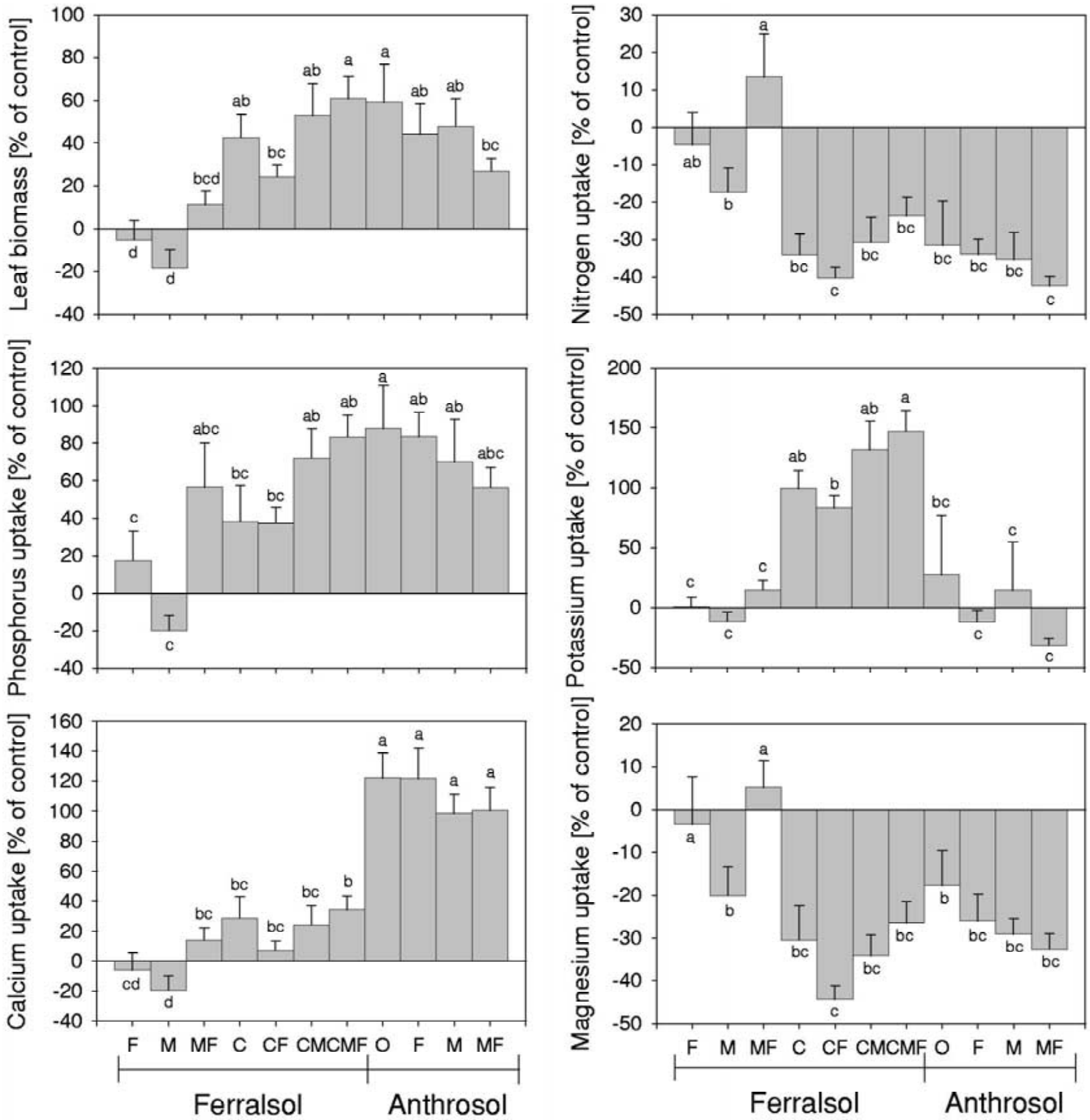

Figure 1. Biomass production and nutrient uptake by cowpea (*Vigna unguiculata*) amended with inorganic and organic fertilizers and charcoal on a Xanthic Ferralsol and a Fimic Anthrosol in relation to the control (no amendments to Xanthic Ferralsol); O no amendment, F fertilized, M animal manure, C charcoal; bars with the same letter are not significantly different at $P < 0.05$; means and standard errors ($N = 5$).

Nutrient leaching

The amount of nutrient leaching was largely a result of nutrient input, nutrient uptake or retention, but not a result of varying water percolation, which did not differ between soil amendments during the first 15 days (Figure 3). Differences in cumulative water percolation at the end of the experiment were caused by higher water uptake of plants with more vigorous growth. Therefore, the cumulative amount of water leached from the soil correlated with the biomass production and not with soil amendments, with the notable exception of the Anthrosol (Figure 3).

Nutrient leaching of NH_4^+ and Mg was significantly ($P < 0.05$) lower in the unfertilized Anthrosol than the Ferralsol (Figure 4). Manure additions did not significantly ($P < 0.05$) affect leaching results and were therefore not shown. Charcoal additions increased leaching of K, but not that of Ca and Mg. Nutrient leaching increased during the first 10–20 days

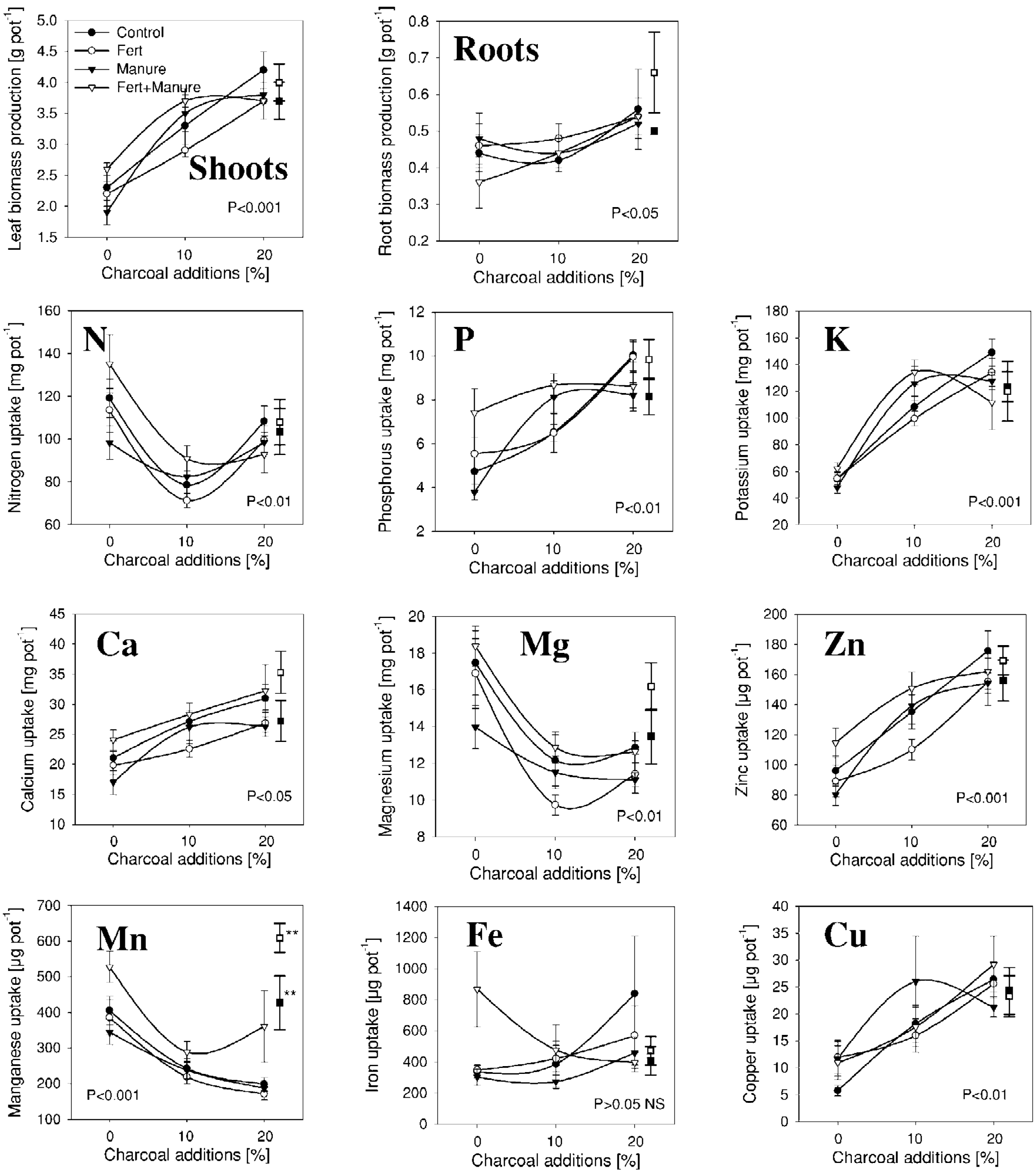

Figure 2. Effects of the amount of charcoal amendments on biomass production and nutrient uptake by cowpea (*Vigna unguiculata*) grown on a Xanthic Ferralsol; analysis of variance tests the significance of increasing charcoal amendments; fertilized (■) and not fertilized (□) amendment of 20% charcoal as pieces (no manure added); ** significant effects of charcoal size (pieces or ground); means and standard errors ($N = 5$).

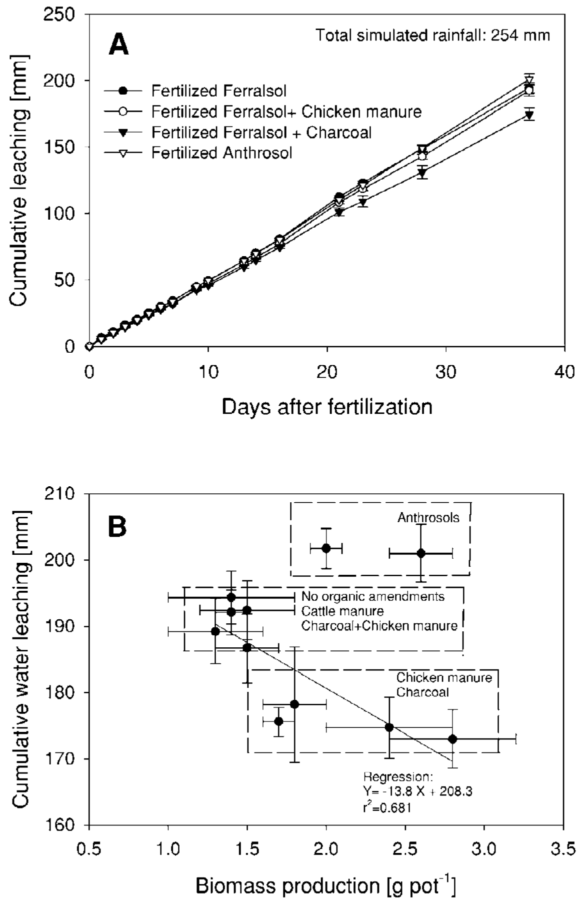

Figure 3. (A) Cumulative water leaching and (B) relationship between biomass production of rice (*Oryza sativa*) and total leached water from lysimeters filled with a Xanthic Ferralsol and a Fimic Anthrosol amended with inorganic and organic fertilizers and charcoal (only Ferralsol); means and standard errors ($N = 4$); regression was done without the Anthrosols.

after fertilizer application, longer for K and shorter for Ca. Fertilization caused intensive leaching of K when charcoal was applied to the Ferralsol. Calcium leaching after fertilization was significantly higher in the Anthrosol than the Ferralsol, whereas it was reverse for Mg. Leaching of NH_4^+ was significantly ($P < 0.05$) lower from both fertilized and unfertilized Ferralsols when charcoal was applied. Nitrate leaching, on the other hand, was higher with than without charcoal, but showing very low total amounts of leaching. Charcoal additions did not significantly ($P < 0.05$) reduce total Ca or Mg leaching from the fertilized Ferralsol. However, during the first week after fertilizer application leaching losses of both Ca and Mg were significantly ($P < 0.05$) reduced due to the charcoal additions.

Figure 5 shows the percentage of inorganic N, K, Ca, and Mg leached or taken up by the plant into aboveground biomass in relation to the total soil contents at planting. Whereas the proportions of N and Ca uptake was little affected by the soil amendments, K and Mg show a marked response. Fertilization with K was very effective and proportionally increased K uptake. The reverse was found for Mg (and a trend for Ca) and the proportion of Mg uptake from limed soil decreased. Applied N and K were mobile in soil and the proportion of leaching increased in fertilized treatments. Whereas charcoal applications decreased the proportion of leached N and Ca, K and Mg were unaffected by charcoal additions. The unfertilized Anthrosol showed high ratios of uptake-to-leaching for all investigated nutrients. After fertilization, however, leaching increased more than uptake and the ratios decreased. For all nutrients, the ratios of nutrient uptake-to-leaching increased when charcoal was applied to soil.

Discussion

Fertilizer and manure effects on plant production

Both mineral fertilizer and manure did not increase plant production suggesting that either the amounts applied were too low or that one or several nutrients limiting plant growth were not supplied by the fertilizers. In Western and Central Amazônia, long-term experiments have shown that mineral fertilizer is principally able to sustain crop production (Cravo and Smyth, 1997; Sanchez et al., 1983). Possibly higher amounts of K and additions of micronutrients could have improved crop performance in our study. The manures were applied at a rate which were shown to be too low to meet plant demands for nutrients. In a recent field experiment, large yield increases of 5.5 times of fertilized rice could be found with an application of 69 Mg ha^{-1} of chicken manure (C. Steiner, pers. comm.) and similar results are available for a compost application of 30 Mg ha^{-1} to green pepper in a lysimeter experiment (Trujillo, 2002).

Nitrogen nutrition may not have been critical for improving crop growth as foliar N levels were 50% lower in the crops grown on the Anthrosol, whereas at the same time biomass production was higher on the Anthrosol than on the Ferralsol. However, P and K

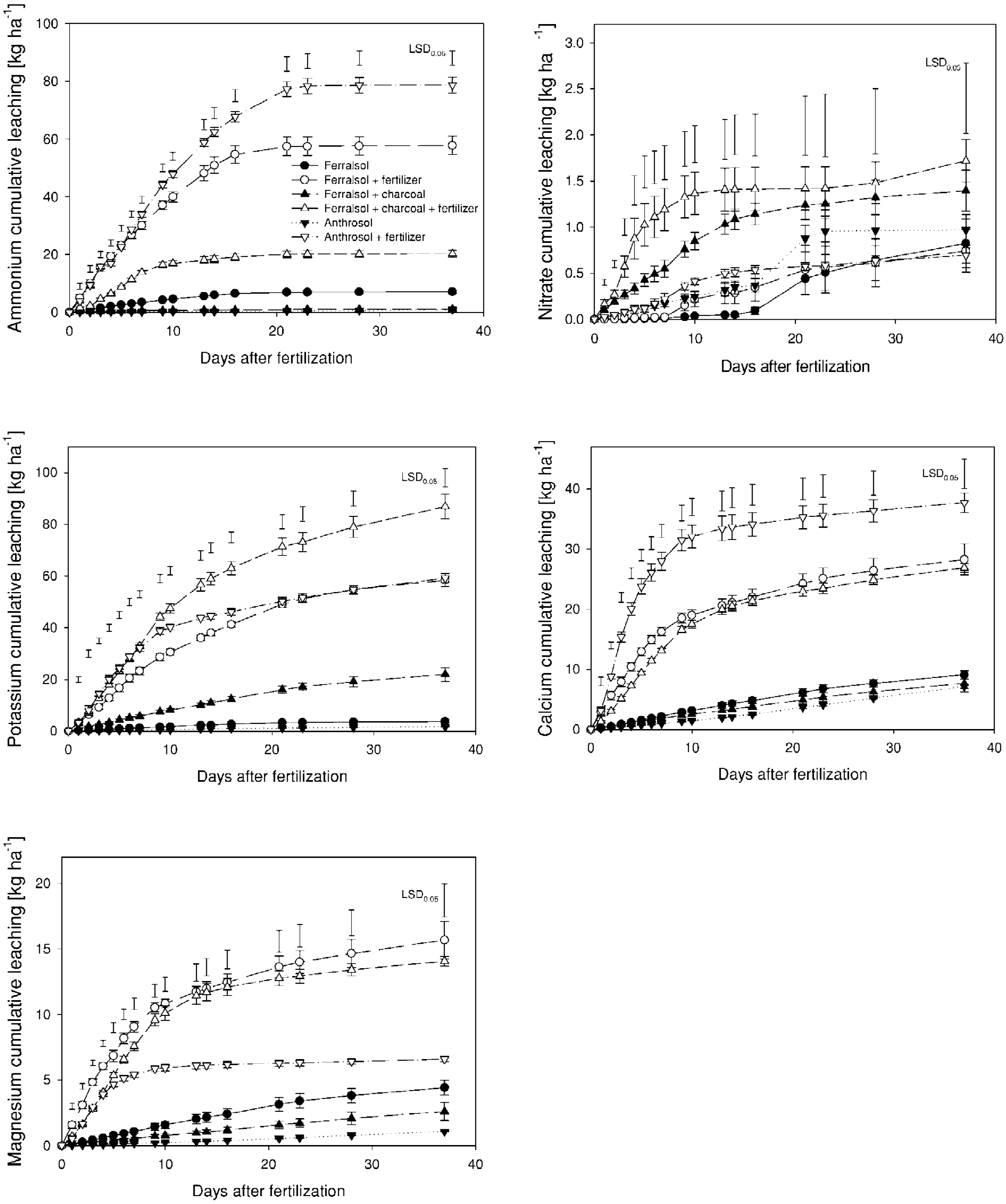

Figure 4. Cumulative nutrient leaching in a Xanthic Ferralsol and a Fimic Anthrosol amended with inorganic fertilizers and charcoal (only Ferralsol) cropped to rice (*Oryza sativa*) determined with lysimeters in the greenhouse during 38 days); means and standard errors ($N = 4$).

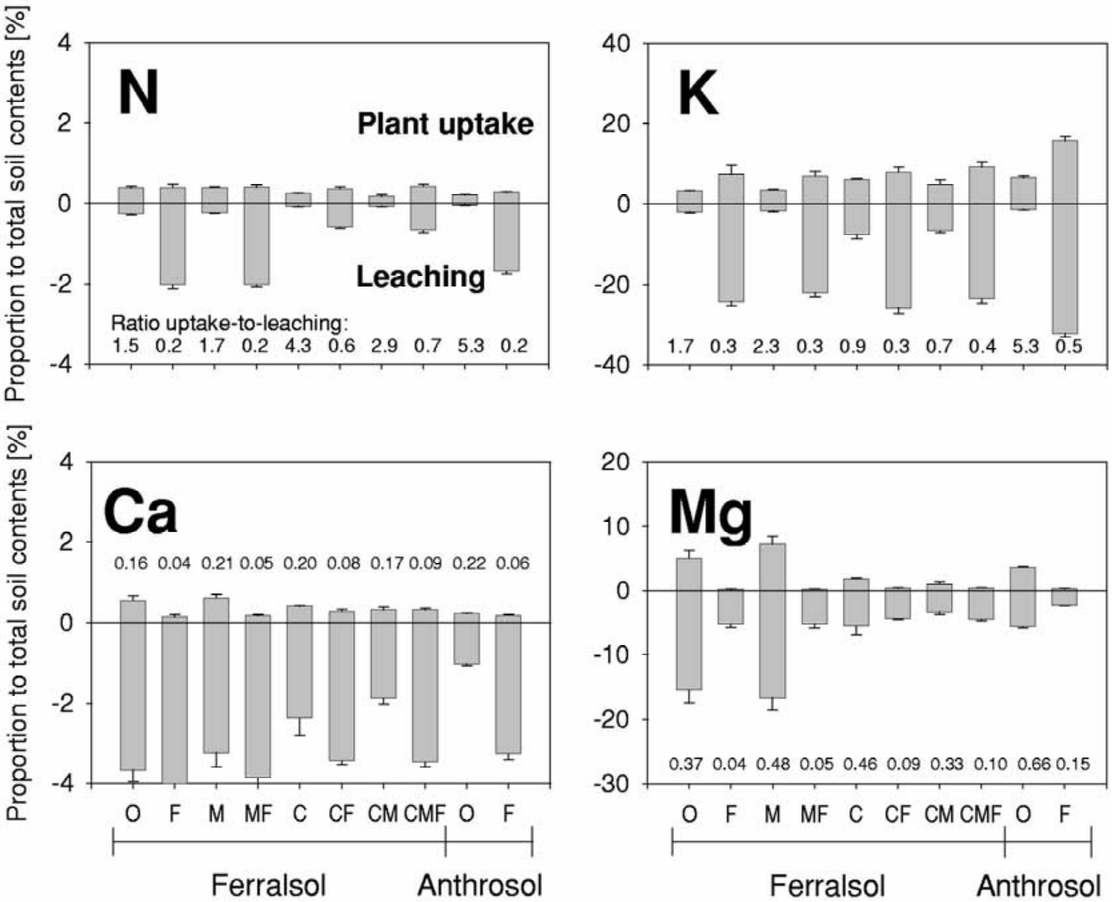

Figure 5. Proportion of N, K, Ca, and Mg uptake by rice (*Oryza sativa*) and cumulative leaching to the total amount of the respective nutrient in the soil at the beginning of the experiment and ratio of uptake-to-leaching in a Xanthic Ferralsol and a Fimic Anthrosol amended with inorganic and organic fertilizers and charcoal (only Ferralsol); O no amendment, F fertilized, M animal manure, C charcoal; only inorganic N was considered in the leachate; means and standard errors ($N = 4$).

additions were important for plant development which is in agreement with earlier studies for cowpea, maize and rice at the same site (Cravo and Smyth, 1997; Smyth and Cravo, 1990). Especially K proved very mobile in soil and large amounts of up to 30% of the amount present in fertilized soil were rapidly leached. The retention of K should be specifically targeted with slow-releasing nutrient additions or improved adsorption capacity of the soils. Similar to our study, Cahn et al. (1993) and Melgar et al. (1992) showed large leaching of NO_3^-, Ca and Mg using repeated soil sampling in nearby Ferralsols. For a Ferralsol in subhumid Togo, Poss and Saragoni (1992) reported leaching of 40–150 kg N ha^{-1} year^{-1}, 50–150 kg Ca ha^{-1} year^{-1}, and 13–60 kg Mg ha^{-1} year^{-1} from maize being larger for N but lower for Ca and Mg than in our soils.

Soil fertility of an archaeological Anthrosol

The higher crop growth in the Anthrosol compared to the Ferralsol was largely an effect of an improved P availability. Also beneficial for plant performance may have been higher soil Ca and micronutrient levels, especially Zn and Mn. Elevated P and Ca (Kern and Kämpf, 1989; Smith, 1980; Sombroek, 1966) as well as Zn and Mn availability (Kern et al., 1999) have been frequently reported from various Anthrosols of prehistoric origin in the Amazon. The total N contents were higher in the Anthrosol than the Ferralsol, but N availability was low due to a high C-to-N ratio. However, the low N availability did not seem to reduce crop growth. In contrast to the potential cation exchange capacity (Sombroek, 1966), the effective cation exchange capacity was not higher in the Anthrosol than the Ferralsol, which resulted in low retention of applied nutrients and high leaching. The high fertility of the prehistoric Anthrosols may have been more related to nutrient release from successively available soil pools than high ion contents at exchange sites. Without fertilization, the leachate in the Anthrosols had extremely low concentrations of nutrients while nutrient availability was high compared to the Ferralsol. Low leaching at high nutrient availability ensures sustainable soil fertility. These results coincide with observations made by Petersen et al. (2001) who found Anthrosols in Western Amazônia which have been under continuous cultivation without fertilization for 40 years.

The demonstrated properties of the relict anthropogenic soils have important implications for soil management of Ferralsols indicating that organic applications can be used for sustainable crop production under humid tropical conditions. On the other hand, these results also imply that such Anthrosols should not be fertilized with inorganic nutrients but organic applications be continued.

Charcoal amendments for increasing soil fertility

Similar to the Anthrosol, charcoal applications to the Ferralsol led to a lower N availability due to high C-to-N ratios. The increased biomass production and nutrient uptake are mainly a result of direct nutrient additions with the added charcoal, especially of K, but also of P, Ca, Zn and Cu. At the same time, also the nutrient losses were relatively low. The soil K contents increased by one order of magnitude and exceeded those of fertilized soils, whereas the leaching losses in charcoal-amended soils were less than half of that in fertilized soils. Furthermore, the leaching of applied fertilizer NH_4^+ and in the first week Ca and Mg could be reduced by charcoal and the ratio of uptake to leaching increased for all nutrients upon charcoal application indicating a high efficiency of nutrients applied with charcoal. It has not been clearly demonstrated how charcoal amendments can aid in retaining nutrients. Several possibilities exist: (i) the creation of sites for electrostatic adsorption; (ii) the retention of soil water and therefore nutrients contained in it. Our results showed that charcoal did not decrease water percolation, and nutrient retention was therefore caused by adsorption to an exchange complex created by the charcoal additions. Similarly, Tryon (1948) could show that charcoal from both hardwood and softwood increased the cation exchange capacity by up to 50%. It must be born in mind, however, that the surface properties of the charcoal vary greatly depending on the organic matter used for making the charcoal and the charring environment such as temperature and O_2 supply (Glaser et al., 1998; Schmidt and Noak, 2000; Strazhesko et al., 1975; Tryon, 1948).

Particle size of charcoal

The size of the charcoal pieces amended to soil had only minor effects on nutrient uptake and biomass production of cowpea. This could mean that either the surface area or the amount of nutrients supplied with the charcoal were sufficient with larger pieces or that either of the two factors was not important for increasing crop growth in the studied soil. We can assume that nutrient retention was not an important reason for the increased nutrient uptake and growth of cowpea, since nutrient leaching was negligible from the pots and the contents for those nutrients who could be supplied by the charcoal were high. This may change after several cropping seasons and more intense leaching, and should be tested in long-term field experiments.

Secondly, the amount of nutrients supplied with charcoal pieces may have been sufficient for plant growth, either because the total amount of ground charcoal already exceeded plant demands or because nutrients contained inside the charcoal pieces were available to the plants. The latter effect is corroborated by our observations that plant roots were found to be clustered around the charcoal pieces or even sometimes grow into charcoal pieces indicating that nutrient availability in the charcoal was high and plants could access them. Nutrients may have been leached or moved by diffusion from the inside of the charcoal pieces into the rhizosphere.

Effect of the amount of charcoal on soil fertility

The amounts of charcoal added were clearly critical for the effects on crop growth and nutrition. Already at charcoal additions of 10% (w/w) plant growth improved significantly and larger quantities added further increased biomass production. This amount corresponds to a C addition of 67.6 Mg C ha^{-1} by charcoal, which is at the upper range of possible charcoal yields (58.3–65.7 Mg C ha^{-1}) by the aboveground woody biomass of primary forests in Amazônia which were calculated from various references in Table 2. Potential charcoal yields of secondary forests, however, were much more variable and calculated to

3.1–31.7 Mg C ha^{-1} (Table 2). Already at an application of 13.3 Mg C ha^{-1} charcoal seedlings of *Inga edulis* Mart. grew as rapidly as those amended with 67 Mg C ha^{-1} or with full fertilization (Lehmann et al., 2002). For sustained growth and yield over several seasons, however, additional nutrients need to be applied. Such a land use technique of charcoal production and application to soil is only sensible, if the charcoal is produced from the same fallow vegetation which would be burned anyways for forest clearing. Plot trials must be conducted to test whether the positive results for plant nutrition and growth obtained in this greenhouse experiment can be replicated in the field. Charcoal amendments may not be feasible on the large scale but could be especially suitable for high-value crops and are at present used in nurseries (Jaenicke, 1999) and in raised gardens in Amazônia (W. Woods, pers. comm.).

Additionally, charcoal can be found in many soils of the Amazon basin as a result of anthropogenic activities or natural fires (Bassini and Becker, 1990; Fearnside et al., 1993, 1999; Glaser et al., 2000; Sanford et al., 1985). As much as 80% of the soils investigated by Sanford et al. (1985) in southern Venezuela showed charcoal pieces with a total weight of 5–14 Mg DM ha^{-1}, calculating to approximately 4–12 Mg C ha^{-1}. Therefore, charcoal is abundant in such quantities in soils of the Amazon that would lead us to expect an effect on plant growth and nutrition. Charcoal is not only present as large pieces in soils but also fine particles of less than 20 μm (Glaser et al., 2000). Haumaier and Zech (1995) provided evidence that a large portion of the stable C pool in soil is present as so-called black carbon and may have derived from charred organic matter. Skjemstad et al. (1997) reported high amounts of stable black carbon in grassland soil which had been frequently burned. Black carbon has become an important research subject (Schmidt and Noack, 2000) due to its likely importance for the global biogeochemical C cycle (Kuhlbusch and Crutzen, 1995). However, charred organic matter and black carbon in terrestrial soils have not been evaluated regarding their importance for nutrient supply and retention in soil. Long-term studies with charcoal applications are needed to evaluate their effects on sustained soil fertility and nutrient dynamics.

Acknowledgements

We thank the staff at the Embrapa, Manaus, Marcia Pereira de Almeida and Luciana Ferreira da Silva for their commitment in experimental setup and sample analysis. Funds were provided by Cornell University and by the Brazilian-German cooperation through the SHIFT program (BMBF and Cnpq No. 0339641 5A).

References

Bassini F and Becker P 1990 Charcoal's occurrence in soil depends on topography in terra firme forest near Manaus, Brazil. Biotropica 22, 420–422.

Buschbacher R, Uhl C and Serrao EAS 1988 Abandoned pastures in eastern Amazonia II. Nutrient stocks in the soil and vegetation. J. Ecol. 76, 682–699.

Cahn M D, Bouldin D R and Cravo M S 1992 Nitrate sorption in the profile of an acid soil. Plant Soil 143, 179–183.

Cahn M D, Bouldin D R, Cravo M S and Bowen W T 1993 Cation and nitrate leaching in an oxisol of the Brazilian Amazon. Agron. J. 85, 334–340.

Correia A A 1988 Conversão quimica de madeiras da Amazônia – Carvão e briquettes de carvão vegetal. Acta Amazonica 18, 97–107.

Cravo M S and Smyth T J 1997 Manejo sustentado da fertilidade de um latossolo da amazônia central sob cultivos successivos. R. Bras. Ci. Solo 21, 607–616.

Embrapa 1979 Manual de métodos de análise de solo. Serviço Nacional de Levantamento e Conservação de Solos, Rio de Janeiro, Brazil. 220 p.

Fearnside P M, Leal N and Fernandes F M 1993 Rainforest burning and global carbon budget: biomass, combustion efficiency, and charcoal formation in the Brazilian Amazon. J. Geophys. Res. 98, 16,733–16,743.

Fearnside P M, Graça P M L A, Filho N L, Rodrigues F J A and Robinson J M 1999 Tropical forest burning in Brazilian Amazonia: measurement of biomass loading, burning efficiency and charcoal formation at Altamira, Pará. For. Ecol. Manage. 123, 65–79.

Gehring C, Denich M, Kanashiro M and Vlek PLG 1999 Response of secondary vegetation in Eastern Amazonia to relaxed nutrient availability constraints. Biogeochemistry 45, 223–241.

Glaser B, Haumaier L, Guggenberger G and Zech W 1998 Black carbon in soils: the use of benzenecarboxylic acids as specific markers. Org. Geochem. 29, 811–819.

Glaser B, Balashov E, Haumaier L, Guggenberger G and Zech W 2000 Black carbon in density fractions of anthropogenic soils of the Brazilian Amazon region. Org. Geochem. 31, 669–678.

Glaser B, Haumaier L, Guggenberger G and Zech W 2001 The Terra Preta phenomenon – a model for sustainable agriculture in the humid tropics. Naturwissenschaften 88, 37–41.

Goyal S, Chander K, Mundra M C and Kapoor K K 1999 Influence of inorganic fertilizers and organic amendments on soil organic matter and soil micobial properties under tropical conditions. Biol. Fertil. Soils 29, 196–200.

Graça PMLA, Fearnside PM and Cerri CC 1999 Burning of Amazonian forest in Ariquemes, Rondônia, Brazil: biomass, charcoal formation and burning efficiency. For. Ecol. Manage. 120, 179–191.

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

Hughes RF, Kauffman JB and Cummings DL 2000 Fire in the Brazilian Amazon 3. Dynamics of biomass, C, and nutrient pools in regenerating forests. Oecologia 124, 574–588.

Iswaran V, Jauhri K S and Sen A 1980 Effect of charcoal, coal and peat on the yield of moong, soybean and pea. Soil Biol. Biochem. 12, 191–192.

Jaenicke H 1999 Good tree nursery practices: practical guidelines for research nurseries. International Centre for Research in Agroforestry, Nairobi, Kenya. 93 pp.

Johnson CM, Vieira ICG, Zarin DJ, Frizano J and Johnson AH 2001 Carbon and nutrient storage in primary and secondary forests in eastern Amazônia. For. Ecol. Manage. 147, 245–252.

Kato MSA, Kato OR, Denich M and Vlek PLG 1999 Fire-free alternatives to slash-and-burn for shifting cultivation in the eastern Amazon region: the role of fertilizers. Field Crops Res. 62, 225–237.

Kern D C and Kämpf N 1989 Antigos Assentamentos indigenas na formação de solos com terra preta arqueológica na região de Oriximina, Pará. Rev. Bras. Ci. Solo 13, 219–225.

Kern D C, Lima da Costa M and Frazao F J 1999 Geoquímica de sítio arqueológico com terra preta no céntro da cidade de Quatipuru-PA. *In* VI Symposium on Geology of the Amazon, Manaus. pp. 408–411.

Kishimoto S and Sugiura G 1985 Charcoal as a soil conditioner. *In* Symposium on Forest Products Research International Achievements for the Future 5: 12/23/1–12/23/15.

Kuhlbusch T A J and Crutzen P J 1995 Toward a global estimate of black carbon in residues of vegetation fires representing a sink of atmospheric CO_2 and a source of O_2. Global Biogeochem. Cyc. 9, 491–501.

Laurance W F 1998 A crisis in the making: responses of Amazonian forests to land use and climatic change. Trends Ecol. Evol. 13, 411–415.

Lehmann J, Silva Jr J P, Rondon M, Cravo M S, Greenwood J, Nehls T, Steiner C and Glaser B 2002 Slash-and-char – a feasible alternative for soil fertility management in the central Amazon? *In* Proceedings of the World Congress of Soil Science, 2002, Thailand. (In press).

Little T M and Hills F J 1978 Agricultural Experimentation. John Wiley and Sons, New York, USA. 350 pp.

Mackensen J, Tillert-Stevens M, Klinge R and Fölster H 2000 Site parameters, species composition, phytomass structure and element stores of a terra-firme forest in East-Amazonia, Brazil. Plant Ecol. 151, 101–119.

Melgar R J, Smyth T J, Sanchez P A, and Cravo M S 1992 Fertilizer nitrogen movement in a Central Amazon Oxisol and Entisol cropped to corn. Fertil. Res. 31, 241–252.

Olsen S R and Sommers L E 1982 Phosphorus. *In* Methods of Soil Analyses: Part 2 Chemical and Microbiological Properties. Eds. A L Page et al. pp. 403–430. Am. Soc. Agron., WI, USA.

Petersen J B, Neves E G and Heckenberger M J 2001 Gift from the past: Terra preta and prehistoric amerindian occupation in Amazonia. *In* Unknown Amazonia. Ed. C McEwan. pp. 86–105. British Museum, London, UK.

Poss R and Saragoni H 1992 Leaching of nitrate, calcium and magnesium under maize cultivation on an oxisol in Togo. Fertil. Res. 33, 123–133.

Sanchez P A, Villachia J H and Bandy D E 1983 Soil fertility dynamics after clearing tropical rainforest in Peru. Soil Sci. Soc. Am. J. 47, 1171–1178.

Sanford R L, Saldarriaga J, Clark K E, Uhl C and Herrera R 1985 Amazon rain-forest fires. Science 227, 53–55.

Schmidt M W I and Noack A G 2000 Black carbon in soils and sediments: Analysis, distribution, implications, and current challenges. Global Biogeochem. Cyc. 14, 777–793.

Skjemstad J A, Clarke P, Golchin A and Oades J M 1997 Characterization of soil organic matter by solid-state ^{13}C NMR spectroscopy. *In* Driven by Nature: Plant Litter Quality and Decomposition. Eds. G Cadisch and K E Giller. pp. 253–271. CAB International, Wallingford, UK.

Smith N J H 1980 Anthrosols and human carrying capacity in Amazonia. Ann. Assoc. Am. Geog. 70, 553–566.

Smyth T J and Cravo M S 1990 Phosphorus management for continuous corn-cowpea production in a Brazilian Amazon Oxisol. Agron. J. 82, 305–309.

Sombroek W 1966 Amazon Soils – a reconnaissance of soils of the Brazilian Amazon region. Centre for Agricultural Publications and Documentation, Wageningen, The Netherlands. 292 p.

Strazhesko D N, Tarkovskaya I A, Zavyalov A N, Kislitsyn A N, Divnich L F and Goba V E 1975 Study of the sorption and ion exchange properties of oxidized wood charcoals. Adsorbtsiya Adsorbenty 3, 8–13. (In Russian)

Truijillo L 2002 Fluxos de nutrientes em solo de pastagem abandonada sob adubação orgânica e mineral na Amazônia Central. MSc thesis, Instituto Nacional de Pesquisa da Amazonia, Manaus, Brazil. 87 pp.

Tryon E H 1948 Effect of charcoal on certain physical, chemical, and biological properties of forest soils. Ecol. Monogr. 18, 81–115.

Uhl C and Jordan CF 1984 Succession and nutrient dynamics following forest cutting and burning in Amazonia. Ecology 65, 1476–1490.

Van Wambeke A 1992 Soils of the Tropics. McGraw-Hill, New York. 343 pp.

Woods W, McCann J M and Meyer D W 2000 Amazonian dark earth analysis: state of knowledge and directions for future research. *In* Papers and Proceedings of Geography Conferences Vol. 23. Eds F A Schoolmaster and J Clark. pp. 114–121. Tampa, FL.

Section editor: A.A. Meharg