English Summary

Slash and Char as Alternative to Slash and Burn

Soil charcoal amendments maintain soil fertility and establish a carbon sink

Dissertation

Faculty of Biology, Chemistry and Geosciences
University of Bayreuth, Germany

Christoph Steiner

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Table of Co-authors and their contributions

Contributor	Chapter	Contribution
Christoph Steiner	I	Field work, data and sample collection, manuscript preparation
William I. Woods		Measurement of total nutrient contents, comments on the manuscript
Wenceslau G. Teixeira		Brazilian project partner, providing EMBRAPA research facilities
Wolfgang Zech		Project leader SHIFT ENV 45, Budget acquisition and advices
Sundari Narayan Swami	II	Field work, data collection, data analyzes and manuscript preparation
Christoph Steiner		Help and advices for the field work, data analyzes and manuscript preparation
Wenceslau G. Teixeira		Help and advices for the field work
Johannes Lehmann		Advices for the field work and comments on the manuscript
Christoph Steiner	III	Data collection, observations and preparation of the book chapter
Wenceslau G. Teixeira		Brazilian project partner, providing EMBRAPA research facilities
Wolfgang Zech		Project leader SHIFT ENV 45, Budget acquisition and advices
Christoph Steiner	IV	Study setup, respiration measurements, data collection and analyses, manuscript preparation
Keshav C. Das		Comments and contribution to the manuscript
Marcos Garcia		Brazilian project partner, providing EMBRAPA research facilities
Bernhard Förster		Introduction into IRGA SIR measurements, comments on the manuscript and data analyses
Wolfgang Zech		Project leader SHIFT ENV 45, Budget acquisition and advices
Christoph Steiner	V	Study setup, data collection, respiration measurement and manuscript preparation
Marcos Garcia		Brazilian project partner, providing EMBRAPA research facilities
Wolfgang Zech		Project leader SHIFT ENV 45, Budget acquisition and advices
Christoph Steiner	VI	Experimental setup, field work, data collection, sample analyses, manuscript preparation
Wenceslau G. Teixeira		Brazilian project partner, providing EMBRAPA research facilities
Johannes Lehmann		Advices for the study setup and data collection, comments on the manuscript
Thomas Nehls		Experimental setup, field work, data collection, sample analyses (first crop)
Jeferson L. V. de Macedo		Brazilian project partner, providing EMBRAPA research facilities (first crop)
Winfried E.H. Blum		Austrian Supervisor, Budget acquisition (ÖAW grant)
Wolfgang Zech		Project leader SHIFT ENV 45, Budget acquisition, advices and comments on the manuscript
Christoph Steiner	VII	Study setup, respiration measurements, data collection and analyses, book chapter preparation
Wenceslau G. Teixeira		Brazilian project partner, providing EMBRAPA research facilities
Johannes Lehmann		Advices for the field work and study setup, comments on the manuscript
Wolfgang Zech		Project leader SHIFT ENV 45, Budget acquisition and advices

Christoph Steiner	VIII	Study setup, sample collection, data analyses and manuscript preparation
Bruno Glaser		Sample analyzes (^{15}N), advices for data analyses and manuscript preparation
Wenceslau G. Teixeira		Brazilian project partner, providing EMBRAPA research facilities
Johannes Lehmann		Advices for the field work and study setup
Winfried E.H. Blum		Austrian Supervisor, Budget acquisition (ÖAW grant)
Wolfgang Zech		Project leader SHIFT ENV 45, Budget acquisition and advices
Julie Major	IX	Weed cover assessment, data analyses and preparation of the manuscript
Christoph Steiner		Study setup, soil nutrient contents, comments on the manuscript
Antonio DiTommaso		Advices for field work and comments on the manuscript
Newton P.S. Falcão		Brazilian project partner, providing INPA research facilities
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Christoph Steiner	X	Study setup (banana), soil respiration measurements, data analyses and manuscript preparation
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Wenceslau G. Teixeira		Study setup, soil nutrient contents (banana)
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Christoph Steiner	XI	Study setup, data collection and analyses, manuscript preparation
Wenceslau G. Teixeira		Study setup, data collection, soil physics
Wolfgang Zech		Project leader SHIFT ENV 45, Budget acquisition, advices and comments on the manuscript

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ABSTRACT

Introduction

Tropical forests account for between 20 and 25% of the world terrestrial carbon (C). Soils under tropical forest contain approximately the same amount of C as the lush vegetation above it. The current conversion of Amazonian forest to agricultural land makes disturbance of this C stock important to the global C balance and net greenhouse gas emissions. Changes in land use, particularly by clearing forests, reduce organic C by 20% to 50% in the upper soil layers. Furthermore, this reduction of soil organic matter (SOM) is causing soil degradation. Thus agriculture is not sustainable without nutrient inputs beyond 3 years of cultivation. The efficiency of conventional fertilizers (such as nitrogen (N)) is limited by a low nutrient retention capacity conjoined with strong tropical rains. On the other hand, large amounts of phosphate fertilizers are needed to overcome the soil's high P-fixation capacity.

To overcome these limitations, slash-and-burn agriculture (shifting cultivation) is practiced by about 300 to 500 million people, affecting almost one third of the planet's 1500 million ha of arable land. This traditional agricultural practice is considered to be sustainable if adequate fallow periods follow a short time of cultivation. In most agricultural systems the tendency has been for population pressure to increase, leading to shorter fallow periods, and therefore agriculture is doomed to fail without soil fertility management.

The existence of an anthropogenic and C-enriched dark soil in different parts of the world and especially in Amazonia (Amazonian Dark Earths (ADE) or *Terra Preta de Índio*) proves that the predominant Ferralsols and Acrisols can be transformed into fertile soils. The ADE's fertility is most likely linked to an anthropogenic accumulation of phosphorus (P), calcium (Ca), and black C as charcoal. Charcoal persists in the environment over centuries and is responsible for the stability of the ADE's SOM. Today and as assumed also in the past, those soils have been intensively cultivated by the native population.

Charcoal formation and deposition in soils seems to be a promising option to transfer an easily decomposable biomass into refractory SOM pools. However, charcoal represents just 1.7% of the pre-burn biomass if a forest is converted by the traditional slash-and-burn technique. The production of charcoal for soil amelioration purposes (slash and char) out of the aboveground biomass (secondary forest and crop residues) instead of converting it to carbon dioxide (CO_2) through burning (slash and burn) could establish a C sink and could be an important step towards sustainability and SOM conservation in tropical agriculture.

Objectives and Scope

The aim of this dissertation is to examine the use of charcoal in agricultural practice and management of a highly weathered Xanthic Ferralsol on *terra firme* north of Manaus (Brazil). This dissertation comprises field (chapters VI, VII, VIII, IX, X, and XI), greenhouse (chapter V) and laboratory experiments (chapter IV). In addition, data and information were gathered at local charcoal production sites (chapters II and III) and indigenous soil fertility management (chapter I) was observed and described. A socio-economic study on charcoal producers collected information on household economic activity, charcoal production technique, and efficiency. The feasibility of slash and char with and without carbon trade mechanisms for small farmers and the potential for carbon sequestration was discussed. The influence of charcoal and condensates from smoke (pyroligneous acid, PA) on the microbial activity was assessed in a pot experiment via measurements of substrate induced respiration (SIR). The effectiveness of charcoal as slow-release nutrient carrier (N, P, and K) was studied in a greenhouse experiment. In a field trial 15 different amendment combinations based on

equal amounts of applied C in chicken manure, compost, charcoal and forest litter were tested during four cropping cycles with rice (*Oryza sativa* L.) and sorghum (*Sorghum bicolor* L.) in five repetitions. We assessed the efficiency of applied nutrients and the influence on the soil microbial population. The influence of charcoal, organic and inorganic fertilization on perennial crops (*Musa sp., Paullinia cupana*) was assessed by measuring soil respiration and soil chemical properties. One trial was carried out on an expanding banana plantation in order to test the suitability of charcoal application in the local farming context.

Most important research findings

Fire and organic matter are the main components of indigenous soil fertility management (chapter I). Small fires are used to create burned soil (*Terra Queimada*), and burned organic materials (ash and charred residues) are used to increase the fertility in patches for medicinal plants and vegetables. After a burn (*Terra Queimada*) the soil had a strong scent of pyroligneous acid (*Terra Cheirosa*) which is stimulating soil microorganisms (chapters I and IV). Although most total nutrient contents in newly created *Terra Preta* (TPn) are below the average *Terra Preta* (TPp) contents, most (Ca, K, Mg, Zn, Mn) are within the range.

The investigation of socioeconomic aspects of charcoal production and carbon conversion efficiency (chapter II) could show that access to markets in the city enables charcoal producers to earn seven times more money from charcoal production than producers without access to markets. The most important reason (77% of respondents) for making charcoal is the inability to sustain agricultural activities at a profitable level. The average C conversion efficiency of the brick kilns was 42% (C in the wood feedstock converted to charcoal C) and the charcoal recovery by wood weight was 25%. Only about 3.7% of the C in the wood would be transferred into a refractory soil carbon pool if just the waste were used for soil amelioration at the production site. A further big proportion of waste is generated during marketing and bagging of charcoal which is usually collected for agricultural purposes at the city market. Considering the low charcoal production costs (~ 48 USD per ton) in shifting cultivation systems, much more charcoal could be used as soil amendment if profit from C emission trading could be generated.

The uses of charcoal production residues are manifold and reach from chicken fodder amendment to direct applications and the creation of charcoal compost. The production of charcoal is practiced as an alternative clearing method (slash and char), although charcoal is not always used for soil amelioration purposes, and if so, only the accumulated waste (powder and pieces) is used (chapter III).

When charcoal was applied in unweathered condition the microbiological parameters (respiration, biomass, population growth, and efficiency) increased linearly and significantly with increasing charcoal concentrations (50, 100 and 150 g kg^{-1} soil). Application of pyrogenous acid caused a sharp increase in soil respiration, biomass, and reproduction. We suppose that the condensates from smoke contain easily degradable substances which could be utilized by the microbes for their metabolism (chapter IV).

In a greenhouse experiment, leaching of N was significantly ($P < 0.05$) reduced if ammonium sulphate was applied with charcoal (chapter V). In contrast, leaching of K was significantly ($P < 0.05$) increased if potassium chloride was applied with charcoal, due to the charcoal's K content. At the end of the experiment soil N as well as soil K contents were significantly higher in the charcoal treatment. Charcoal simultaneously served as K fertilizer and increased the retention of N.

Long-lasting soil fertility improvement due to organic fertilization and a synergistic effect if both charcoal and mineral fertilizer were applied was observed in a field experiment (chapters VI, VII, VIII and IX). Chicken manure amendments resulted in the highest ($P < 0.05$) cumulative crop yield (12.4 Mg ha^{-1}) of four successive harvests. Most importantly, surface soil pH, P, Ca and magnesium (Mg) were significantly enhanced by chicken manure. Charcoal significantly improved plant growth and doubled grain production if fertilized with NPK in comparison to the NPK-fertilizer without charcoal ($P < 0.05$). Soil charcoal additions reduced exchangeable soil aluminium (Al) significantly.

The soil microbial population growth potential showed a significant positive correlation to nutrient availability in the soil and plant biomass production (chapter VII). Mineral fertilized soils amended with charcoal and *Terra Preta* soils had a significantly higher potential for microbial population growth coupled with a low microbial respiration in absence of an easily degradable C source (glucose). The soil respiration before substrate addition correlated positively with the population growth rate on the plots, whereas *Terra Preta* had a very low soil respiration and very high population growth after substrate additions. Forest soils had a higher respiration rate but a very low population growth. These results reflect the relatively high biodegradable OM content of primary forest topsoil but low available nutrients (requirement for microbial population growth), in contrast to refractory *Terra Preta* SOM with high available soil nutrient contents.

The ^{15}N recovery (chapter VIII) in biomass was significantly higher on compost-amended plots due to significantly higher biomass production. The retention in soil was significantly higher in the charcoal-amended plots after the second harvest due to higher N retention and cycling of crop residues which remained on the plots after harvesting. Total N recovery (in soil, crop residues and grains) was significantly ($P < 0.05$) higher on charcoal (18.1%), charcoal plus compost (17.4%), and compost (16.5%) treatments in comparison to only mineral fertilized plots (10.9%).

After abandonment of cropping, additions of inorganic fertilizer, compost, and chicken manure resulted in increases in weed ground cover of 40, 22 and 53%, respectively, and increases in species richness of 20, 48, and 63%, respectively (chapter IX). While charcoal additions alone did not significantly affect weed ground cover or species richness, a synergistic effect occurred when both charcoal and inorganic fertilizers were applied. The percentage ground cover of weeds was 45% within plots receiving inorganic fertilizer, 2% within plots receiving charcoal, and 66% within plots receiving both amendments.

The comparison of mineral and organic fertilization in perennial plantations (chapter X) showed that charcoal increased pH, total N, availability of sodium (Na), zinc (Zn), manganese (Mn), copper (Cu), humidity, and decreased available Al and acidity only in the mineral fertilized plantation. Decreased acidity due to charcoal application was also found in a banana plantation at a farm (chapter XI).

Conclusions

Charcoal is influencing soil quality in manifold ways, most importantly by reducing available Al and reducing acidity. Furthermore, charcoal adds K to the soil and has the potential to reduce N leaching. Charcoal amendments increased the reproduction rate of the microbial population after substrate addition whether the plot was fertilized or not. The effects of charcoal on soil biological, chemical and physical properties are complex, making it difficult to isolate single significant charcoal effects, but added up they caused significantly increased plant growth and crop production.

More information is needed on the agronomic potential of charcoal, the potential to use alternative biomass sources, and the production of by-products to evaluate the opportunities for adopting a slash and char system. The access to a global C trade mechanism would facilitate charcoal use for soil amelioration and thus would increase C sequestration and create a strong incentive to prevent further deforestation. Both of these actions would help to mitigate global climate change.

EXTENDED SUMMARY

Introduction

Tropical forests account for between 20 and 25% of the world terrestrial carbon (C) budget (Bernoux *et al.* 2001). Soils under tropical forest contain approximately the same amount of C as the lush vegetation above it. On average they contain 2.7% C in the surface horizons and 0.5% in the subsurface horizons to 100 cm depth (Sombroek *et al.* 2000).

The current rapid conversion of Amazonian forest to agricultural land makes disturbance of this C stock important to the global C balance and net greenhouse gas emissions. The net release of soil C was 8.5 Mg ha^{-1}, or 11.7 Gg of C for the 1.38 million hectares cleared in 1990. C emissions from soil alone as a result of deforestation in the Amazon represent a quantity of C approximately 20% as large as Brazil's annual emission from fossil fuels (Fearnside and Barbosa 1998).

Changes in land use, particularly by clearing forests, reduce organic C by 20% to 50% in the upper soil layers (Sombroek *et al.* 1993). This reduction of soil organic matter (SOM) is responsible for soil degradation. A slash-and-burn site investigated by Tiessen *et al.* (1994) had lost 81% of its litter layer and 29% of its soil C to 0.15 m depth over 3 years. Tiessen *et al.* (1994) concluded that the accelerated SOM decay under agriculture will lead to mineralization of over half the nutrients in 2 years. Thus agriculture is not sustainable without nutrient inputs beyond 3 years of cultivation, although the release of remaining nutrients can provide for the re-establishment of secondary successions (Tiessen *et al.* 1994).

On soils with low nutrient retention capacity the strong tropical rains easily leach available and mobile nutrients, such as those supplied by inorganic nitrogen (N) fertilizers, rapidly into the subsoil where they are unavailable for most crops (Giardina *et al.* 2000; Hölscher *et al.* 1997; Renck and Lehmann 2004) limiting the efficiency of conventional fertilizers.

Therefore slash-and-burn agriculture is practiced by about 300 to 500 million people, affecting almost one third of the planet’s 1500 million ha of arable land (Giardina *et al.* 2000; Goldammer 1993). This traditional agricultural practice is considered to be sustainable if adequate fallow periods (up to 20 years) follow a short time of cultivation (Kleinman *et al.* 1995). A growing population with changing socio-economic habits may not be able to practice slash-and-burn in a sustainable way. In most agricultural systems the tendency has been for population pressure to increase, leading to shorter fallow periods (Fearnside 1997).

Maintaining high levels of SOM in tropical soils would be a further step towards sustainability and fertility on tropical agricultural land, thus reducing the pressure on intact primary forests. Charcoal formation and deposition in soils seems to be a promising option to transfer an easily decomposable biomass into refractory SOM pools (Fearnside *et al.* 2001; Glaser *et al.* 1998, 2001b; Zech *et al.* 1990). However, charcoal formed through traditional slash-and-burn techniques represents just 1.7% of the pre-burn biomass (Fearnside *et al.* 2001).

The existence of an anthropogenic and C-enriched dark soil in different parts of the world and especially in Amazonia (Amazonian Dark Earths (ADE) or *Terra Preta de Índio*) proves that the predominant Ferralsols and Acrisols can be transformed into fertile soils. The ADE’s fertility is most likely linked to an anthropogenic accumulation of phosphorus (P), calcium (Ca) associated with bone apatite (Lima *et al.* 2002, Zech *et al* 1990), and black C as charcoal (Glaser *et al.* 2001a). Charcoal persists in the environment over centuries and is responsible for the stability of the ADE’s SOM. Fertility persists to the present under continuous agriculture by contemporary and likely intensive cultivation by native populations.

Objectives

The sustained fertility in charcoal-containing ADE and the frequent use of charcoal as a soil conditioner (Steiner *et al.* 2004) in Brazil and other parts of the world (mainly Japan) (Ogawa 1994a) provided the incentive to study the effects of charcoal application to a highly weathered soil (Lehmann *et al.* 2003). The production of charcoal for soil amelioration purposes (slash and char) out of the aboveground biomass (secondary forest and crop residues) instead of converting it to carbon dioxide (CO_2) through burning (slash-and-burn) could establish a significant C sink and could be an important step towards sustainability and SOM conservation in tropical agriculture.

Therefore, the aim of this dissertation is to examine the use of charcoal in agricultural practice and management of a highly weathered Xanthic Ferralsol on *terra firme* north of Manaus (Brazil). The first chapter describes indigenous soil fertility management by burning and use of organic amendments. A socio-economic study on charcoal producers collected information on household economic activity, demographic composition, and access to land, labour, and capital. Particular attention was given to charcoal production, wood procurement, labour input, charcoal output, and economic returns in comparison to their agricultural activities. Discussions and first-hand observations provided more general information about production techniques, risks and use of charcoal waste in agriculture. The second chapter (II) discusses the feasibility of slash and char with and without carbon trade mechanism for small farmers and the potential for carbon sequestration. Observations about present charcoal use are summarized in chapter III. The influence of charcoal and condensates from smoke (pyroligneous acid, PA) on the microbial activity was assessed via measurements of basal respiration, substrate induced respiration, and exponential population increase after substrate addition (chapter IV). The effectiveness of charcoal as slow release nutrient carrier (N, P, and K) was studied in a greenhouse experiment. Rice seedlings were fertilized with mineral N, P, and K either based on charcoal or kaolin as a nutrient carrier in order to assess the availability of nutrients to plants and microorganisms (chapter V). Long term effects of different organic matter (OM) applications and mineral fertilization on soil fertility and crop production were assessed in the chapters VI, VII, VIII and IX. Chapter VII delineates the influence on the soil microbial population by measurement of soil respiration. Potential microbial growth after substrate (glucose) addition served as a soil fertility indicator for *Terra Preta* and Ferralsol soils. Fertilization with ^{15}N labelled nitrogen provided information about the retention of N on plots amended with charcoal or compost in comparison to only mineral fertilized plots (chapter VIII). Weed succession, pressure and species composition on these plots is described in chapter IX. Chapter X investigated organic and inorganic soil fertility management in two different perennial crops by comparing soil respiration, and soil chemical properties. Finally an experiment was established on an expanding banana plantation in order to test the suitability of charcoal application in the local farming context. Chapter XI deals with foliar and soil nutrient contents, nutrient leaching, bulk density and water retention in soils amended with charcoal (powder, pieces, and waste as available) in comparison to the normal agricultural practice.

Material and Methods

This Dissertation comprises field (chapters VI, VII, VIII, IX, X, and XI), greenhouse (chapter V) and laboratory experiments (chapter IV). In addition, data and information were gathered at local charcoal production sites (chapters II and III) and indigenous soil fertility management (chapter I) was observed and described.

Study Locations

Most experiments (chapters IV, V, VI, VII, VIII, IX, and X) were established 30 km north of Manaus, Amazonas, Brasil (3°8´S, 59°52´W, 40–50 m a.s.l.) 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 a relative humidity of 85 % (Correia and Lieberei 1998). The soil is classified as a highly weathered Xanthic Ferralsol (FAO 1990) derived from Tertiary sediments. The soil is fine textured with up to 80% clay. It is strongly aggregated and has medium contents of organic C (24 g kg^{-1}), low pH values of 4.7 (in H_20), low CEC of 1.6 cmol$_c$ kg $^{-1}$ and low base saturation (BS) of 11.2 % (chapter VI; appendix, table II).

The data for the chapters I, II, III, and XI were collected outside the research station. An indigenous family group was visited several times over a time period of one year (chapter I). For 9 years they have been settled at the Ariau River about 40 km southwest from the city Manaus, between the Negro and Solimões rivers. The village location is close to the river and the forested part of it is influenced by seasonal flooding.

Information about charcoal production and marketing were gathered in the vicinity of Manaus (chapters II and III). Primary research was carried out in the Taruma Mirim Settlement situated at km 21 on the BR 174 highway that links Manaus, Amazonas to Boa Vista, Roraima. It was created in 1992 as an agricultural settlement by INCRA (*Instituto de Nacionalizacao Colonizacao e Reforma Agraria* or the National Institute for Colonization and Agricultural Reform) and is situated between the streams of Taruma Acu and Taruma Mirim. Other areas in the region were also explored on an informal basis as a source of information on charcoal making activities near Manaus, including the banks of the BR-174 highway and the settlement Canoas/Rio-Pardo. The latter was created by INCRA for the same purposes as Taruma Mirim.

One trial was carried out in the local farming context (chapter XI) in order to provide cheap sustainable options to improve crop yields in the tropics. This experiment was established within an existing and expanding banana plantation north of Manaus on kilometre 99 along the road BR 174 leading to Boa Vista.

Experimental Setups and Designs

Study IV (chapter IV) used fifty kg sieved topsoil (0-0.1 m) from an experimental bare soil area (see table 4-1, chapter IV, for chemical characteristics). Chicken manure was mixed with the soil to ensure a high microbial activity. The manure was dosed to apply about 65 Mg ha^{-1} (65 g kg^{-1}) in the first 10 cm of soil. The prepared soil was stored in a box for 10 weeks in the dark at a humidity of 28 %. To assess effects of charcoal portions of 40 g of soil (dry weight) were amended with 0 (treatment C), 2 (treatment CI), 4 (treatment CII), or 6 g (treatment CIII) charcoal powder (0, 50, 100, 150 g kg^{-1} respectively) prior to measurement (chapter IV, table 4-2). The humidity of the charcoal powder was equalized to that of the soil. Each treatment was measured in 3 repetitions. The effect of pyroligneous acid (PA) on microbial respiration was tested in a factorial design (chapter IV, table 4-2). A volume of 0.5 ml of “biopirol” (Biocarbo, Itabirito, MG, Brazil) mixed with 2 g charcoal or kaolin was added per 40 g soil. Biopirol is the first fraction obtained during distillation of wood tar. Two ml H_2O accounted for the factor "humidity" and 240 mg (6 g kg^{-1}) glucose were applied as usual after measurement of the basal respiration.

Two kinds of mineral fertilizers were prepared for the experiment delineated in chapter V. One treatment was based on charcoal powder as a nutrient carrier and the other on kaolin. OSP, $(NH_4)_2SO_4$, and KCl and were either mixed with kaolin or with charcoal powder prior to fertilization. The fertilizers were dosed to apply 3.6 g elemental N, K and P per kg of charcoal or kaolin which corresponds to about 40 kg ha^{-1} of these elements at a charcoal application of 11 Mg ha^{-1}. The mineral fertilizers were dissolved in distilled water, charcoal or kaolin was stirred into the solution and left for drying at room temperature. Topsoil (0-0.1 m) was collected and sieved (<2mm). After adding water (humidity of 30%) the soil was amended with dried and milled elephant grass (*Penissetum pupurium*) (1 kg DW 50 kg^{-1} of soil) and stored in a closed box for two months. Elephant grass was added to ensure a basic biodegradable C-stock for microbes. The soil was fertilized in a manner to create 5 treatments and divided into 5 different boxes. Treatment 1 contained unfertilized soil *Penissetum* mix (C); Treatment 2 (CI) was fertilized with charcoal based fertilizer (11 Mg ha^{-1}, N, P, K 40 kg ha^{-1}); in treatment 3 (KI) the same amount of NPK was applied but kaolin based (11 Mg ha^{-1}); and, treatments 4 and 5 were fertilized with twice the amount of either charcoal (CII) or kaolin based fertilizer (KII), respectively (chapter V, table 5-1). Pots of 11.5 cm height and 12.5 cm diameter were filled with 840 g (DW) soil each. Twenty-five pots were filled to form 5 repetitions of each treatment. The pots were randomly distributed on a table in the centre of the greenhouse. In each pot 5 pre-germinated rice seedlings were planted (February 2nd 2003). Insect control (caterpillars) was done manually and every day if encountered. The rice plants were watered with 25 ml per pot for the first 3 days. No water occurred at the bottom of the pot at that watering level. From 10th February to 6th May 100 ml of water was applied daily and the leachate was collected for analyses of N, P, K, and pH. After 4 months the pots were emptied, the rice biomass was dried at 65°C and weighed separately as roots and aboveground biomass.

The studies delineated in the chapters VI, VII, VIII, and IX were part of a long term field experiment. Fifteen different amendment combinations (table 6-1) based on equal amounts of applied C in chicken manure, compost, charcoal and forest litter were tested during four cropping cycles with rice (*Oryza sativa* L.) and sorghum (*Sorghum bicolor* L.) in five repetitions. After clearing of about 3600 m^2 secondary forest, and removing the aboveground biomass, the treatments were applied on 4 m^2 plots (2x2 m). Charcoal derived from secondary forest wood, was bought from a local distributor. It was manually crushed to particle sizes smaller than 2 mm. The applied 11 Mg ha^{-1} charcoal corresponded to the amount of charcoal-C which could be produced by a single slash-and-char event of a typical 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, litter and chicken manure amendments. From the 12th to the 20th of February 2001 the fields were hoe-harrowed to 0.10 m depth and the organic amendments were mixed in with the soil. Mineral fertilizer (NPK and lime) was applied as ammonium sulphate [$(NH_4)_2SO_4$], ordinary super phosphate (OSP), and potassium chlorite (KCl) as recommended by Embrapa (Fageria 1998). Organic materials were applied just once at the beginning of the experiment (February 3rd 2001). Mineral fertilizer was applied in March 2001 and after the second harvest in April 2002 (table 6-1, chapter VI). At the second fertilization the treatments L, and CCp+$^1/_2$CO+F additionally received micronutrients. Those treatments received mineral fertilization for the first time. As a first crop rice (*Oryza sativa* L.) was planted followed by three repeated sorghum (*Sorghum bicolor* L. Moench) crops. Rice was planted March 10th 2001 in a density of 200 seeds per m^2, followed by sorghum planted on October 15th 2001 in a density of 12.5 plants per m^2, the 3rd crop was established in a density of 25 plants per m^2 on April 18th 2002, the latter producing two harvests by ratooning.

Table 6-1. Treatments and applications of organic matter (in brackets Mg ha^{-1}) and nutrients (in brackets kg ha^{-1}), lime (2100 ~ 460 Ca, 270 Mg) 2800 ~ 613 Ca, 360 Mg), lime (430 ~ 94 Ca, 55 Mg)

Treatment	Organic Matter [Mg ha^{-1}]	Nutrient contents of organic matter [kg ha^{-1}]	1st fertilization [kg ha^{-1}]	2nd fertilization [kg ha^{-1}]
C	control	--------------------------------	---------------------	-------------------------------------
L	litter (13)	N (114), P (0.3), K (4.3), Ca (13.3), Mg (4.7)	---------------------	N (55), P (40), K (50), lime* (2800), Zn (7), B (1.4), Cu (0.6), Fe (2.3), Mn (1.6), Mo (0.08)
LB	burned litter (13 Mg litter burned on the plot)	N (??), P (0.3), K (4.3), Ca (13.3), Mg (4.7)	---------------------	N (55), P (40), K (50), lime* (2800)
F	mineral fertilizer	--------------------------------	N (30), P (35), K (50), lime*(2100)	N (55), P (40), K (50), lime* (430)
CM	chicken manure (47)	N (774), P (324), K (836), Ca (784), Mg (143)	---------------------	-------------------------------------
CO	compost (67)	N (681), P (49), K (191), Ca (219), Mg (101)	---------------------	-------------------------------------
CC	charcoal (11)	N (59), P (0.3), K (2.5), Ca (9.0), Mg (1.9)	---------------------	-------------------------------------
CO+F	compost (67)	N (681), P (49), K (191), Ca (219), Mg (101)	N (30), P (35), K (50), lime*(2100)	N (55), P (40), K (50), lime* (430)
CC+F	charcoal (11)	N (59), P (0.3), K (2.5), Ca (9.0), Mg (1.9)	N (30), P (35), K (50), lime*(2100)	N (55), P (40), K (50), lime* (430)
CC$^{1}/_{2}$ + $^{1}/_{2}$CO	charcoal (5,5), compost (33,5)	N (370), P (24.5), K (96.8), Ca (114), Mg (51.6)	---------------------	-------------------------------------
CC$^{1}/_{2}$ + $^{1}/_{2}$CO + F	charcoal (5,5), compost (33,5)	N (370), P (24.5), K (96.8), Ca (114), Mg (51.6)	N (30), P (35), K (50), lime*(2100)	N (55), P (40), K (50), lime* (430)
CC + $^{1}/_{2}$CO	charcoal (11), compost (33,5)	N (399), P (24.7), K (98.1), Ca (118.6), Mg (52.5)	---------------------	-------------------------------------
CC + $^{1}/_{2}$CO + F	charcoal (11), compost (33,5)	N (399), P (24.7), K (98.1), Ca (118.6), Mg (52.5)	N (30), P (35), K (50), lime*(2100)	N (55), P (40), K (50), lime* (430)
CCp + $^{1}/_{2}$CO	charcoal pieces (11), compost (33,5)	N (399), P (24.7), K (98.1), Ca (118.6), Mg (52.5)	---------------------	N (55), P (40), K (50), lime* (2800), Zn (7), B (1.4), Cu (0.6), Fe (2.3), Mn (1.6), Mo (0.08)
CCp + $^{1}/_{2}$CO	charcoal pieces (11), compost (33,5)	N (399), P (24.7), K (98.1), Ca (118.6), Mg (52.5)	---------------------	N (55), P (40), K (50), lime* (2800)

*lime (2100) ~ 460 Ca, 270 Mg, (2800) ~ 613 Ca, 360 Mg, (430) ~ 94 Ca, 55 Mg)

In order to study the influence of charcoal, N and P two field experiments were established with two different perennial crops (banana, *Musa sp.*; guarana, *Paullinia cupana*) in a confounded factorial design (chapter X). Each plantation tested three different factors in three different levels making up 27 (3^3) treatment combinations. Whereas the banana plantation received mineral fertilization in addition to the charcoal applications the guarana was fertilized organically using chicken manure and bones meal as the corresponding factors. The banana plants (variety *Caipira*) were planted in planting holes (0.4 x 0.4 x 0.6 m) with a spacing of 3.0 x 2.0 m in May 2001. The planting holes were prepared 30 days before planting and filled with a mixture of soil, charcoal (0, 8 and 16 litre), chicken manure (5 litre), OSP (200, 300 and 400 g) and lime (200 g). Urea (0, 200, 400 g) was fertilized on the soil surface. The application of urea, simple super phosphate and charcoal was repeated on the soil surface (chapter X, table 10-1). Furthermore the plants were fertilized with KCl (200 g in January 03 and March 2004), zinc sulphate ($ZnSO_4$, 50 g in October 2002) and FTE BR 12 (micronutrient mix, 50 g in February 2004). These combinations of three doses of charcoal, P and N form 27 treatments consisting of 162 plants (6 plants each). The guarana plantation covers 4 ha with 1604 plants. From October to December the area was cleared and the plants were planted in March 2003. As the intention of the experiment was to produce organic guarana, weed and pest control was done without pesticides. Fertilization was restricted to organic amendments only. In July 2003 ground charcoal was applied to the soil surface. Bone meal was applied in August 2003 and chicken manure in October 2003 (chapter X, table 10-1). Charcoal, bone meal and chicken manure were applied in three different doses allowing the formation of 27 different treatment combinations, each treatment consisting of 6 guarana plants. The entire experiment was established in five repetitions with five different varieties of guarana. For soil respiration curves only one variety (*Maués*) was chosen.

Four different treatments were applied in the local farming context (chapter XI) and designated as: (a) Normal agricultural practice (NAP); (b) NAP + 6.5 litre (~2.2 kg) of charcoal powder; (c) NAP + 6.5 litre charcoal in small pieces (sieved to obtain a size between 0.2 and 1 cm); and, (d) NAP + 13 litre of charcoal mix (available as charcoal production waste from local charcoal producers). The experiment was designed as completely randomized with four repetitions of each treatment. The NAP is to plant bananas in planting holes 0.3 m deep and 0.45 m wide. The holes are filled with a mixture of 10 litre fresh chicken manure, 500g powdered lime, 50g micronutrient-mix (4.5 g Zn, 0.9 g B, 0.4 g Cu, 1.5 g Fe, 1.0 g Mn, 0.05 g Mo), 300g OSP (23.22 g P) and soil. The other treatments received an additional charcoal amendment. The holes were established in lines with a distance of 2.5 m between the holes and 3.5 m between the lines. Until harvest (February 26th to March 7th 2003) two further fertilizations were applied on the soil surface. In April 2002 60 g magnesium sulphate ($MgSO_4$), 80 g KCl, 39 g $ZnSO_4$, 30g FTE BR12 (micronutrients), 30 g Borax, 90 g $(NH_4)_2SO_4$ and 60 g OSP were applied. In July 2002 270 g KCl and 135 NH_4SO_4 were applied. On 22nd of April 2002 the bananas were planted as small clones (0.1 to 0.2 m plant size) of the variety *Caipira*. Six banana plants were planted per treatment in 4 repetitions.

Soil Samples

In order to study indigenous soil management (chapter I) soil samples were taken at seven different locations (0 – 0.2 m depth) with a small shovel and placed in plastic bags. The locations were chosen according to the soil management (chapter I, table 1-1). The various forms included burned soil termed *Terra Queimada* (TQ), *Terra Queimada* with burned organic amendments (TQ + bOM), soil called *Terra Preta* or *Terra Preta Nova* (TPn), newly burned soil termed *Terra Cheirosa* (TC), and unmanaged background soil was taken in proximity of the football ground (BS). The samples from the field experiment (0 – 0.1, 0.1 – 0.3 and 0.3 – 0.6 m depth) were taken after the 4 consecutive harvests (chapters VI, VII, and VIII). Top soil (0 – 0.1 m) samples were taken on April 8th 2004 in the banana plantation and April 23rd 2004 in the guarana plantation (chapter X). One composite sample was formed out of 4 sub-samples taken in the fertilized area. The first and sixth plant was not sampled to minimize the influence of adjacent treatments. In the banana plantation (chapter XI) samples were taken from the planting holes (0 – 0.2, and 0.2 – 0.4 m depth). Immediately after sampling the soil was treated and analyzed. Samples from the pot experiment (chapter V) were analyzed after harvesting the plant biomass.

For the extraction of exchangeable nutrients the Mehlich-3 (Mehlich 1984; chapters V, and VI) or Mehlich 1 extraction (EMBRAPA standard, Claessen *et al.* 1997); chapters I, X and XI) were used. We analyzed the soil samples for N, P, K, sodium (Na), Ca, magnesium (Mg), aluminium (Al), acidity (Al+H), iron (Fe), zinc (Zn), manganese (Mn) and copper (Cu). Plant available P, K, Na, Zn, Mn, and Cu was analyzed in Mehlich 1 or 3 extracts and Mg, Ca, and Al in KCl extracts. The micro-nutrients (Fe, Zn, Mn and Cu), Ca and Mg were determined by atomic absorbtion spectrometry (GBL Avanta Σ Analitica, Australia, AA-1475 or Varian Associates, Inc., Palo Alto, CA). Exchangeable acidity and exchangeable Al were determined by titration (McLean 1965) after extraction with 1 N KCl and P was measured using a photometer (Heλios ß, Thermo Spectronic, Cambridge, UK) with the molybdene blue method (Olsen and Sommers 1982). Potassium was analyzed with a flame photometer (Micronal B 262, Sao Paulo, Brazil). pH was determined in water and 1 N KCl (1:5 w/v) using an electronic pH meter with a glass electrode (WTW pH 330, WTW, Weilheim, Germany) and conductivity was measured (HI 8733, HANNA Instruments). Total C and N were analyzed by dry combustion with an automatic C/N- Analyzer (Elementar, Hanau, Germay). Plant- available NH_4 and NO_3 (chapter VI) were determined photometrically in soil extracts (in KCl) using a rapid flow analyzer (Scan Plus analyzer, Skalar Analytical B.V., Breda, The Netherlands). Cation exchange capacity (CEC) was calculated as the sum of ammonium acetate-exchangeable cations and acidity (Claessen *et al.* 1997).

Before the total elemental determination (chapter I) large inclusions (organics, stones, ceramics, etc.) were removed from each sample by hand picking. The samples were then ground with a blender and materials larger than 2.0 mm screened out. The extraction was with concentrated HNO_3 and 6.0 *M* HCl. The elements in the resulting aliquot were determined by ICP (IAP Solid State Spectrograph, Thermo Electron Corporation).

Plant Samples

For the determination of foliar nutrient contents a digestion with a mixture of H_2SO_4, salicylic acid, H_2O_2 and selenium was used according to Walinga (1995). N was analyzed using the method of Kjeldahl and titration or by dry combustion with an automatic C/N- Analyzer (Elementar, Hanau, Germay). The elements P, K, Ca, Mg, sulphur (S), boron (B), Cu, Fe, Mn, and Zn (chapter XI) were analyzed according to (Malavolta *et al.* 1997).

Soil Solution

The treatments NAP and NAP+charcoal-mix (chapter XI) were established with 6 suction cups each. The suction cups were installed in an angle to be situated in 0.5 m depth (~0.2 m beneath the planting hole) for soil solution collection. Soil solution was taken on May 3rd, June 22nd and July 3rd 2002 for analysis of pH, conductivity, Mg, Ca and K. Ca and Mg were determined by atomic absorbtion spectrometry (GBL Avanta Σ Analitica, Australia) and K was analyzed with a flame photometer (Micronal B 262, Sao Paulo, Brazil). The pH (WTW pH 330, WTW, Weilheim, Germany) and conductivity (HI 8733, HANNA Instruments) were determined in the solution. Leached N contents were measured by the Kjeldahl technique (chapter V).

15N Tracer Application

Five treatments were chosen for ^{15}N isotope enrichment using ^{15}N labelled $(NH_4)_2SO_4$ with 10 atom % ^{15}N excess (chapter VIII). The tracer was mixed in a ratio 1:1 with conventional $(NH_4)_2SO_4$ and applied at a rate of 55 kg N ha^{-1} in April 2002 (chapter VIII, table 8-1,). Soil and plant samples were taken at each harvest and analyzed for $\delta^{15}N$. Only the top 0.1 m of soil was sampled, this was also the depth into which the organic amendments were mixed. Two soil samples were taken per plot to form one composite sample. The labelled ^{15}N remaining in soil or found in plant biomass was calculated after equation (1).

(1) $$N_f * \delta^{15} N_f = \left(N_f * \delta^{15} N_c\right) + \left(\mathrm{Y} * \delta^{15} N_{NPK}\right)$$

N_f = nitrogen content of fertilized treatment (biomass or soil)

$\delta^{15}N_f$ = measured $\delta^{15}N$ value of fertilized treatment (biomass or soil)

$\delta^{15}N_c$ = measured $\delta^{15}N$ value of unfertilized control treatment (biomass or soil)

$\delta^{15}N_{NPK}$ = $\delta^{15}N$ 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 Equation (2)

(2) $$\mathrm{Y} = \frac{N_f * \delta^{15} N_f - N_f * \delta^{15} N_c}{\delta^{15} N_{NPK}}$$

The percentage of N taken up by biomass or remaining in the soil was calculated according to Equation (3).

(3) $$N\% = \frac{N_{(\mathrm{NH_4})2\mathrm{SO_4}}}{\mathrm{Y}} * 100$$

$N_{(NH4)2SO4}$ = amount of tracer fertilized (27.5 kg/ha $(NH_4)_2SO_4$ 10 atom % ^{15}N excess)

Soil and Plant samples were analysed for their N content 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.

Microbiological Activity

The respiration of soil samples was determined by hourly measuring the CO_2 production of each sample in a continuous-flow system at a constant flow rate of 300 ml ambient air per minute (chapters I, IV, V, VII, and X). The ECT-Soil Respiration Device (ECT Oekotoxikologie GmbH, Germany) based on infra-red gas analysis (IRGA) was used, according to the procedure described by Förster and Farias (2000). The SIR method is a physiological method for the measurement of the soil microbial biomass. When easily degradable substrates, such as glucose, are added to a soil, an immediate increase of the respiration rate is observed, the size of which is assumed to be proportional to the size of the microbial biomass (Stenström *et al.* 1998). The basal respiration is measured without the addition of a substrate while the substrate induced respiration (SIR) is measured shortly after the substrate (240 mg glucose) addition. Microbial respiration was calculated according to Anderson and Domsch (1978). The following parameters served as indicators of soil quality, OM turnover (chapters IV, V, and VII; figures 4-1, 5-4, and 7-2) and nutrient availability: basal respiration (BR, OM turn over), substrate induced respiration (SIR), velocity of population increase (k) after substrate addition (nutrient availability and soil quality), activation quotient (QR = BR/SIR, microbial efficiency, metabolic quotient (CO_2-C h^{-1} C_{mic}^{-1}).

Interviews

Interviews were conducted for the chapters I, II and III. Information about indigenous soil fertility management (chapter I) was collected by informal interviews and observation. A total of 18 households who make charcoal were interviewed (chapter III). First, a questionnaire was tested over the space of one month, and then revised in order to obtain more accurate information. The interviews solicited both quantitative and qualitative socio-economic information and were semi-structured in format and in-depth in nature.

Statistical Analyses

Treatment effects were analyzed by general linear model (GLM) univariate analysis of variance (ANOVA). For refitting parameters not normally distributed and without equal variances a Box Cox transformation (Box and Cox 1964) was used (chapter VI). Homogeneous subsets were separated by the Student-Newman-Keuls test. Statistical analyses and plots were performed using SPSS 12.0, Sigma Stat32 and SigmaPlot (SPSS Inc.). SYSTAT 8.0 was used to perform a GLM to evaluate significant influences of each factor (chapter X) and interactions. The field plan (chapter VII) was drawn with CorelDRAW (Corel Corporation). The Pearson Product Moment Correlation was performed to assess correlation between the measured parameters.

The effects of the treatments in chapter VII and XI were analysed by one way analysis of variance (ANOVA). Significant treatment effects were detected using the Dunnett's pairwise multiple comparison t test and the Fisher’s LSD (least significant difference) was inserted in figures.

Homogeneous subsets in chapter V were separated by the LSD test. The influence of PA (chapter IV), glucose, charcoal and humidity were assessed using a complete 2^4 factorial design (two-levels, four-factors). The effects of the factors and their interactions were estimated by applying Yates’ algorithm according to Morgan (1991). The results of the algorithm were used to calculate the sum of squares for an ANOVA test. The 3- and 4-factor interactions were assumed to negligible and combined to yield a measure of residual error.

Most Important Research Findings

Indigenous Knowledge about Terra Preta Formation

Fire and OM are the main components of indigenous soil fertility management. Small fires are used to create burned soil (*Terra Queimada*), and burned organic materials (ash and charred residues) are used to increase the fertility in patches for special plants like medicinal plants and vegetables (chapter I, figure 1-1). After a burn (*Terra Queimada*) the soil had a strong scent of pyroligneous acid (*Terra Cheirosa*) which is stimulating soil microorganisms (chapter IV, figure 4-3). Although most total nutrient contents in newly created *Terra Preta* (TPn) are below the average *Terra Preta* (TPp) contents most (Ca, K, Mg, Zn, Mn) are within the range. P and S levels are similar to those found in *Terra Mulata* (TM) soils. Addition of OM as manure or compost are important for the maintenance of the productivity of ADE soils under long-term cultivation (Madari et al. 2003). Presently, chicken manure is frequently used to maintain soil fertility on TP (personal observation). The abandonment and revitalization due to additions of incompletely burned materials might explain the formation of TP and why horizons of more than 1 m depth were created. The soil fertility management for special plantings (vegetables and medicinal plants) between the houses likely creates a TP. TPp is often accompanied by dark brown bands of TM with the same high amount of SOM. According to Sombroek *et al.* (2002) and Woods and McCann (1999) TM are pre-Columbian agricultural fields around the former Indian major villages. Therefore we suppose that this might be the product of long term creation of TQ (for the main food crops).

Economic Aspects of Production and Carbon Conversion Efficiencies

The investigation of socioeconomic aspects of charcoal production and carbon conversion efficiency (chapter II) could distinguish two types of charcoal makers: the first group makes charcoal as their only source of income since their agricultural activities failed to produce returns (solely charcoal makers SC), while the second group of producers makes charcoal to supplement income from employment in the city (additionally charcoal makers AC). Access to markets in the city enables AC to earn seven times more money from charcoal production than SC (chapter II, table 2-1). The most important reason (77% of respondents) for making charcoal is the inability to sustain agricultural activities in the settlement at a profitable level.

AC are more likely to benefit from charcoal waste powder use for soil amelioration because their economic advantages enable them to invest in further soil fertility improvements. SC producers would profit if they would have access to global carbon trading mechanism. The average C conversion efficiency of the brick kiln was 42% (C in the wood feedstock converted to charcoal C) and the charcoal recovery by wood weight was 25.3% (chapter II, table 2-2). Only about 3.7% of the C in the wood (although higher than charcoal produced by slash-and-burn events) would be transferred into a refractory soil carbon pool if just the waste were used for soil amelioration at the production site. A further large proportion of waste is generated during marketing and bagging of charcoal which is usually collected for agricultural purposes at the city market. Considering the low charcoal production costs (~ 48 USD per ton) in shifting cultivation systems much more charcoal could be used as soil amendment if profit from C emission trading could be generated. Slash and char as an alternative to slash-and-burn would offer a manageable carbon sink (chapter II, table 2-3).

Charcoal Use in Agriculture

The agricultural practice of slash and char produces charcoal out of the aboveground biomass instead of converting it to CO_2 through burning. Slash and char practiced as an alternative to slash-and-burn throughout the tropics could serve as a significant carbon sink and could be an important step towards sustainability in tropical agriculture. The use of charcoal for soil amelioration purposes was observed at various locations in the vicinity of Manaus. The uses of charcoal production residues are manifold and reach from chicken fodder amendment to direct applications and the creation of charcoal compost. The production of charcoal is practiced as an alternative clearing method (slash and char), although charcoal is not always used for soil amelioration purposes and if so only the accumulated waste (powder and pieces) is used (chapter III, figure 3-1).

Charcoal and Smoke Extract (PA) Stimulate the Soil Microbial Community

When charcoal was applied in unweathered condition (fresh from the kiln) the soil respiration, microbial biomass, population growth and the microbes' efficiency, expressed by the metabolic quotient as CO_2 production per microbial biomass unit, increased linearly and significantly with increasing charcoal concentrations (50, 100 and 150 g kg^{-1} soil; chapter IV, figure 4-2).

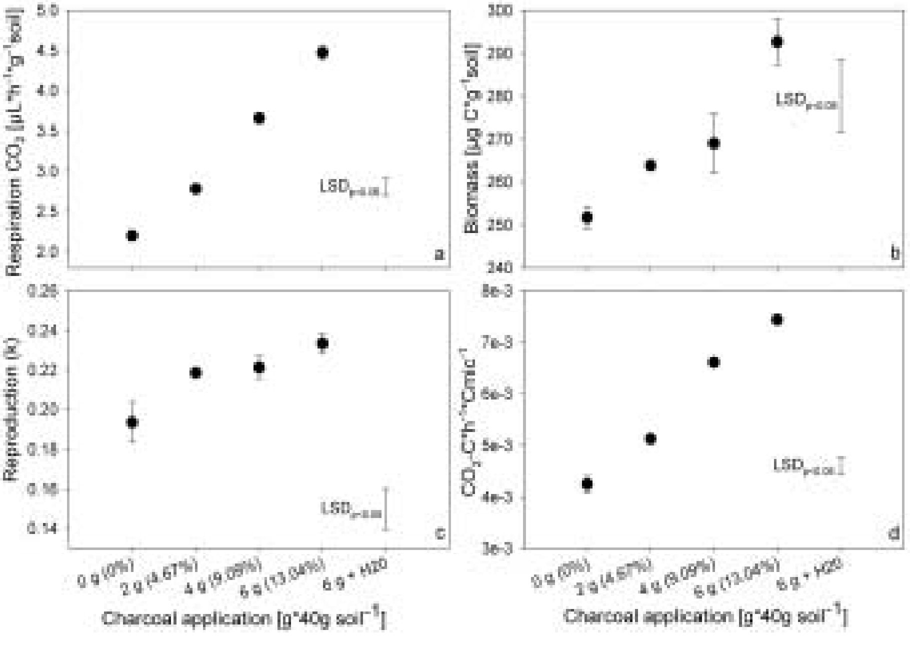

Figure 4-2. a) basal respiration, b) microbial biomass, c) reproduction potential (k, $N = N_0e^{kt}$), and d) CO_2 production per microbial C (metabolic quotient) with increasing soil charcoal concentration. Means and standard errors (*n* = 3).

Application of pyrogenous acid (PA) caused a sharp increase in soil respiration, microbial biomass, and reproduction. We suppose that the condensates from smoke contain easily degradable substances (and only small amounts of inhibitory agents) which could be utilized by the microbes for their metabolism (chapter IV, figure 4-3).

Charcoal as Slow Release Nutrient Carrier

In a greenhouse experiment leaching of N was significantly ($P < 0.05$) reduced if $(NH_4)_2SO_4$ was applied with charcoal (chapter V, figure 5-1). In contrast, leaching of K was significantly ($P < 0.05$) increased if KCl was applied with charcoal due to the charcoal's K content. At the end of the experiment soil N as well as soil K contents were significantly higher in the charcoal treatment. Charcoal simultaneously served as K fertilizer and increased the retention of N. P contents were only influenced by the level of fertilization not by the nutrient carrier (charcoal or kaolin). Plant biomass production and microbial population growth potential were not influenced by the nutrient carrier because nutrients were available in excess (figure 5-3). The soil respiration in relation to the microbial population size (CO_2-C h^{-1} $Cmic^{-1}$) was smaller in charcoal containing soil.

Long Term Effects of Manure, Charcoal and Mineral Fertilization

Long lasting soil fertility improvement due to organic fertilization and a synergistic effect if both charcoal and mineral fertilizer were applied was observed in a field experiment (chapters VI, VII, VIII and IV). Chicken manure amendments resulted in the highest (P <0.05) cumulative crop yield (12.4 Mg ha^{-1}) of four successive harvests (chapter VI, table 6-2, figure 6-1). Most importantly, surface soil pH, P, Ca and Mg were significantly enhanced by chicken manure (chapter VI, figure 6-3). A single compost application produced four fold more grain yield ($P < 0.05$) than plots mineral fertilized in split applications. Charcoal significantly improved plant growth and doubled grain production if fertilized with NPK in comparison to the NPK-fertilizer without charcoal ($P < 0.05$). The bigger yields caused a significantly higher nutrient export (chapter VI, figure 6-2), but available nutrients did not decrease to the same extent as on the just mineral fertilized plots. Soil charcoal additions reduced exchangeable soil Al significantly. The resilience of SOM in charcoal amended plots (8% and 4% soil C loss, mineral fertilized or not fertilized, respectively) indicates the refractory nature of charcoal in comparison to chicken manure (27%), compost amended (27%), and control plots (25% loss).

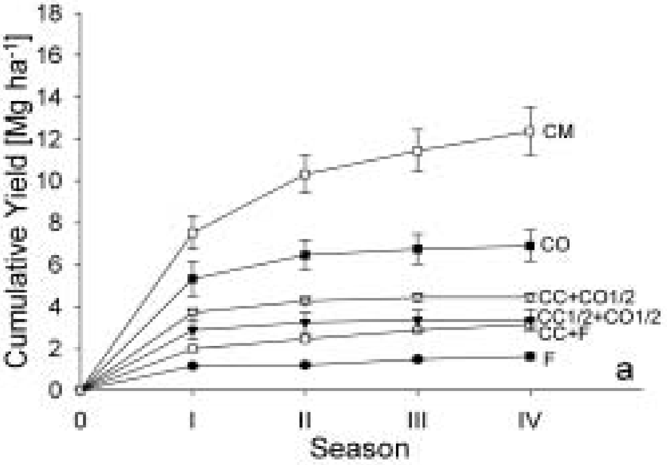

Figure 6-1. (a) Cumulative yields of selected treatments and (b) the yields as a percentage of the yield at first harvest. Mineral fertilization without any OM input is indicated by an arrow (means and standard errors; $n = 5$).

The soil microbial population growth potential showed a significant positive correlation to nutrient availability in the soil and plant biomass production (chapter VII, figure 7-3). Mineral fertilized soils amended with charcoal and *Terra Preta* soils had a significantly higher potential for microbial population growth coupled with a low microbial respiration in absence of an easily degradable C source (chapter VII, figure 7-6). The soil respiration before substrate addition correlated positively with the population growth rate on the plots, whereas

Terra Preta had a very low soil respiration and very high population growth after substrate additions. Forest soils had a higher respiration rate but a very low population growth. These results reflect the relatively high biodegradable OM content of primary forest topsoil but low available nutrients in contrast to refractory *Terra Preta* SOM with high available soil nutrient contents. A carbon source of low bio-degradability (such as charcoal) together with a mineral nutrient source might cause a starving microbial community with enough available nutrients in the soil to grow rapidly in the presence of a degradable C source.

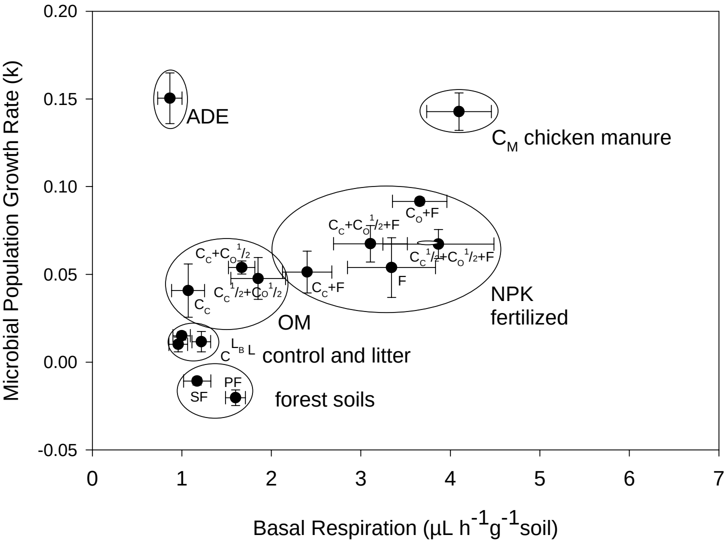

Figure 7-6. Relationship between basal respiration and microbial population growth rate (*k*) after the first harvest. ADEs are exceptional with a low basal respiration (*BR*) and high growth rate. Primary Forest soil (*PF*) has relatively high BR but low *k*. *Error bars* indicate the standard error of the mean ($n = 5$ for plot experiment; $n = 5$ for secondary and primary forests; $n = 5$ for ADE).

The ^{15}N recovery (chapter VIII, figure 8-1) in biomass was significantly higher on compost amended plots due to significantly higher biomass production. The retention in soil was significantly higher in the charcoal amended plots after the second harvest due to higher N retention and cycling of crop residues which remained on the plots after harvesting. Total N recovery (in soil, crop residues and grains) was significantly ($P < 0.05$) higher on compost (CO+F, 16.5%), charcoal (CC+F, 18.1%) and charcoal plus compost treatments (CC+1/2CO+F, 17.4%) in comparison to only mineral fertilized plots (F, 10.9%).

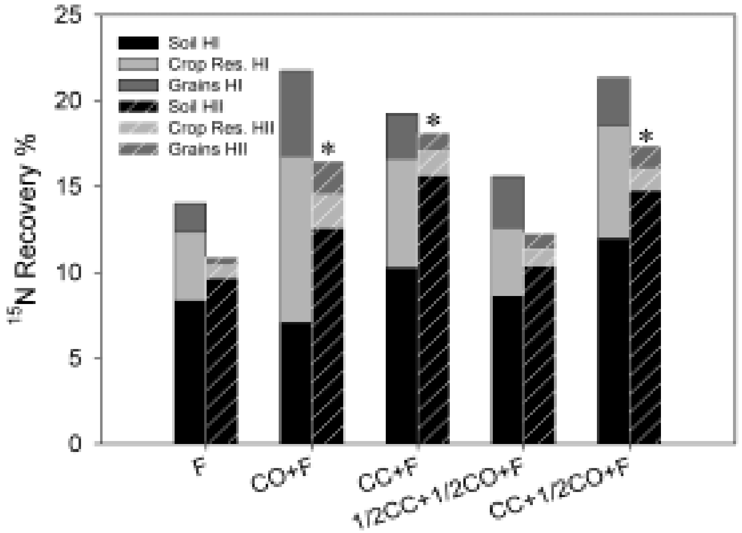

Figure 8-1. Amount of mineral N fertilizer remaining in the system (soil and crops) after the first (HI) and second harvest (HII) as a percentage. Crop residues remained in the field, grains were removed. The asterisk indicates significant differences ($P < 0.05$) between treatments and control (F = only mineral fertilizer) using Dunnett's pairwise multiple comparison t test ($n = 5$).

After abandonment of cropping additions of inorganic fertilizer, compost, and chicken manure resulted in increases in weed ground cover of 40, 22 and 53%, respectively, and increases in species richness of 20, 48, and 63%, respectively (chapter IX, table 9-3). When chicken manure was applied, dominance by a few weed species was reduced such that different species were more evenly represented. While charcoal additions alone did not significantly affect weed ground cover or species richness, a synergistic effect occurred when both charcoal and inorganic fertilizers were applied. The percentage ground cover of weeds was 45% within plots receiving inorganic fertilizer, 2% within plots receiving charcoal and 66% within plots receiving both amendments. These effects on weed populations were observed nearly 2.5 years after the addition of charcoal, chicken manure and compost, and more than one year after the last application of inorganic fertilizer.

Perennial Plantations (Musa sp. and Paullinia cupana)

The comparison of mineral and organic fertilization in perennial plantations (chapter X) showed that charcoal is a valuable component especially in inorganic fertilized agricultural systems. Charcoal increased pH, total N, availability of Na, Zn, Mn, Cu, humidity, and decreased available Al and acidity only in the mineral fertilized plantation (chapter X, figure 10-1). This caused a significant increase in basal respiration (BR) and microbial efficiency in terms of CO_2 release per microbial biomass unit in the soil (chapter X, 10-2). The microbial biomass, efficiency, and population growth after the substrate addition was significantly increased with increasing levels of organic fertilizer amendments, because the organic amendments increased the soil nutrient content and availability. In particular, chicken manure was capable of increasing all studied elements except Al and Fe which decreased ($P < 0.05$). Bone meal increased the soil's Mg and N contents and decreased available Al.

Decreased acidity due to charcoal application was also found in a banana plantation at a farm (chapter XI, figure 11-2). The charcoal further increased K levels significantly in 0.2 – 0.4 m soil depths. Foliar Ca, Mg, and S contents were significantly higher in plants that received charcoal (chapter XI, table 11-1). No differences could be found in banana fruit production which was assessed only for the first harvest.

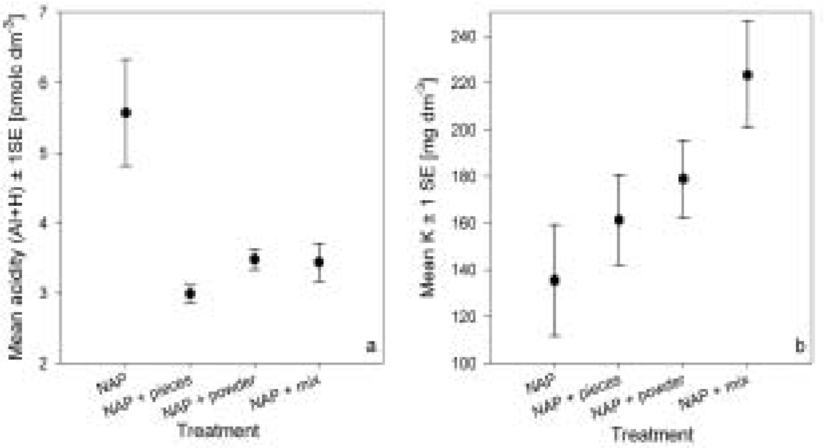

Figure 11-2. a) Charcoal applications significantly lowered the acidity; (Dunnett's pairwise multiple comparison t test, P <0.05, n = 4) in the top 0.2 m soil depth. b) Effect of charcoal application on plant available K in 0.2 m – 0.4 m depth. The amount of charcoal applied as pieces and powder does not differ in weight but in surface area. NAP = normal agricultural practice, mix = regular charcoal production waste double dosage. The error bars indicate the standard error.

Conclusions and Outlook

Charcoal production is a common activity of many settlers in the Amazon and is frequently used as an alternative land clearing method. The residues from charcoal production are abundant and used to some extent for soil amelioration purposes. However, many farmers fail to produce enough crops for a sufficient family income mainly due to the soils' infertility and the family's incapability to afford fertilizers.

Charcoal is influencing soil quality in manifold ways, most importantly by reducing available Al and reducing acidity. Furthermore, charcoal has the potential to reduce N leaching and adds K to the soil. Charcoal amendments increased the reproduction rate of the microbial population after substrate addition whether the plot was fertilized or not. The same was observed in *Terra Preta* soils, although the soil respiration was as low as found at unfertilized control plots. The effects of charcoal on soil biological, chemical and physical properties are complex, making it difficult to isolate single significant charcoal effects, but added up charcoal amendments caused significantly increased crop production.

More information is needed on the agronomic potential of charcoal, the potential to use alternative biomass sources (crop residues) and production of by-products to evaluate the opportunities for adopting a slash and char system. Most C is lost if burned in a slash-and-burn scenario and lost to a high percentage (~50%) if used for charcoal production. Therefore, a C trade could provide an incentive to cease further deforestation; instead re-forestation and recuperation of degraded land for fuel and food crops would gain magnitude.

Today, crop residue biomass represents a considerable problem as well as new challenges and opportunities. Before the green revolution and the introduction of mineral fertilizers, crop residues were a valued resource and mostly either returned to the soil as organic fertilizer or used for various other purposes (fuel, fodder, building material, others). Since then, the importance of these uses declined continuously, mainly because of the availability of cheap inorganic fertilizer and the increasing opportunity costs of organic fertilizer use (Pandey 1998). Simultaneously, increasing yields lead to ever greater quantities of residues available and intensification of land use resulted in less and less decomposition time between cropping seasons for managing them. Therefore, many farmers find it more expedient to burn crop residues than to incorporate them into the soil. The field burning is causing severe air pollution, particularly in north-western India and China.

A system converting biomass into energy (hydrogen-rich gas) and producing charcoal as a by-product (Day *et al.* 2005) might offer an opportunity to address these problems. Charcoal (*bio-char, agri-char*) can be produced by incomplete combustion from any biomass and it is a byproduct of the pyrolysis-technology used for biofuel and ammonia production (Day *et al.* 2005). This establishes the possible link of this technology to crop residues in general and the now widespread new interest in bioenergy. Energy from crop residues could lower fossil energy consumption and CO_2-emissions, and become a completely new income source for farmers and rural regions. The bio-char byproduct of this process could serve to recycle nutrients, improve soils and sequester carbon. A review by Lehmann *et al.* (2006) and the article "*Black is the new green*" (Marris 2006) emphasise the potential of bio-char on a global scale. The described mixture of driving forces and technologies has the potential to use residual waste carbon-rich residues to reshape agriculture, balance carbon and address nutrient depletion.

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