Slash-and-char: a feasible alternative for soil fertility management in the Central Amazon?

LEHMANN Johannes (1), **DA SILVA Jose Pereir Jr.** (2), **RONDON Marco**(1), **DA SILVA Cravo Manoel** (3),**GREENWOOD Jacqueline** (1), **NEHLS Thomas** (4), **STEINER Christoph** (4) **and GLASER Bruno** (4)

(1) College of Agriculture and Life Sciences, Department of Crop and Soil Sciences, Cornell University, Ithaca, NY 14853, USA
(2) Embrapa Amazonia Ocidental, 69011-970 Manaus, Brazil
(3) Embrapa Amazonia Oriental, Belem, Brazil
(4) Institute of Soil Science, University of Bayreuth, 95440 Bayreuth, German

Abstract

The application of charcoal to nutrient-poor upland soils of the central Amazon was tested in lysimeter studies in comparison to unamended control to evaluate the effects of charcoal on plant nutrition and nutrient leaching. Testing the application of charred organic matter was stimulated by the fact that anthropogenic soils in the Amazon (so-called "Terra Preta") with high soil organic matter contents contain large amounts of pyrogenic carbon. These soils also show high cation exchange capacity and nutrient availability. Charcoal additions significantly increased biomass production of a rice crop in comparison to a control on a Xanthic Ferralsol. This increase was largely an effect of improved P, K, and possibly Cu nutrition, whereas N and Mg uptake decreased in charcoal amended soils. In order to improve crop growth, fertilizer applications of N, S, Ca, and Mg may be necessary in addition to charcoal for optimizing rice growth. Combined application of N with charcoal resulted in a higher N uptake than what would have been expected from sole fertilizer or charcoal applications. The reason is a higher nutrient retention of applied ammonium by the charcoal amended soils. Charcoal applications therefore acted in two ways, first as a direct fertilizer and secondly as an adsorber which retained N. The amount of charcoal which can be produced from forest biomass is significant and corresponds to charcoal amounts needed for effectively improving crop growth. The slash-and-char technique is an alternative to burning of the above ground biomass and only the biomass from the same cropping area will be used for charring. Field trials need to be conducted to investigate the efficiency of charcoal production and applications under field conditions.

Keywords: Amazon, humid tropics, Ferralsols, leaching, nutrient cycling, slash-and-burn

Introduction

Upland soils in the humid tropics such as in the Amazon are highly weathered and therefore possess low plant available nutrient contents (Cravo and Smyth, 1997). This is a result of both high rainfall and low nutrient retention capacity. Applied nutrients are rapidly leached below the root zone of annual crops (Melgar *et al.,* 1992; Cahn *et al.,* 1993). Two basic approaches can be used to reduce nutrient leaching, first to apply slow-releasing nutrient forms such as organic fertilizers or secondly to increase adsorption sites and thereby retain applied inorganic nutrients.

Slash-and-burn is one of the main land use system in the Amazon. Secondary or primary forest is cut and burned to clear the field but also to release plant-available nutrients from slashed plant biomass. The ash from the burn increases soil pH and supplies nutrients to crops which show elevated nutrition and yields (Sanchez *et al.,* 1983). This effect of the ash accumulation is, however, rather short-lived. Already after a few cropping seasons the soil nutrient availability decreases and field crops have to be fertilized for optimum production (Sanchez *et al.,* 1983). Although adequate applications of mineral fertilizers were shown to sustain yields in the Amazon (Smyth and Cassel, 1995), our efforts are intended to improve the use of biomass and nutrients contained in the plant biomass as well as that of applied fertilizer nutrients, since fertilization is expensive and crop production often has to rely on soil nutrients alone.

It is well known that about 50% of the carbon in the above ground biomass of forests can be lost upon burning (Kauffman *et al.,* 1995). Sixty and 43% of the biomass N and S and 18, 7 and 7% of the P, Ca, and K were lost from the site (Kauffman *et al.,* 1995). A large portion may be deposited or absorbed in surrounding ecosystems but does not contribute to the fertility of the cropped soil. The first approach should therefore aim at improving the efficiency of land clearing to preserve C and nutrients. Slash-and-mulch was successfully tested in eastern Amazonia when fertilizer was applied (Kato *et al.,* 1999) and has a long history in the per-humid tropics (Thurston, 1997). We are seeking an alternative technique that can be applied to the existing slash-and-burn system with minimal changes and that has the potential of being used in tree cultures as well.

Anthropogenic Dark Earths-Evidence of Sustainable Soil Management

Instead of burning the above ground biomass to clear the agricultural field, the biomass may be charred to produce charcoal and added to soil. Testing the application of charred organic matter was stimulated by the fact that anthropogenic dark soils in the Amazon (so-called "Terra Preta") with high soil organic matter contents contain large amounts of pyrogenic carbon (Glaser *et al.,* 2000). These soils also show high cation exchange capacity, nutrient availability and organic matter (Sombroek, 1966; Kern and Kämpf, 1989). The origin of the dark earths is not entirely clear, and several conflicting theories were discussed in the past. Currently the most convincing theory states that these soils were not only used by the local population but a product of indigenous soil management as proposed by Gourou (1949).

Soil fertility increases have been observed on remnants of charcoal hearths in the Appalachian Mountains (Young *et al.,* 1996). Tryon (1948) showed higher nutrient availability in clayey to sandy soils from the Western United States after additions of charcoal produced from conifer and hardwood. Coal from geological deposits were successfully tested for the improvement of soil physical properties (Piccolo *et al.,* 1996). No information is available about the effects of charcoal applications on nutrient availability of highly weathered soils in the humid tropics such as the central Amazon. It is also unclear whether the cation exchange capacity can be improved thereby leading to higher nutrient retention and to lower nutrient losses by leaching.

A slash-and-char technique does not advocate the destruction of existing primary forests. It should be a carbon-and nutrient-conserving alternative to the existing slash-and-burn technique. In this way, carbon will rather be retained in the system compared to slash-and-burn, since only the biomass from the same cropping area will be used for producing the charcoal.

Charcoal Additions for Soil Fertility Improvement

Experimental description

Pot experiment

A greenhouse study was carried out at the Embrapa Amazonia Ocidental near Manaus, Brazil. The mean temperature in the greenhouse was between 28-32ºC. 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 prior to the 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 3 kg of the Ferralsol or the Anthrosol. The effect of soil type, mineral fertilizer and charcoal on growth, nutrient uptake and leaching was tested using rice (*Oryza sativa* L.) as a test plant. Charcoal was applied at 20% weight which was produced by local farmers originating from secondary forests. The charcoal was ground by hand to a grain size of about 1 mm. Fertilizer was applied 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) Circular Técnica 18, Embrapa, unpublished).

After the soil was filled into the lysimeters, water was gently poured onto the soil at a daily rate of 6.85 mm (2500 mm y^{-1}). After four days the electrolyte content in the leachate had stabilized and fertilizer was added and rice was planted in 5 stands per pot. The water was applied and drained daily, but only selected samples were analyzed. Nutrient contents were determined daily for the first week, twice a week for three 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 70ºC for 48 hours and weighed.

In a second pot experiment, seedlings of *Inga edulis* were planted in pots with 26 cm diameter and 10 dm^3 soil (Xanthic Ferralsol) in four replicates. Charcoal was added at 0, 1, 5, 10 and 20% weight corresponding to 0, 13.3, 66.7, 133.4 and 266.7 Mg C ha^{-1} (C concentration of charcoal 70.8%). Fertilizer was applied at 100 kg N ha^{-1}, 50 kg P ha^{-1}, and 60 kg K ha^{-1} as urea, triple super phosphate and KCl, respectively. Additionally, 2 Mg ha^{-1} lime were added. Stem diameter was determined at 5cm above soil level, and tree height was measured including the length of the uppermost leaf at 80 day after planting.

Adsorption experiment

In a laboratory experiment, we studied the adsorption of different nutrients by charcoal. The charcoal was made from the wood of black locust (*Robinia pseudoacacia*). Cubes of dried wood with 10 g were isothermically combusted in closed metal containers at 350ºC for 40 minutes (65 replicates). Wood and charcoal were weighed with an accuracy of 0.1%. The charcoal was ground coarsely with mortar and pestle to pass a 2 mm sieve. One gram of charcoal was added to 10 mL of solution containing 0, 20, 50, 100, 200 mg L^{-1} using 20-mL PE bottles. In a preliminary experiment, the adsorption dynamics were determined for 10, 30 minutes, 1 and 6 hours, 1 and 3 days and 1 week using a horizontal shaker. Adsorption changed until 1 day, but did not differ thereafter. Therefore, adsorption experiments were done with a shaking time of one day. The effect of coating with dissolved organic matter (DOC) was tested with a manure extract. Ten grams cow manure were shaken with 20 mL deionized water and filtered. The filtrate was diluted 50 times and 10 mL of the solution was shaken with 1 g of charcoal for 24 hours. Afterwards the same adsorption experiment with different concentrations only of NH_4^+ was performed as described above with and without additions of 10% azide to inhibit microbial activity.

Chemical analyses

The aboveground biomass of rice was ground with a ball mill and analyzed for nutrients and organic carbon. C 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 in the same extract with the molybdenum blue method.

The K, Ca, and Mg contents in the leachate and adsorption solution were measured using atomic absorption spectrometry, nitrate (NO_3^-) and ammonium (NH_4^+) concentrations 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.

Statistics

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

Charcoal as a fertilizer

Charcoal additions increased biomass production of a rice crop by 17% in comparison to a control on a Xanthic Ferralsol (Figure 1). This increase was largely an effect of improved P, K, and possibly Cu nutrition. Nitrogen and Mg uptake decreased in charcoal amended soils which resembled the uptake pattern of rice grown on an Amazonian dark earth (Fimic Anthrosol; Figure 1). Charcoal additions had no significant effects on S, Ca, Fe, Zn, and Mn uptake ($P>0.05$). In addition to charcoal, fertilization was necessary with N, S, Ca, and Mg for optimizing rice growth.

The soil fertility improvement of the dark earth was largely an effect of enhanced P, Ca, and micronutrient availability such as Mn and Cu. Crop nutrition of S and K was not better and that of N and Mg was even lower in rice grown on a dark earth in comparison to the Ferralsol. Fertilization was necessary for those elements and was effective in increasing total nutrient uptake (Figure 1).

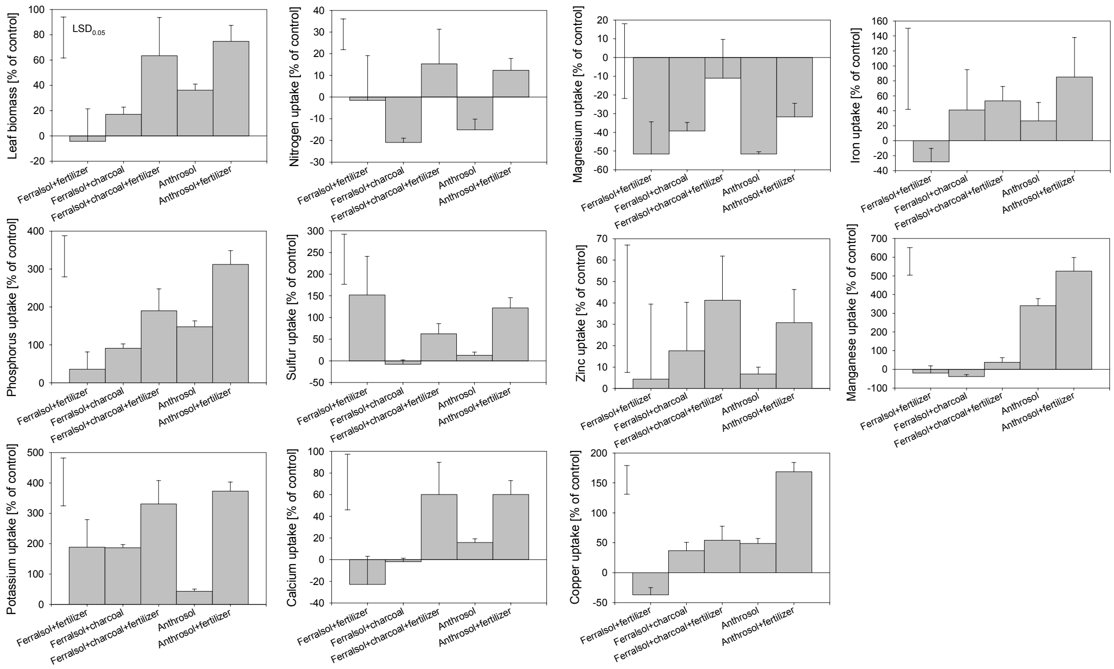

Figure 1 Biomass production and nutrient uptake by rice (*Oryza sativa*) after additions of charcoal and fertilizer on grown on a Xanthic Ferralsol or a Fimic Anthrosol after 37 days (means and standard errors; N = 4).

Therefore, charcoal directly amended the soil with plant-available nutrients such as P, K, and Cu. If fertilizer was applied together with the charcoal some nutrients showed a higher uptake efficiency than the added effects of fertilization and charcoal amendment would suggest. This was the case for N, Ca, and Mg. In the following we discuss the reasons for a higher efficiency of a combined application.

Charcoal as an adsorber

Under the high leaching conditions in upland soils of the central Amazon, reduction of nutrient losses by leaching is an important aim in order to improve nutrient availability for plants. Immediately after fertilizer application, nutrient contents significantly increased as shown for ammonium (Figure 2) and leveled off to background levels only 21 days after fertilization. This was also the case with K, Ca, and Mg (data not shown).

Leaching from the unfertilized Ferralsol was reduced when charcoal was applied and resembled the low values found in the Anthrosol (Figure 2). Ammonium concentrations in the leachate were also significantly lower in the fertilized Ferralsol after charcoal applications. These results indicate that ammonium was adsorbed by the charcoal and elevated N uptake by rice after the combined application of charcoal and fertilizer (Figure 1) was an effect of ammonium retention. This retention could not be found for other cations or anions, because K, Ca, and Mg were in higher supply with charcoal additions. After several cropping cycles, the nutrients in the charcoal may be depleted and results may differ from those shown here. Since N was applied as ammonium, nitrate contents in the leachate were controlled by biological transformation rather than physical adsorption.

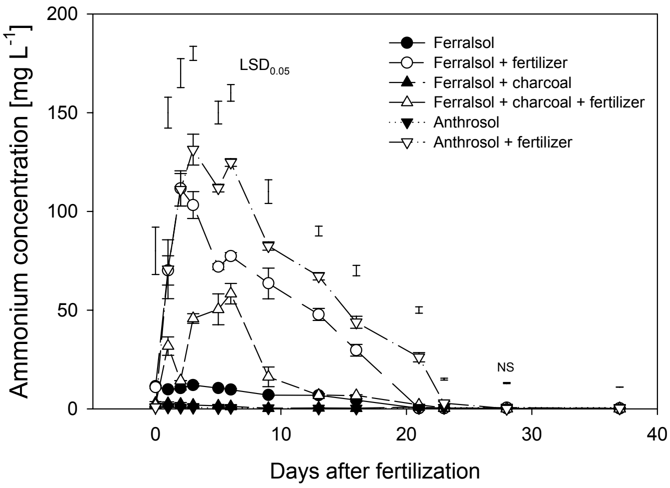

Figure 2 Ammonium concentration in the leachate of a Xanthic Ferralsol amended with charcoal and fertilizer compared to a Fimic Anthrosol; main effects significant at $P<0.001$ apart from one (NS not significant $P>0.05$) (means and standard errors; N=4).

In accordance with the leaching results, only ammonium was adsorbed by charcoal (Figure 3) whereas all other nutrients (P as PO_4^{2-}, Ca, Mg, K) showed higher concentrations in the equilibrium solution than added (data not shown). The process of adsorption is largely a co-adsorption with soluble organic matter, as an addition of dissolved organic carbon (DOC) from a manure extract increased ammonium adsorption. A microbial immobilization or nitrification during shaking can be excluded, since the adsorption was similar when microbial activity was suppressed by additions of azide (Figure 3).

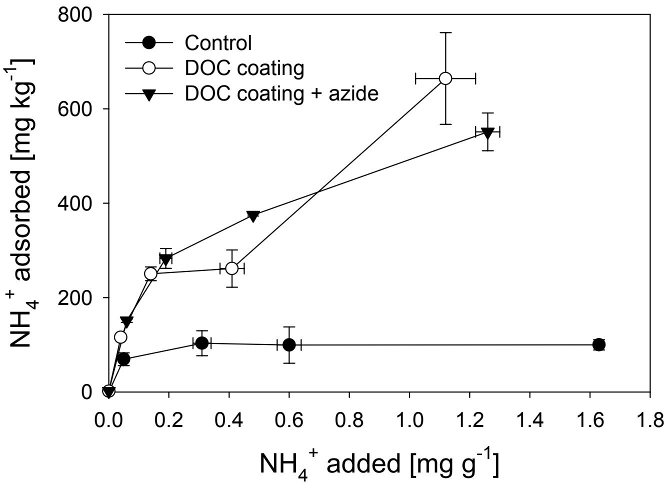

Figure 3 Ammonium adsorption by charcoal produced from black locust (*Robinia pseudoacacia*) in comparison to charcoal coated with manure or additional suppression of microbial activity using 10% azide (means and standard errors; N=2).

Slash-and-char in smallholder agriculture

If a slash-and-char technique is to be successful, (i) the quantity of applied charcoal must be produced from the same area of land which is to be cropped, and (ii) the periods of charcoal production must at least correspond to those of land clearing practiced so far. In other words, the slash-and-char technique must work with the same resources as conventional methods and be an alternative to slash-and-burn or slash-and-mulch. The amount of charcoal which can be produced from different forest vegetation primarily depends on the woody biomass available, and additionally on the production procedure such as charring environment (e.g., oxygen), temperature and time (e.g., Glaser *et al.,* submitted). The average recovery of charcoal mass from woody biomass is 31% according to the published data compiled in Table 1. The effect of different charcoal production methods on its recovery in agricultural fields is not well known and the charring environment such as temperature and charring time is usually poorly documented. The carbon contents of charcoal do not vary much and lie around 63-83% with a mean of 76% (Table 1). The carbon recovery from charred woody biomass is relatively high with 54% (Table 1) due to the high carbon contents of charcoal.

Table 1 Biomass conversion into charcoal.

Tree species	Charring temperature (°C)	Production method	Charcoal recovery by weight (%)	n	Charcoal carbon content (%)	Carbon yield[1] (%)	Source
Acacia mangium	450	laboratory furnace	37.9	60	76.4	64.4	Lelles *et al.* (1996)
Eucalyptus grandis	470	laboratory furnace	33.8	60	80.7	60.6	Vital *et al.* (1986)
Eucalyptus camaldulensis	450	laboratory furnace	32.4	25	76.3	54.9	Vital *et al.* (1994)
Deciduous trees	500	laboratory furnace	30.2	8	84.7	56.8	Zhurinsh (1997)
Pinus sylvestris	300	laboratory furnace	21.6		62.8	30.1	Glaser *et al.* (1998)
Robinia pseudoacacia	350	laboratory furnace	33.2	65	71.3	52.6	this study
Leucaena leucocephala	not given	metal kiln	27.4		83.1	50.6	San Luis *et al.* (1984)
Coconut trunk	not given	metal kiln	25.0		77.8	43.2	San Luis *et al.* (1984)
Mixed tropical wood, Manaus, Brazil	not given	brick kiln	41[3]		74.8	68.2	Correa (1988)
Miombo woodland[2]	not given	earth kiln	23.3		n.d.	-	Chidumayo (1991)
Mixed tropical hardwood	not given	earth pit	nd		69.0	-	FAO (1985)
Average			30.6		75.7	53.5	

[1] Percentage of charcoal carbon from the carbon in wood. Assuming 45%C in wood; determined for *R. pseudoacacia* at 45.7%.

[2] Total conversion of 93% of the woody biomass from a miombo woodland, representing 97% of the total above ground biomass.

[3] Calculating a conversion of 16 m^3 to 9 m^3 with a density of 0.7 and 0.51 Mg m^{-3} for wood and charcoal, respectively.

Several published values of above ground biomass from secondary and primary forests in the central Amazon show a high proportion of woody biomass (Table 2). Biomass of secondary forests increase with age but depend largely on site conditions and previous land use. Larger amounts of charcoal can be produced from primary (57-66 Mg C ha^{-1}) than secondary forests calculated with the average conversion from Table 1. But also secondary forests may produce charcoal equivalents of up to 32 Mg C ha^{-1}. The pot experiment shown in Figure 1 and 2 was conducted with a charcoal amount of 135 Mg C ha^{-1} (20% weight in 10cm depth), but also 67 Mg C ha^{-1} (10%) were shown to significantly improve biomass production of cowpea (Lehmann *et al.,* unpublished).

Table 2 Above ground live biomass of secondary and primary forests in the Amazon.

Region	Type	Age of forest	Total above ground biomass (Mg ha^{-1})	Woody biomass (Mg ha^{-1})	Wood C content[1] (%)	Charcoal yield from biomass[2] (Mg C ha^{-1})	Source
Rondonia and Para	2nd regrowth	4	134.2	119.6	49.6	31.7	Hughes *et al.* (2000)
Rondonia and Para	3rd regrowth	4	90.6	72.7	49.6	19.3	Hughes *et al.* (2000)
San Carlos, Venezuela	Secondary forest	5	40.1	35.2	nd	8.5	Uhl and Jordan (1984)
Paragominas, Para	Secondary forest[3]	3.5	16.3	12.9	nd	3.1	Buschbacher *et al.* (1988)
Paragominas, Para	Secondary forest[3]	8	35.0	30.4	nd	7.3	Buschbacher *et al.* (1988)
Paragominas, Para	Secondary forest[4]	8	86.5	81.8	nd	19.7	Buschbacher *et al.* (1988)
Zona Bragantina, Para	Secondary forest	2.3	22.2	16.5	nd	4.0	Gehring *et al.* (1999)
Zona Bragantina, Para	Secondary forest	10	54.9	49.8	47.3	12.6	Johnson *et al.* (2001)
Zona Bragantina, Para	Secondary forest	20	65.5	59.2	47.9	15.2	Johnson *et al.* (2001)
Zona Bragantina, Para	Secondary forest	40	128.8	119.8	47.6	30.5	Johnson *et al.* (2001)
Manaus, Amazonas	Primary forest	-	264.6	251.2	48.9	65.7	Fearnside *et al.* (1993)
Altamira, Pará	Primary forest	-	262.5	222.3	49.1	58.3	Fearnside *et al.* (1999)
Ariquemes, Rondonia	Primary forest	-	272.2	260.0	44.4	63.5	Graça *et al.* (1999)
Belem, Para	Primary forest	-	256.7	247.6	48.8	59.9	Mackensen *et al.* (2000)
Zona Bragantina, Para	Primary forest	-	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 the mean conversion of wood biomass to charcoal from Table 1.
[3] With previous pasture use of moderate intensity.
[4] With previous pasture use of low intensity.

In a pot experiment with *Inga edulis*, tree height and stem diameter significantly increased through the addition of charcoal (Figure 4; ANOVA P=0.041 and 0.007, respectively). Already at the lowest application rate (13.3 Mg C ha^{-1}), charcoal additions were equivalent to fertilizer applications. Therefore, the charcoal amounts produced from the same area of land which is used for cropping during one charring are sufficient for improving crop performance and for reducing nutrient leaching. Lower amounts of 7.9 Mg C ha^{-1} were shown to have only minor effects on rice yield in the first cropping season under field conditions (Steiner and Nehls, unpublished data) but more information is needed from field experimentation. With increasing charcoal additions, growth of *Inga* decreased when no fertilizer was applied but increased with fertilizer applications.

Charred organic matter from leaves was not accounted for in the calculation and the conversion to charcoal is currently not known. The contribution of leaves to charred organic matter from secondary or primary forests may be small, however, since the proportion of leaves in these forests usually lies below 10% (Table 2). Nevertheless the contribution to total nutrient input may be significant and has to be considered in nutrient budgets.

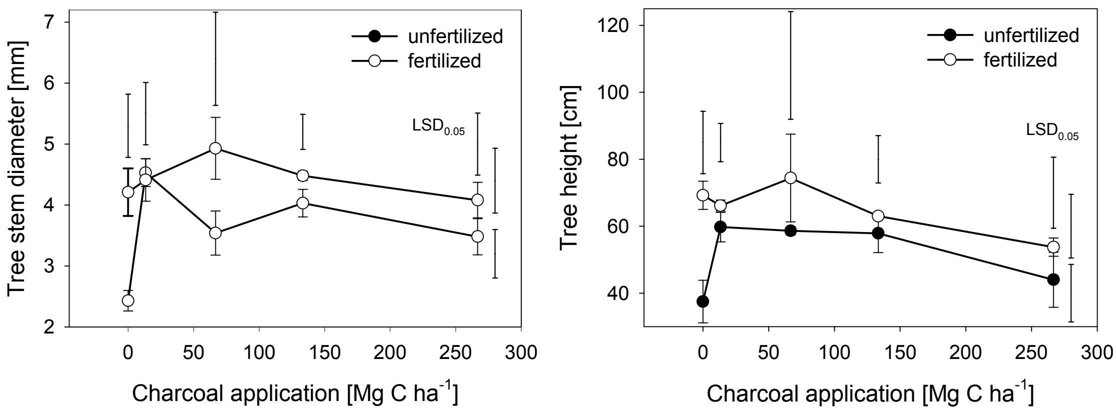

Figure 4 Tree growth of *Inga edulis* seedlings in pots amended with mineral fertilizer and increasing amounts of charcoal after 80 days (means and standard errors; N=4; Rondon *et al.,* unpublished data).

Conclusions

Charcoal applications directly increased nutrient availability such as P and K and additionally increased nutrient retention for ammonium. Whether a net nutrient retention of other cations occurs after excess nutrients have been leached or taken up by plants remains to be shown. In this respect the long-term dynamics of soil fertility with charcoal applications are very interesting in comparison to burning or mulching. It may be assumed that nutrients bound to charcoal are more persistent than those in ash or mulch but direct evidence needs to be gathered.

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