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FERTILITY IMPROVEMENT OF A *TERRA FIRME* OXISOL IN CENTRAL AMAZONIA BY CHARCOAL APPLICATION

Final thesis in Geoecology

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List of Abbreviations

Al	Aluminum
ANOVA	Analysis of Variance
a.s.l.	Above Sea Level
BC	Black Carbon
BS	Base Saturation
B.P.	Before Present
C	Carbon
Ca	Calcium
CEC, ECEC	Cation Exchange Capacity, Effective ~
CO_2	Carbon Dioxide
Coal	Short Form for the Amendment Charcoal (Used for Short Treatment Description in this Thesis)
C_{org}	Organic Carbon
Comp	Short Form for the amendment Compost (Used for Short Treatment Description in this Thesis)
Embrapa	*Empresa Brasileira de Pesquisa Agropecuaria*
FAO	Food and Agricultural Organisation (of the United Nations)
Fert	Short Form for the Amendment Mineral Fertiliser (Used for Short Treatment Description in this Thesis)
K	Potassium
KAK	Kationenaustauschkapazität German: see CEC
KCl	Potassium Chloride
LSD (-test)	Least Significant Difference Test
Mg	Magnesium
$MgCa(CO_3)_2$	Dolomite
MRT	Mean Residence Time
N	Nitrogen

$(NH_4)_2SO_4$	Ammonium Sulphate
NMR	Nuclear Magnetic Resonance
NPK	Nitrogen, Phosphorus, Potassium; mineral fertiliser
OM	Organic Matter
OSP	Ordinary Superphosphate
P	Phosphorus
$P<0.05$ $(N=5)$	P: Significance Level = 5 %, N: Number of Replicates
R^2	PEARSON´s Correlation Coefficient
SD	Standard Deviation
SOM	Soil Organic Matter
TP	*Terra Preta* Portugese: Black Earth

Summary

In this study, charcoal application to a *Terra firme* Oxisol was tested as a method for sustainable soil fertility improvement. This idea is derived from research results about *Terra preta*, a dark fertile Amazonian soil, similar to Mollisols. Increased amounts of charcoal and Black Carbon are held responsible for the high sustaining fertility of these soils. The deforestation of the Amazonian rainforest could be reduced by sustainable improvement of the soil fertility of already cultivated shifting cultivation sites.

In a field experiment in Central Amazonia (*Embrapa*, Manaus) the influences of charcoal, compost, mineral fertiliser/lime and different combinations of them on yield improvements and plant nutrition of upland rice (*Oryza sativa* L.) were investigated.

The exclusively application of charcoal amounts, which are realistic for on-site charring of average biomasses of secondary forests, resulted yields in 7 times higher yield compared to the control treatment, but with 100 kg ha^{-1} the absolute yield was to small. The combination of charcoal and mineral fertiliser/lime did not significantly improve the yield compared to solely fertilised and limed plots (1788 and 1360 kg ha^{-1}). Compared to compost including treatments, the yield was unsatisfying. The combination of compost with full and half amounts of charcoal, improved the yields to 2874 and 3700 kg ha^{-1}. This is comparable to first yields, of unfertilised slash-and-burn sites. The nutrient losses of these treatments were comparatively small in addition to adequate rice yields. In general, combined charcoal and compost amendments resulted in satisfying rice yields. Because of too low pH, the predicted positive effects on ECEC and plant nutrition were not yet observable at the end of the first cropping season. Charring and composting of slashed biomass as a land use system can be assessed as successful because comparable or higher yields could be gained compared to slash-and-burn, but better starting conditions for the following crops could be generated. Biomass-C, which is transformed to Charcoal-C can be saved from the C-pool of the atmosphere for a long time, because of charcoal's persistence.

Zusammenfassung

In dieser Studie wurde die Holzkohleapplikation als Mittel zur nachhaltigen Fruchtbarkeitserhöhung eines *Terra firme* Oxisols untersucht. Diese Idee leitet sich von Forschungsergebnissen zur *Terra preta*, einem schwarzerdeähnlichen Boden Amazoniens, ab. Erhöhte Gehalte an Holzkohle und *Black Carbon* werden für dessen hohe, dauerhafte Fruchtbarkeit verantwortlich gemacht. Durch nachhaltig ertragssteigernde Maßnahmen auf bereits agrarisch geprägten Flächen könnte der Nutzungsdruck auf den primären Regenwald Amazoniens vermindert werden.

In einem Freilandexperiment in Zentralamazonien (Station *Embrapa*, Manaus, Brasilien) wurde der Einfluss von Holzkohle, Kompost, Mineraldünger/Kalk sowie von verschiedenen Kombinationen dieser Komponenten auf die Erträge und die Nährstoffversorgung von Reis (*Oryza sativa* L.) untersucht.

Die alleinige Ausbringung von Holzkohle in Mengen, die der Verkohlung von durchschnittlichen Sekundärwaldbeständen entspräche, erhöhte zwar den Reisertrag verglichen mit der Kontrollfläche um das siebenfache, führte aber absolut gesehen mit 100 kg ha^{-1} zu unbefriedigenden Ergebnissen. Die Kombination von Holzkohle mit mineralischem Dünger und Kalk brachte keine signifikanten Vorteile verglichen mit ausschließlich mineralisch gedüngten und gekalkten Flächen (1788 und 1360 kg ha^{-1}). Verglichen mit Kompost enthaltenden Versuchsgliedern waren diese Erträge unzureichend. Die durch die Kombination von Kompost und Holzkohle (halbe und volle Menge) erzielten Erträge sind mit 2874 bzw. 3700 kg ha^{-1} mit durchschnittlichen Erträgen der ersten Ernte von ungedüngten slash-and-burn Flächen vergleichbar. Die Nährstoffausträge waren auf diesen Flächen vergleichsweise die geringsten bei zufriedenstellendem Reisertrag. Die von der Holzkohle- und Kompostapplikation erwarteten positiven Einflüsse auf KAK_{eff} und Nährstoffversorgung waren wegen zu tiefer pH-Werte am Ende der ersten Anbauperiode noch nicht nachweisbar. Das Konzept kann dennoch als erfolgreich bewertet werden. Ein Landnutzungssystem, in dem die eingeschlagene Biomasse verkohlt und kompostiert in den Boden eingebracht wird, kann vergleichbare oder möglicherweise höhere Erträge liefern und eine günstigere Ausgangssituation für nachfolgende Anbaukulturen schaffen. Der in der Holzkohle gespeicherte Kohlenstoff würde der Atmosphäre langfristig entzogen, da Holzkohle im Boden persistent ist.

1. General Introduction

The *Terra firme* are elevated areas, which are usually not flooded by rivers. They account for 98 % of the entire Amazon Basin (MORAN, 1995). Geologically it developed from tertiary fluvial-lacustrine deposits, which are up to 300 m thick and consist of sandstone and argilites with quartz as the predominant and feldspar respectively muscovite as minor minerals. During soil genesis, desilification was the predominant process, resulting in relative accumulation of Al-hydroxides and crystallisation of kaolinite (CHAUVEL et al. 1987). Deeply weathered, clayey, acidic, infertile soils developed over the last 20 million years. According to soil taxonomy (USDA, 1998) the corresponding soils are mostly classified as Oxisols and Ultisols (75 % of the 484 millions of ha of the Amazon Basin), show Al-toxicity (73 % of the Amazon Basin), are poor in K (56 % of the Amazon Basin), Ca, Mg and P (90 % of the Amazon Basin). These soils are among the least fertile ones on Earth. Besides the relevance for Amazonia, Oxisols and Ultisols represent also 50 % of the soils of humid tropical America and 35 % of the soil cover of the humid tropics in the world. In the future, these soils will become more and more important for crop production (SANCHEZ et al. 1982).

Within the *Terra firme* annual precipitation varies from 1500 mm to 3600 mm (SALATI AND MARQUES, 1984). This intensive rainfall, combined with several nutrient limitations, lead to evolution of the tropical forest, one of the most efficient nutrient recycling systems in nature. This system is preserved from remarkable nutrient losses because of nutrient storage in biomass, humus enriched top soils, fast turnover and mineralization of organic material, effective interception due to canopy and the dense superficial root and mycorrhiza system (CUEVAS AND MEDINA, 1988; HERRERA et al. 1978; STARK AND JORDAN, 1978). Apart from its enormous biodiversity and the pool of genetic resources, for example for pharmaceutical use, the Amazonian rainforest has an important function for the Earth's climate. It works as a source for atmospheric steam and a dynamic sink for CO_2. Therefore, the preservation of the tropical rainforest is one of our most important tasks nowadays.

1.1 Land Use at the *Terra Firme* - The Problems of Modern Slash-and-Burn

Slash-and-burn is still the most widespread land use practice in Amazonia. After clearing of the rainforest by slash-and-burn practice, the efficient nutrient recycling is disrupted. The nutrients released into the soil by burning of biomass improve maize, rice and manioc yields for a few years (SANCHEZ et al. 1983), but the particulate and gaseous nutrient losses especially for N and bases (K, Na, Ca and Mg) are remarkable. Furthermore, the burning of biomass results in a rapid release of CO_2. Due to missing canopy after slashing, increased soil temperature and soil moisture lead to a fast decomposition of soil organic matter (SOM). The mean residence time (MRT) for particulate SOM in an undisturbed Venezuelan rainforest was estimated to be less than 4 years and it is half of that under cultivation (TIESSEN et al. 1994). SOM has a major importance in these nutrient-poor soils maintaining cation exchange capacity (CEC) and it is a major source of nutrients. Multiple nutrient deficiencies and yield declines develop early in annual crop rotations as a consequence of accelerated decomposition, nutrient removal due to crop and leaching (CRAVO AND SMYTH, 1997). Therefore, the repeated application of fertilisers is necessary for gaining fair yields on these well-drained soils with soils with low CEC (SANCHEZ et al. 1983; SMYTH AND CASSEL, 1995). Smallholders in particular can rarely afford commercial fertilisers. With a rising population density and shortened fallow periods, slash-and-burn and shifting cultivation are no longer a sustainable land use system (SANCHEZ, 1976). Due to the special Amazonian socio-economic situation, abandoned sites are often transformed to pasture or to soybean production areas by big landowners. Smallholders are forced to cut more and more primary forest accompanied by negative consequences of deforestation on biodiversity and Earth's climate.

1.2 *Terra Preta do Indio* – Ancient Heritage

Beginning with HARTT in 1871, several authors reported on patches of Amazonian dark earths also called *Terra preta do indio* (TP), in between the infertile soils on the *Terra firme*. After SOMBROEK´s definition it is a "well-drained soil characterized by the presence of a thick black, or dark grey, topsoil" (SOMBROEK, 1966). The sizes of single TP sites vary in from 0.1-2 ha to 120 ha, averaging 20 ha (MANN, 2000; PABST, 1985;

ZECH et al. 1990). This very fertile soil has higher pH values than adjacent soils, higher CEC and higher levels of nutrients like N, P, K and Ca (SMITH, 1980; ZECH et al. 1979), but it has the same texture and mineralogy. Additionally, TP has higher amounts of stable soil organic matter. In the name "*Terra preta do indio*" the suffix "*do indio*" refers to the hypothesis that the genesis of this soil is in some way related to activities of pre-Columbian Indians. It is assumed that these soils were formed 1500-2500 years B.P. (PETERSEN et al. 2001). Frequent artefact and potsherd findings played an important role for the classification as an Anthrohumox (USDA, 1998). Pottery was identified to be of pre-Columbian origin as well. SALDARRIAGA AND WEST (1986) reported on ceramic potsherds that were found near San Carlos, Colombia, presumably in a TP. They had a thermo luminescence age of 3750 years B.P. ± 20 % (SD), which is the oldest evidence of human presence in interior Amazonia up to now.

Since potsherds cannot be interpreted as an evidence for a man-made soil, they can only be seen as a hint for human settling. The Indians might be attracted by already fertile soils as well. A more valuable hint for the anthropogenic origin of these soils is that sites are often situated near navigable waterways. They can be found especially on outer bends of the rivers, where the water meets the upland without floodplain (SOMBROEK, 1966). TP was also found on edges of the *Terra firme* and on strategically exposed sites on higher elevations (SMITH, 1999). The exposition of the TP sites and the similarity in texture and mineralogy to surrounding poor soils corroborate the hypothesis that this kind of soils is man-made. However, this argumentation is based on circumstantial evidence and there is no conclusive certainty about TP's genesis. The question remains, why these soils still are extraordinary fertile. If *Terra preta* soils were fertile before human cultivation, how did pre-Columbian Indians manage to maintain or increase the soil fertility over many centuries? And if TP is man-made, can it be re-created currently and how long will it take?

1.3 Hints for the Importance of Charcoal for Terra Preta Formation

It has not been conclusively demonstrated how the TP's large and stable pool of SOM with a great amount of highly aromatic humic substances developed. It has been shown that, besides polyphenoles and condensates (STEVENSON, 1994), it consists at least partly of Black Carbon (GLASER et al. 2001). "Black Carbon" (BC) is a collective name for a group of polycyclic aromatic hydrocarbons. It is a major component in the residues of charred plant material such as charcoal (, and a product of incomplete burning of organic material (GLASER et al. 1998).

Charcoal is assumed to be ubiquitous in Amazonian soils as the residue of forest fires. The occurrence of these forest fires coincides with dry seasons since the last 6000 years (SALDARRIAGA AND WEST, 1986). Pieces of charcoal are frequently found in different depths of TP horizons having higher amounts than other soils (SOMBROEK et al. 1993). SALDARRIAGA AND WEST (1986) found 248 Mg (metric tons) charcoal ha^{-1} 0.5 m^{-1} in an assumed Anthrosol near San Carlos de Rio Negro, Colombia. They reported also on sites without pottery findings with charcoal amounts varying from 31 to 174 Mg charcoal ha^{-1} 0.5 m^{-1}. TP has up to 70 times higher BC contents and the contribution to total organic C is about twice as high as in adjacent soils. TP could be the product of disposal of debris from indigenous settlements like faeces, kitchen debris, plant debris and charred material from cooking (GLASER et al. 2001; SOMBROEK, 1966) and/or of a special cropping culture (HILBERT, 1968; ZIMMERMANN, 1958).

The average charcoal formation rate for tropical forest burnings was calculated to 1.9 % referring to dry matter of the biomass (FEARNSIDE et al. 1997). The loss of C as CO_2 by burning the rainforest depends on the structure of the burned forest, especially the amount of wood with a diameter bigger than 0.1 m. The higher the amount of stems bigger than 0.1 m the smaller is the conversion rate to CO_2. In Amazonia the average C-loss during the burning of rainforest was calculated to be 39.3 % (FEARNSIDE, 1999). That means 39.3 % of the stored carbon is released as CO_2 directly during the burning process. Proceeding on the assumption that slash-and-burn fires were the only source of BC, estimated BC amounts in the top 1 m of investigated TPs, could be explained by only 25 forest fires (GLASER et al. 2001). A total of one to two on-site charrings would be sufficient to incorporate the same amounts of BC.

The therefore assumed charcoal yield of 20 % is not unrealistic. Affordable on-site charring techniques for smallholders, such as charcoal pits, earth mound kilns or the "Tongan oil drum kiln" reach charring efficiencies of 15 % and 30 % respectively. The widespread Brazilian Beehive Brick Kiln reaches efficiencies of up to 60 % referring to dry matter, but it is not that adequate for smallholders (EMRICH, 1985).

Assuming 20 % charring efficiency, 20 % of that lost amount could be stored as charcoal-C using slash-and-char technique instead of slash-and-burn. Newer global CO_2 balances consider the pool of BC on the global scale (SCHULZE et al. 2000). This demonstrates the importance of the stable BC pool as a storage and as a sink for CO_2 and therefore for the Earth's climate.

On the other hand, little is known about persistence and decomposition rates of BC. GLASER et al. (2001) assumed that due to its polycyclic aromatic structure, BC is microbially stable and persists over centuries. SCHULZE et al. 2000 supposed a decomposition of BC e.g. in Siberian soils (personal information). GLASER et al. (2001) also assumed the formation of carboxylic groups at the edges of the aromatic backbone due to oxidation. These organic acids are thought to be responsible for the increased CEC of TP. However, charcoal application increased the CEC of sandy and loamy European soils in a field experiment under temperate conditions (TRYON, 1948).

The amounts of nutrients that could be stored physically in pores of charcoal and the dimension of their availability for plants have been little investigated. Column experiments, pot experiments and lysimeter experiments gave valuable information about the effects of charcoal application on nutrient and water dynamics in soil and the underlying processes (ISWARAN et al. 1980, LEHMANN et al. submitted). However, field experiments are needed for the assessment of the yield improvement potential and of effects of charcoal on nutrient availability. Field experiments are state of the art in agricultural science for investigating new varieties of crops or yield response to fertilisers.

1.4 Objectives

The objectives of this study were to test the short-term effects of charcoal application to an infertile *Terra firme* Oxisol under field conditions with respect to first biomass yields and second soil fertility. In this field experiment with rice as test plant, the influence of the amendments charcoal, compost, mineral fertiliser and lime, and combinations of them on rice yield and soil chemical properties will be compared.

According to the theory that the oxidation of BC in charcoal leads to increased CEC, the addition of easy degradable organic material is vital for the microbial co-metabolic oxidation. Because accumulation of organic materials like plant and food debris and compost in connection to charcoal are assumed to be important for the genesis of TP, different combinations of these amendments will be tested. This will provide the possibility to compare different land use techniques symbolised by the different treatments and to find the best combination of amendments.

The benefit of charcoal application during the first crop period is of great importance for the development and introduction of a practicable land use system based on the replacement of burning by charring. Thus, the yield is of greatest interest because the return of invested capital and labour must be acceptable and should not be worse than in usual slash-and-burn systems.

In the experiment the following hypotheses were investigated:

1. charcoal addition to the topsoil leads to higher yields compared to common slash-and-burn practices,
2. charcoal as substitute for or in addition to other organic amendments like compost leads to an improved nutrient availability and decreases the nutrient losses due to leaching.

Beside yields, soil chemical parameters and plant nutrition of the different treatments are necessary for the assessment of the sustainability of different fertility improving strategies, which are symbolised by the different treatments.

2. Materials and Methods

2.1 Site Characteristics

This study was conducted in Central Amazonia, Brazil at the *Embrapa* (*Empresa Brasileira de Pesquisa Agropecuaria Amazonia Occidental*) station, 30 km north of Manaus (3°8´S, 59°52´W, 40–50 m a.s.l.). The climate is of Am type according to KOEPPEN´s classification system. The mean annual precipitation is 2530 mm (1971–1997) with a seasonal maximum between December and May (COREIA AND LIEBEREI, 1998). The mean annual temperature is 25.8 °C (1987-1997). The warmest months are August to November with mean temperatures from 26.0 to 26.6 °C. The coolest months are January to April, with mean temperatures from 25.4 to 25.6 °C. The average relative humidity is 85 % (COREIA AND LIEBEREI, 1998).

The potential natural vegetation of the *Terra firme* is tropical rainforest. The experimental field of this study was neighboured by primary and secondary forests and a fallow area.

The soil was classified as Xanthic Ferralsols according to FAO/UNESCO (FAO, 1990) or as Xanthic Hapludox according to soil taxonomy (RENCK, 2000). They are clayey with more than 80 % clay. The soil is strongly aggregated. The Xanthic Ferralsol has a medium content of organic C (28 g kg^{-1}), a pH value of 4.5–5.0 (H_20), a low effective CEC of 4.9 $cmol_c$ kg^{-1} and a low base saturation of 33 % (LEHMANN et al. 2000).

2.2 Experimental Design

2.2.1 The Treatments

Ten different treatments were investigated, each including different amendments or different combinations of them. A reference unit for comparable applied amounts of the respective amendments had to be found. The added C amount was chosen to be the reference unit because changing of the C_{org} of the soil was a main step of this experiment.

The added C amount was chosen to be equal to the amount of charcoal-C, which could be produced out of a single cutting and charring of a common secondary forest. For the top 0.1 m this was 0.94 ≈ 1%[1] (w/w) or 34 % (compared to the original C_{org} of the Ferralsol). Charcoal therefore was calculated according to published biomass data for secondary forests (Table 3) and an assumed average charring efficiency of 20 % (see section 1.3). The experiment included an increase step of charcoal application in addition to compost.

Table 1: Description of the Treatments of this experiment

Treatment Label	Treatment description
Control	Ferralsol, no additions
Fert & Lime	mineral fertiliser and lime were added
Comp 1 %	only compost was applied in the full amount
Coal 1 %	only charcoal was applied in the full amount
Comp 1 % + Fert & Lime	the full amount of compost was applied and mineral fertiliser and lime were added
Coal 1 % + Fert & Lime	the full amount of charcoal was applied and mineral fertiliser and lime were added
Coal 0.5 % + Comp 0.5 %	charcoal and compost were each applied in half amounts
Coal 0.5 % + Comp 0.5 % + Fert & Lime	charcoal and compost were each added in half amounts and mineral fertiliser and lime were added
Coal 1 % + Comp 0.5 %	charcoal was applied with full amount and compost was applied in half amount
Coal 1 % + Comp 0.5 % + Fert & Lime	charcoal was applied with full amount and compost was applied in half amount and mineral fertiliser and lime were added

[1] $M_{Charcoal}$ = 8.3 Mg ha^{-1} (Table 3); Bulk Density (soil) = 0.88 Mg m^{-3} (SCHROTH et al. 1999); $C_{Ferralsol}$ = 28 g kg^{-1} (LEHMANN et al. 2000), $C_{Charcoal}$ = 750 g kg^{-1}

The employed amendments were charcoal (***Coal 0.5 %, Coal 1 %***) and compost (***Comp 0.5 %, Comp 1 %***) (Table A). Additionally some treatments were mineral fertilised and limed (***Fert & Lime***). The amount of added fertiliser and lime was not varied and corresponded to recommendations (BRESEGHELLO AND STONE, 1998).

The different treatments symbolise different strategies for soil fertility improvement proceeding from the need to substitute slash-and-burn by other ways of on-site biomass transformation than burning.

Table 2: Total nutrient additions in the treatments concerning P, N, K, Ca and Mg and proportional nutrient additions of K, Ca and Mg in relation to origin exchangeable contents in the top 0.6 m (P and N were not part of the soil analysis program)

Treatment label	**total nutrient addition [kg ha^{-1}]** ***(proportional addition of bases) (%)***				
	P	**N**	**K**	**Ca**	**Mg**
Control	0	0	0	0	0
Fert & Lime*	35	30	20 *(30)*	528 *(3076)*	274 *(1533)*
Comp 1 %	5377	175	94 *(140)*	722 *(4206)*	54 *(302)*
Coal 1 %	81	122	10 *(15)*	14 *(81)*	4 *(22)*
Comp 1 % + Fert & Lime	5412	205	114 *(170)*	1250 *(7283)*	328 *(1835)*
Coal 1 % + Fert & Lime	116	152	30 *(45)*	542 *(3158)*	278 *(1555)*
Coal 0.5 % + Comp 0.5 %	2729	149	52 *(78)*	368 *(2144)*	29 *(162)*
Coal 0.5 % + comp 0.5 % + Fert & Lime	2764	179	72 *(107)*	896 *(5220)*	303 *(1695)*
Coal 1 % + Comp 0.5 %	2770	210	57 *(85)*	375 *(2185)*	31 *(173)*
Coal 1 % + Comp 0.5 % + Fert & Lime	2805	240	77 *(115)*	904 *(5273)*	304 *(1700)*

*** symbolizes the recommended doses for rice cultivation**

Although the main idea of that project is to substitute slash-and-burn by slash-and-char, a slash-and-burn treatment was not part of the experiment. On-site burning with an adequate amount of biomass was not feasible, because of the limited size of the plots. Literature data were employed for the comparison of the experimental data with common slash-and-burn rice yields (SANCHEZ, 1976).

The utilised charcoal was bought from a local dealer who declared it to be derived from secondary forest wood. The charcoal was manually crushed to particle size smaller than 2 mm. The utilised compost was also bought from a local distributor and contained secondary forest material, fruit residues and lime.

**Table 3: Biomass data of different Amazonian secondary forests and amounts of charcoal, which can be produced thereof;
literature data in bold letters, calculated values in italic letters**

source	woody biomass [Mg ha^{-1}]	age [years]	charcoal [a] [Mg ha^{-1}]	charcoal-C [b] [Mg ha^{-1}]
BUSCHBACHER et al. 1988	**12.9**	**3.5**	*2.58*	*1.9*
GEHRING et al. 1999	**16.5**	**2.3**	*3.3*	*2.5*
BUSCHBACHER et al. 1988	**30.4**	**8**	*6*	*4.5*
MACKENSEN et al. 1996	**31.2**	**7**	*6.2*	*4.7*
JOHNSON et al. (2001)	**49.8**	**10**	*10*	*7.5*
this experiment	*55* [d]	*8-20* [e]	**11**[c]	*8.3*
JOHNSON et al. (2001)	**59.2**	**20**	*11.8*	*8.9*
BUSCHBACHER et al. 1988	**81.8**	**8**	*16.4*	*12.3*
MACKENSEN et al. 1996	**95**	**40**	*19*	*14.3*
JOHNSON et al. (2001)	**119.8**	**40**	*24*	*18*

[a] **assuming an average charring efficiency of 20 % by weight referring to dry matter**

[b] **assuming an average C-content of charcoal of 75 % (EMRICH, 1985)**

[c] **chosen charcoal amount**

[d] **calculated values using charring efficiency and chosen charcoal amount**

[e] **possible age of secondary forests according to calculated biomass load and literature**

2.2.2 The Crop

Upland Rice (*Oryza sativa* L.) of the variety Maravilha[2] was chosen as the test plant for the following reasons:

- Maravilha is adapted to rain fed cultivation and to the climatic conditions of Amazonia
- as a species of *Graminaea*, Rice can be grown in a large number of individuals on limited space (240 plants m^{-2}) making the experiment robust against losses of single plants due to grasshoppers, ants or other pests and diseases
- rice is not N-fixing, therefore it fully depends on soil nutrients
- it has small seeds with little storage capacity for nutrients, thus, it has to use the nutrients of the soils very early during the growth period and therefore, the yield is mainly a function of soil nutrients
- the grain is overground, which makes it possible to observe the ripen process and to control for pests and diseases
- rice is of great economic relevance in Amazonia, which is important for the symbol character of the experiment

Rice was planted in lines with a space in between of 0.3 m. The planting density was 60 individuals per line meter. Therefore, in the line, the holes for the seeds had distances of 0.1 m and six seeds per hole were sown without pre-germination (BRESEGHELLO AND STONE ,1998). The first rice-seedlings were exterminated by grasshoppers and destroyed by a drought. The experiment finally started by sowing rice at the 24 March 2001.
Grasshoppers infestation was treated with MALATHION 500 CE (NITROSIN, Indol do Brasil Agroquímica Ltda) periodically following dose recommendations of PAES (1990).
The plots were weeded periodically. After the experiment, residual straw was applied again to the plots, as it is routine for farmers for nutrient recycling.

2.2.3 Mineral Fertiliser Application

Fertilisation took place one week after germination at the 19 March 2001. The amount of added N, P, K and lime followed recommendations for single applications (BRESEGHELLO AND STONE, 1998). Single application was chosen instead of repeated application in order

[2] Variety Key: Tox1010-49-1/IRAT 121/COLOMBIA 1 x M 312 A, 1992

to get one pronounced fertiliser response in the soil samples instead of many small and indistinct signals.

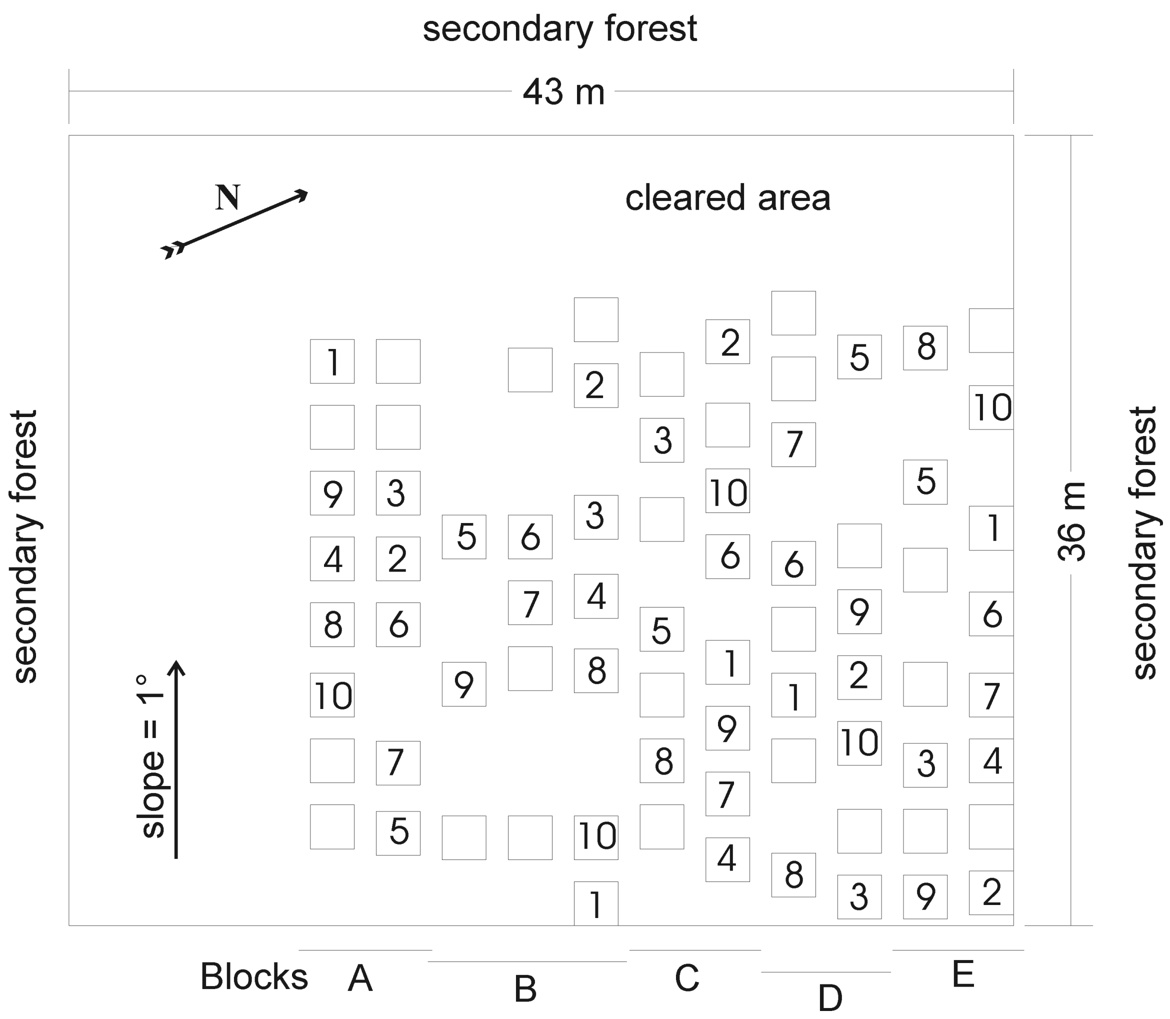
The following amounts were applied: 30 kg ha^{-1} N as Ammonium sulphate (143 kg ha^{-1}), 80 kg ha^{-1} P_2O_5 as ordinary superphosphate (OSP) with 436 kg ha^{-1}. This form of P-addition was chosen instead of triple super phosphate (TSP) because of the slow P release, that is more effective. Furthermore, 60 kg ha^{-1} K_2O as KCl (95 kg ha^{-1}), and 2100 kg ha^{-1} lime as dolomite ($CaMg(CO_3)_2$)were applied, which is equivalent to a Mg addition of 234 kg ha^{-1} and a Ca addition of 530 kg ha^{-1}.

2.2.4 The Experimental Field

A seven years old secondary forest site was chosen to be the experimental site. Thus, the common slash-and-burn conditions with shortened fallow periods were met. The area has a very small slope (appr.1°) towards northwest. An size of approximately 1600 m² was manually stubbed. It was cleared of smaller trunks, litter and of the superficial root mat. This step had two objectives: first removing debris and mulch was the only possibility to get equal initial conditions for all plots. In some parts of the area there where small depressions with humus and litter accumulation up to 0.1 m other parts lied bare without a litter layer. Second, humus was removed in order to see the effects of the applied amendments more clearly. The distance between the plot area and the remaining secondary forest was 9-10 m, which avoided shading. The distance between the plots was at least 1 m, but it differed because of larger remaining trunks, which could not be removed.

The plots were protected against runoff from the uphill side by tinplate metal sheets. Rice was planted into the spaces between plots as an active barrier in order to decrease the risks of cross contamination by runoff.

Fifty plots of 4 m² were arranged in 5 blocks, each containing 10 plots. In the blocks the treatments were randomly arranged forming a *randomised block design*. At the 3 February 2001, the top 0.1 m of the soil were manually tilled and the amendments were mixed in with the commonly used hoes.



No.	Treatment	No.	Treatment
1	***Control***	6	***Coal 1 % + Fert & Lime***
2	***Fert & Lime***	7	***Coal 0.5 % + Comp 0.5 %***
3	***Comp 1 %***	8	***Coal 0.5 % + Comp 0.5 % + Fert & Lime***
4	***Coal 1 %***	9	***Coal 1 % + Comp 0.5 %***
5	***Comp 1 % + Fert & Lime***	10	***Coal 1 % + Comp 0.5 % + Fert & Lime***

Figure 1: Plan of the experimental field with the arrangement of the plots[3] of this study in a *randomised block design*

[3] In the following text, the treatments are indicated by ***special formatting***. Combinations of amendments building one treatment are connected by " + ". In enumerations, different treatments are not separated by commas but by "and" in order to keep a better clearness.

2.3 Sampling and Chemical Analyses

2.3.1 Plant Material

Plant samples were taken twice. Flag leafs were sampled 46 days after sowing at early flowering, for assessment of the plant nutritional status. At early flowering the nutrient demand of rice is at its maximum in the growth period (BERGMANN, 1986).

At the ***Control*** and the ***Coal 1 %*** treatments, the flag leafs were not properly developed and therefore not sampled.

At the 7 July 2001, 105 days after sowing, rice from all treatments excluding the ***Control*** and the ***Coal 1 %*** treatment was harvested. The plants of these treatments were not completely developed at this time and therefore they were harvested 23 days later (30 July 2001). Only the central square meter of each plot was sampled leaving a border of 0.5 m in order to avoid margin side effects like increased sunlight. At the first sampling date, the total above ground biomass of one quarter of the central zone (0.5 by 0.5 m) was sampled. At maturity, the opposite quarter was chosen to minimize border effects. The plant material was stored in paper bags and immediately dried at 65°C until constant weight. Rice grains and straw were weighed separately. Leaf material was ground using a ball mill for digestion.

For determination of K, Mg and Ca, a digestion with a mixture of H_2SO_4, salicylic acid, H_2O_2 and selenium according to WALINGA et al. (1995) was used. In case of flag leafs N and P was additionally determined in order to allow a complete assessment of the nutrient status. Metals were determined using Atomic Absorption Spectrometer (AAS, Perkin Elmer Atomic Absorption Spectrometer 2280). In the same extract, P was detected using a photometer with the molybdenum blue method (OLSEN AND SOMMERS, 1982). Nitrogen was also photometrically determined as NH_4^+ in the same extract after reduction due to salicylates in the extraction solution with a continuous flow analyser (RFA-300, Alpkem Corp., Clackamas, OR and Scan Plus analyser, Skalar Analytical B.V., Breda, The Netherlands). The same procedure was used for chemical analysis of charcoal and compost.

2.3.2 Soil Samples

Soil Samples were taken four times: before and after application of amendments, on 9 May 2001 and after the final harvest (11 May 2001, 30 May 2001). For soil sampling three depths were chosen to be relevant: 0-0.1 m, 0.1-0.3 m and 0.3-0.6 m. The maximum rooting depth for rice (LANDON, 1991) and most annual crop species is 0.6 m. Two samples per plot were taken and combined to one composite sample. Soil samples were air dried and separated from litter and sieved to pass 2 mm.

The effective cation exchange capacity (ECEC) was calculated as the sum of Ammonium acetate exchangeable cations and acidity (EMBRAPA, 1979). For the extraction of exchangeable K, Ca and Mg, the Mehlich 3 extraction was used without any modification (MEHLICH, 1984). The amounts of exchangeable bases (K, Mg, Ca, Na) determined by the Mehlich 3 method are nearly identical to those obtained by the ammonium acetate method (CARTER, 1993). The filtrated solutions were cooled and immediately analysed for K, Ca and Mg using the AAS. Exchangeable acidity and exchangeable Al were determined using the 1 N KCl extraction and the titration method (MCLEAN, 1965).

The soil pH was determined in water and KCl using an electronic pH meter with a glass electrode (WTW pH 330). Deionised water and 1M KCl and were applied in the ratio 1:5 soil: dilution medium.

2.4 Calculations and Statistical Analyses

2.4.1 Biomass and Rice Yield Data

The statistical analysis[4] showed that there is no block effect in the *randomised block design* at the 5 % significance level for leaf biomass data, rice yields, nutrient contents at early flowering and at the final harvest. Thus, a one-factorial ANOVA was computed for the treatment effect at 5% significance level in order to compare the different treatments. Mean separation was computed by least significant difference test (LSD-test) at the same significance level. This procedure was employed for analysis of leaf biomass and for foliar nutrient contents.

[4] All statistical calculations were done using the program STATISTICA (STATSOFT, Inc., Tulsa, UK)

Due to inhomogeneity of variances, rice yield data were log-transformed before analysis of variances (ANOVA). ANOVA was then followed by LSD-test for mean separation.

2.4.2 Soil Samples Data

Statistical analysis showed no block effect for soil nutrient contents, pH and CEC. For comparison of exchangeable soil contents of K, Ca, Mg and for pH and CEC, the data were computed using ANOVA and LSD-test.

Furthermore an approximation of the quantity of "unproductive" nutrient losses from the plant available nutrient pool was made employing the same data for exchangeable soil contents. Unproductive nutrient losses during the cropping season were calculated as the difference between initial soil contents and soil contents at the end of the experiment.

$$\textit{unproductive loss} = start_i - harvest_i$$

unproductive loss = not plant-available nutrients

$start_i$ ***= initial nutrient amount of element i***

$harvest_i$ ***= nutrient amount of element i at the harvest***

In case of mineral fertilised treatments, the particular amounts of nutrients applied by fertiliser were assumed to become fully available during the first cropping season. Therefore, these amounts were added to the initial exchangeable nutrient contents.

Plant uptake and nutrient removal contribute to the farmer's income or can be recycled and were therefore excluded from unproductive losses. The consideration of nutrients stored in leaf biomass pays attention to farmer's practice to re-apply the straw to the fields after harvest.

$$\textit{unproductive loss} = (start_i + fert_i) - (harvest_i + straw_i + grain_i)$$

$fert_i$ ***= amount of element i, added by fertiliser and lime***

$straw_i$ ***= amount of element i, stored in leaf biomass***

$grain_i$ ***= amount of element i removed through grain***

Using this equation will overestimate the unproductive losses because the nutrient amounts stored in root biomass are not considered due to missing data.

Concentration data gained from chemical analysis were calculated to contents in kg ha^{-1} 0.1 m^{-1} by multiplying the concentrations with volumes of the soil increments and bulk densities (0.88, 0.98 and 0.92 Mg m^{-3} for 0-0.1 m, 0.1-0.3 m and 0.3-0.6 m respectively) estimated by SCHROTH et al. (1999). This literature could be used because SCHROTH worked with the same soil. Bulk density changing through application of organic material only affected the top 0.1 m, therefore the mistake is comparatively small.

The nutrient loads in leaf biomass were gained from multiplication of biomass weights with nutrient concentrations derived from the chemical analysis of the plants at the harvest. The nutrients removed by rice grains were calculated using grain weights and analysis data for nutrient concentrations of rice.

Because the tests showed no block effects, normal ANOVAs were computed for the comparison of losses of K, Ca and Mg, which were followed by LSD-test for mean separation.

2.4.3. Cost-Benefit Approximation

For the assessment of the profitability of the different treatments, two scenarios were calculated. In the scenario "market", the actual (2001) prices for all amendments were considered as experienced in Manaus. Compost, charcoal, mineral fertiliser and lime have to be bought by the farmer. In the scenario "autarky", costs are only considered for the mineral fertiliser and the lime. Here, it is assumed that the farmer can produce compost and charcoal by him self. Affordable low-tech kilns like the "Tongan oil drum kiln" show comparatively high charring efficiencies and can be handled easily. This kiln is made of old oil drums (industrial waste which can easily afforded) and therefore causes only little costs and also only little working time. Special tools are not needed apart from a common *tessado*, a typical long working knife, also known as *machete* (EMRICH, 1985).

The on-site production of compost from plant debris and fruit residues from weekly markets is common in the region, as it were observed by the author near Manaus.

The man-power and different working time requirements of the different treatments were not considered in the scenarios as his own work is gratis for the farmer. Transport costs were also not considered. A market price for rice of R$ 9.30 for the 60 kg sack was used for calculations. This was the minimum price in August 1998 (BRESEGHELLO AND STONE, 1998). The cumulative price for the employed fertiliser mixture, which are used for the calculations was 940 R\$ ha^{-1} in December 2001 and derived from the following individual prices: Ammonium Sulphate 0.60 R\$ kg^{-1}, OSP 0.90 R\$ kg^{-1}, Potassium Chloride 0.85 R\$ kg^{-1} and lime 0.25 R\$ kg^{-1} (Distributors: Oro Verde, Manah). The prices for the amendments, which are used for the calculations are: compost 0.18 R\$ kg^{-1} and charcoal 0.30 R\$ kg^{-1}.

Calculations included division of rice yield and price per kg rice for the gross income and subtractions of costs of the different scenarios from gross incomes for the net income, were made with mean values.

3. Results

3.1 Rice Yield and Biomass Production

3.1.1. Rice Yield

The treatments ***Comp 1% + Fert & Lime*** and ***Coal 0.5 %+Comp 0.5 % + Fert & Lime*** and ***Coal 1 %+Comp 0.5 % + Fert & Lime*** , which included compost, no matter the full or the half amount, and mineral fertiliser and lime had the highest yields of rice (Table 4). These treatments showed no significant difference to the ***Comp 1 %*** treatment and are not significantly different among them. An effect of the increased charcoal content on yield was not observable for additionally mineral fertilised and limed treatments.

The yields of plots amended with charcoal and compost but without mineral fertiliser and lime (***Coal 0.5 %+Comp 0.5 %*** and ***Coal 1 %+Comp 0.5 %***) had significantly lower yields than the additionally mineral fertilised and limed plots. They showed no significant difference among them. An effect of the increased charcoal content on the yield is not significant in this comparison.

The yields of the ***Fert & Lime*** treatment and of those with additional charcoal application (***Coal 1 % + Fert & Lime***) are significantly lower than the compost including plots. Application of charcoal, fertiliser and lime in contrast to exclusive application of fertiliser and lime did not result in significantly higher yields.

The control and the plots solely amended with charcoal (***Control*** and ***Coal 1 %***) needed 23 days longer for ripening and they showed the lowest yields of all treatments. Compared with the control, the application of charcoal without any other amendment resulted in a significantly higher yield.

3.1.2. Leaf Biomass Production

The differences in leaf biomass production are not as big as in the rice yield, but show the same pattern (Figure 2). The application of charcoal resulted in a biomass production significantly higher compared to the control plots. The biomass production of plots amended with compost and other amendments cannot be differentiated by the parameters charcoal amount and fertilisation. With similar addition of total C, compost addition resulted in significantly higher biomass and rice grain production in contrast to charcoal.

3.2 Foliar Nutrient Contents

The nutrition status of rice was investigated using samples of the flag leafs. As flag leafs were not developed at the control and charcoal plots at the sampling date (46 days after sowing) there are no comparable data for these two treatments. This is a sign for a very low nutrition status, which resulted in delayed plant growth. Foliar contents of Ca and N are not significantly different among the individual treatments (Table 4).

3.2.1 Phosphorus

The application of charcoal in addition to fertiliser and lime did not lead to significantly increased P values compared to mineral fertilised and limed plots without charcoal application. The treatments ***Fert & Lime*** and ***Coal 1 % + Fert & Lime*** showed no significant differences to all other treatments, except the ***Comp 1 % + Fert & Lime*** and the ***Comp 1 %*** treatment, which showed the significantly highest values for P in the experiment.

Compared to the treatments ***Comp 1 %*** and ***Comp 1 % + Fert & Lime***, the treatments ***Coal 0.5 % + Comp 0.5 %*** and ***Coal 0.5 % + Comp 0.5 %*** + ***Fert & Lime*** are not significantly different.

The fully charcoal amended treatments (***Coal 1 % + Comp 0.5 %*** and ***Coal 1 % + Comp 0.5 % + Fert & Lime***) showed significantly lower P values compared to the fully compost amended treatments (***Comp 1 %*** and ***Comp 1 % + Fert & Lime***), while the compost and charcoal amended treatments with the half level of charcoal application (***Coal 0.5 % + Comp 0.5 %*** and ***Coal 0.5 % + Comp 0.5 % + Fert & Lime***) showed no significantly different P values compared to the compost treatments (Table 4).

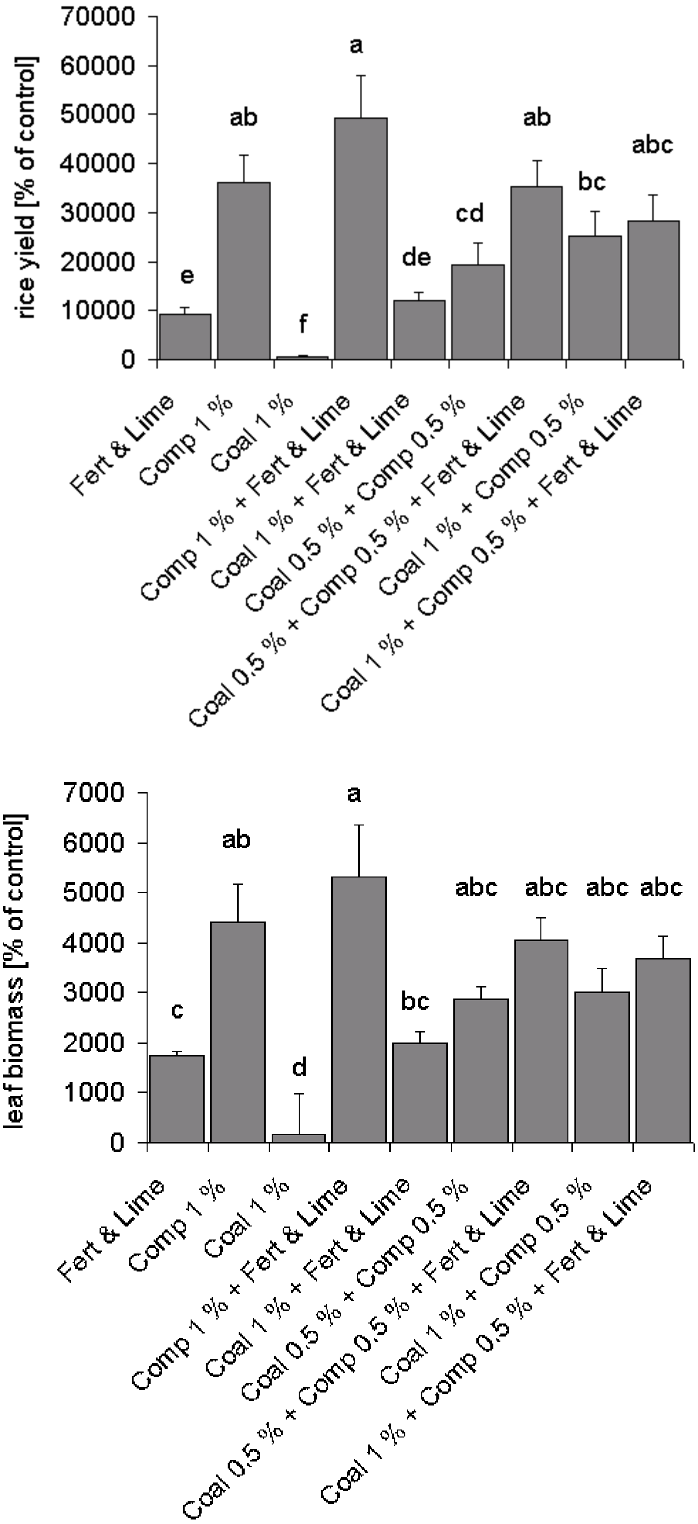


Figure 2: Yields of upland rice (*Oryza sativa* L.) and respective leaf biomass at maturity on a Xanthic Ferralsol in Central Amazonia amended with charcoal, mineral and organic fertilisers in relation to *Control*;
bars with the same letter are not significantly different at P<0.05 (N=5); error bars show standard errors

Table 4: Rice yield, biomass production (maturity) and foliar nutrient contents (early flowering) of upland rice (*Oryza sativa* L.) grown with different amendments of charcoal, inorganic and organic fertilisers; values in one column followed by the same letter are not significantly different at P<0.05 (N=5)

Treatment	maturity 105 days [kg ha⁻¹]		early flowering 46 days [g kg⁻¹]				
	grain yield	leaf biomass	N	P	K	Ca	Mg
Control *	15 g	108 e	n.d.	n.d.	n.d.	n.d.	n.d.
Fert & Lime	1360 e	1977 c	27.95	1.39 b	18 b	2.97	1.61 cd
Comp 1 %	5328 ab	4852 ab	29.20	1.83 a	24.31 a	2.68	2.16 ab
Coal 1 % *	100 f	296 d	n.d.	n.d.	n.d.	n.d.	n.d.
Comp 1 % + Fert & Lime	7261 a	5807 a	31.40	1.89 a	24.93 a	2.91	2.48 a
Coal 1 % + Fert & Lime	1788 de	2243 bc	25.20	1.42 b	19 b	2.68	1.92 bc
Coal 0.5 % + Comp 0.5 %	2874 cd	3183 abc	38.44	1.58 ab	19.34 b	2.79	1.84 bcd
Coal 0.5 % + Comp 0.5 % + Fert & Lime	5208 ab	4461 abc	31.80	1.63 ab	20.18 ab	2.95	1.85 bc
Coal 1 % + Comp 0.5 %	3720 bc	3342 abc	28.48	1.34 b	17.85 b	2.10	1.31 d
Coal 1 % + Comp 0.5 % + Fert & Lime	4177 abc	4069 abc	29.77	1.51 b	17.79 b	2.65	1.62 cd

*** needed 128 days until maturity**

Continuation of 3.2.1 Phosphorus

There were no significant differences among the charcoal and compost amended treatments, but there are differences compared to the compost amended treatments. So additional amounts of charcoal lead to lower foliar P values.

3.2.2 Potassium

For foliar contents of K the application of charcoal in addition to fertiliser and lime did not lead to significantly increased values compared to fertilised and limed plots without charcoal.

There are no significant differences between the different treatments apart from the treatments ***Comp 1 % + Fert & Lime*** and ***Comp 1 %***, which showed the highest foliar K contents and which are not significantly different compared to ***Coal 0.5 % + Comp 0.5 % + Fert & Lime***.

In case of foliar K contents a similar phenomenon was observed as for foliar P contents: The increasing step of charcoal at the charcoal, compost and fertiliser and lime amended treatment ***Coal 1 % + Comp 0.5 % + Fert & Lime*** lead to significantly lower foliar K contents compared to the treatment ***Comp 1 % + Fert & Lime***, while the treatment with the lower charcoal content (***Coal 0.5 % + Comp 0.5 % + Fert & Lime***) showed no significantly different foliar K contents compared to the highest values in the experiment.

3.2.3 Magnesium

Application of charcoal in addition to fertiliser and lime did not lead to significantly increased foliar Mg values compared to fertilised and limed plots without charcoal.

As well as for the other nutrients, the fully compost amended and mineral fertilised and limed treatment (***Comp 1 % + Fert & Lime***) showed the significantly highest values for foliar Mg contents of the experiment. All other fertilised and limed treatments build one homogenous group with significantly lower foliar Mg contents.

Rice grown on treatments amended with the full dose of compost (***Comp 1 %*** and ***Comp 1 % + Fert & Lime***) had no significantly different foliar Mg contents.

In general the compost amended and fertilised and limed treatments showed the significantly highest foliar contents of P, K and Mg.

3.3 Soil Chemical Properties

3.3.1 Soil Nutrient Changes During the First Cropping Period

The bases were determined in the Mehlich 3 soil extract, symbolizing the exchangeable soil nutrient contents (Table 5).

The exchangeable K contents are not significantly different for the different treatments at the end of the cropping period. The treatments can be separated by significantly different contents of Ca and Mg.

The nutrient changes of the different treatments during the first cropping season are more relevant for sustainability assessment than the absolute contents at the end of a cropping period, because the experiment started with different additions of nutrients (Table 2). The exchangeable soil nutrient contents are nevertheless important parameters, especially because of their importance as starting conditions for following crops.

According to the objective of this study to investigate the influence of charcoal on negative changes of nutrients (unproductive losses), an exchangeable soil nutrient balance was approximated. The lost amounts of K and Mg were approximated indirectly and quoted as positive values (Table 6). For Ca, respective data was not available. Total and proportional unproductive losses were calculated for each plot and then showed as means for the different treatments (Figure 3).

Table 5: Concentrations (top 0.1 m) and amounts (0-0.6 m) of exchangeable K, Ca and Mg (Mehlich 3) of a Xanthic Ferralsol amended with charcoal, mineral and organic fertilisers after rice (*Oryza sativa* L.); values in one column followed by the same letter are not significantly different at $P<0.05$ (N=5)

Treatment	K		Ca		Mg	
	0.1 m [mg kg^{-1}]	0 - 0.6 m [kg ha^{-1}]	0.1 m [mg kg^{-1}]	0 - 0.6 m [kg ha^{-1}]	0.1 m [mg kg^{-1}]	0 - 0.6 m [kg ha^{-1}]
Control	25.35	92.3	9.3 d	25.5 g	7.7 c	22.0 d
Fert & Lime	26.67	76.8	156.3 abcd	216.8 cde	81.4 a	91.6 b
Comp 1 %	30.61	90.5	161.8 abc	188.7 cdef	24.8 bc	36.5 cd
Coal 1 %	27.35	103.2	15.3 d	27.3 fg	9.6 c	18.6 d
Comp 1 % + Fert & Lime	31.70	82.5	268.1 a	474.4 a	70.0 a	149.6 a
Coal 1 % + Fert & Lime	27.72	73.1	183.7 abc	281.3 bcd	63.3 ab	80.8 bc
Coal 0.5 % + Comp 0.5 %	37.44	90.5	110.2 bcd	131.4 defg	22.3 c	31.3 cd
Coal 0.5 % + Comp 0.5 % + Fert & Lime	31.41	73.1	234.2 ab	291.7 bc	73.3 a	98.9 ab
Coal 1 % + Comp 0.5 %	38.97	87.4	84.9 cd	105.1 efg	20.4 c	35.5 cd
Coal 1 % + Comp 0.5 % + Fert & Lime	36.87	114.3	212.6 abc	395.7 ab	60.2 ab	117.2 ab

Table 6: Changing of exchangeable K and Mg during the experiment, removed nutrients stored in rice grain and unproductive loss of a Xanthic Ferralsol amended with charcoal, mineral and organic fertilisers; values in one column followed by the same letter are not significantly different at P<0.05 (N=5)

Treatment	K				Mg			
	start	removal	unprod. loss		start	removal	unprod. loss	
	[kg ha^{-1}]-----	-----	-----	%	[kg ha^{-1}]-----	-----	-----	%
Control	77.9 e	0.3	-9.6	-13.2	21.3 f	3.9	0.02 b	-3.5 c
Fert & Lime	119.6 de	1.4	16.9	14.8	294.8 c	22.1	199.7 a	67.9 a
Comp 1 %	206.6 ab	10.3	20.5	8.7	86.2 d	8.2	39.9 b	41.9 ab
Coal 1 %	76.7 e	3.4	-16.8	-26.7	24.8 f	-1.1	-1.9 b	-13.7 c
Comp 1 % + Fert & Lime	246.7 ab	15.8	20.3	7.1	365.2 a	-6.8	206.3 a	55.7 a
Coal 1 % + Fert & Lime	146.6 cd	2.8	35.3	22.9	299.9 c	33.9	212.8 a	71.5 a
Coal 0.5 % + Comp 0.5 %	142.0 cd	4.5	-1.0	-12.9	42.2 ef	-10.3	5.4 b	-5.1 c
Coal 0.5 % + Comp 0.5 % + Fert & Lime	193.8 bc	10.2	37.6	14.2	326.9 b	7.9	218.4 a	66.9 a
Coal 1 % + Comp 0.5 %	211.2 ab	4.7	63.2	28.2	50.1 e	57.4	8.8 b	17.4 bc
Coal 1 % + Comp 0.5 % + Fert & Lime	252.6 a	8.6	66.5	22.5	331.4 b	59.2	206.2 a	62.6 a

In case of K, negative proportional losses, which can be understood as an enlargement of the plant-available nutrient pool, occurred for the treatments ***Control*** and ***Coal 1 %*** and ***Coal 0.5 % + Comp 0.5 %***. The treatments cannot be separated by K-losses, because significantly different proportional losses were not found for the different treatments.
For Mg, negative values were also found for the treatments ***Control*** and ***Coal 1 %*** and ***Coal 0.5 % + Comp 0.5 %***. In contrast to K, the losses are significantly different for the individual treatments. The treatments with negative values and the treatment ***Coal 1 % + Comp 0.5 %*** showed the smallest proportional loss and were not significantly different. All other treatments show significantly higher proportional losses. The treatment, solely amended with compost (***Comp 1 %***) was not significantly different compared to the ***Coal 0.5 % + Comp 0.5 %*** treatment. Especially the mineral fertilised and limed treatments showed higher losses of Mg. The application of charcoal to mineral fertilised and limed plots did not lead to smaller losses of Mg.

The relation of gained rice yield and unproductive losses is important for the assessment of charcoal application (Figure 3).
In general high proportional K losses are not correlated with high rice yields. The charcoal and compost amended treatment with the half charcoal amount (***Coal 0.5 % + Comp 0.5 %***) showed negative values for the proportional loss of exchangeable K in connection with a comparatively high rice yield. Additionally, there was no trend observable that mineral fertilised treatments show higher losses than not fertilised treatments.
For Mg, the treatments with high unproductive losses showed also high rice yields. The application of charcoal to fertilised treatments (***Coal 1 % + Fert & Lime***) did not reduce the unproductive Mg losses. Similar to K, the charcoal and compost amended treatments with the higher charcoal content (***Coal 1 % + Comp 0.5 %***) show the trend for higher Mg losses than the treatments with the smaller charcoal contents but no higher rice yields.

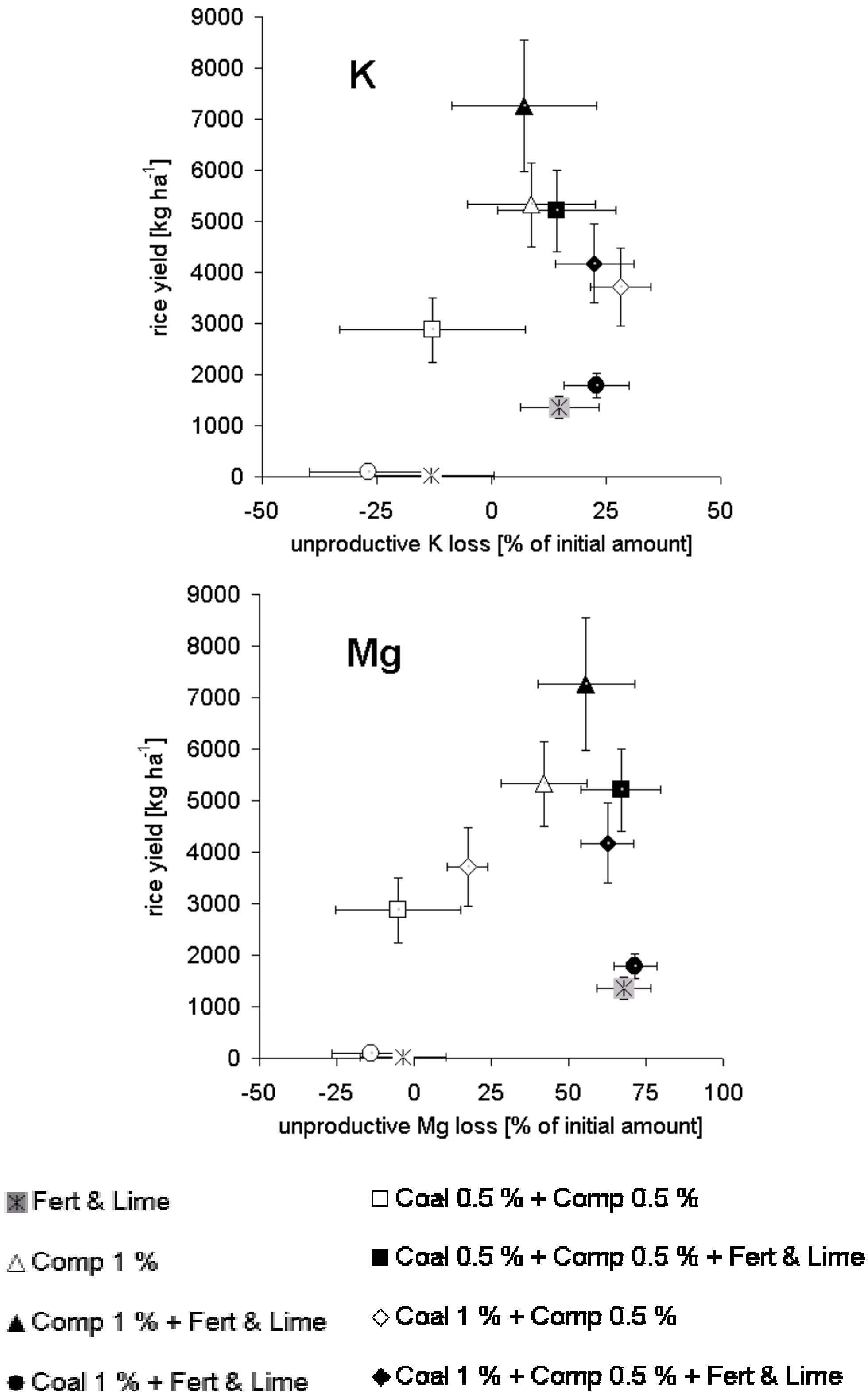


Figure 3: Proportional unproductive losses of K and Mg in relation to rice yields of different combinations of charcoal, mineral and organic fertilisers applied to a Xanthic Ferralsol; error bars show standard errors (N=5)

Table 7: pH, effective cation exchange capacity (ECEC) and base saturation (BS) of a Xanthic Ferralsol amended with charcoal, mineral and organic fertilisers after rice (*Oryza sativa* L.); values in one column followed by the same letter are not significantly different at P<0.05 (N=5)

Treatment	pH (KCl) 0.1 m	pH (KCl) 0.3 m	pH (KCl) 0.6 m	ECEC 0.1 m	Acidity 0.1m	BS* 0.1 m
				[$cmol_c\ kg^{-1}$]	[%]	[%]
Control	3.80 d	3.83 cd	3.91 bc	1.59	13.2 a	11.0 g
Fert & Lime	4.26 a	4.17 a	4.06 a	1.65	1.0 b	63.3 abcd
Comp 1 %	3.91 cd	3.92 bcd	3.97 bc	2.00	1.7 b	55.1 cd
Coal 1 %	3.74 d	3.77 d	3.85 c	1.85	14.7 a	11.9 fg
Comp 1 % + Fert & Lime	4.09 ab	4.00 abc	4.02 ab	2.52	0.5 b	82.2 a
Coal 1 % + Fert & Lime	4.21 a	4.06 ab	4.01 ab	1.78	0.5 b	76.6 ab
Coal 0.5 % + Comp 0.5 %	3.84 d	3.88 bcd	3.94 bcd	2.01	2.7 b	43.2 de
Coal 0.5 % + Comp 0.5 % + Fert & Lime	4.12 ab	4.00 abc	3.97 abc	2.15	0.9 b	68.1 abc
Coal 1 % + Comp 0.5 %	3.83 d	3.87 bcd	3.95 bcd	1.75	4.0 b	33.4 ef
Coal 1 % + Comp 0.5 % + Fert & Lime	4.03 bc	3.99 abc	3.99 abc	1.85	2.1 b	58.6 bcd

*** BS calculated as Ca+Mg+K/CEC*100**

3.3.2 Cation Exchange Capacity, Base Saturation and Soil Reaction

CEC, BS and pH were determined at the end of the experiment (Table 7).

The pH value (KCl) was measured to be 3.8 in the top 0.1 m of the control treatment. There were significantly different pH values for the different treatments (Figure 4). Exclusively addition of charcoal (***Coal 1 %***) did not bring beneficial effects for the soil pH compared to the control plots. Charcoal application in addition to mineral fertilisation and liming (***Coal 1 % + Fert & Lime***) did not lead to a significantly higher pH compared to the solely fertilised and limed plots (***Fert & Lime***). The highest pH values were found on plots where mineral fertiliser and lime were added. For the treatment ***Coal 1 % + Comp 0.5% + Fert & Lime***, the charcoal increase step resulted in pH value depletion below the highest level, which was found for the other mineral fertilised and limed treatments. In direct comparison, both the charcoal and the compost amended and additional mineral fertilised and limed treatments (***Coal 1 % + Fert & Lime*** and ***Comp 1 % + Fert & Lime***) are not significantly different. All treatments, which were not fertilised and limed form another homogenous group with the lowest pH values.

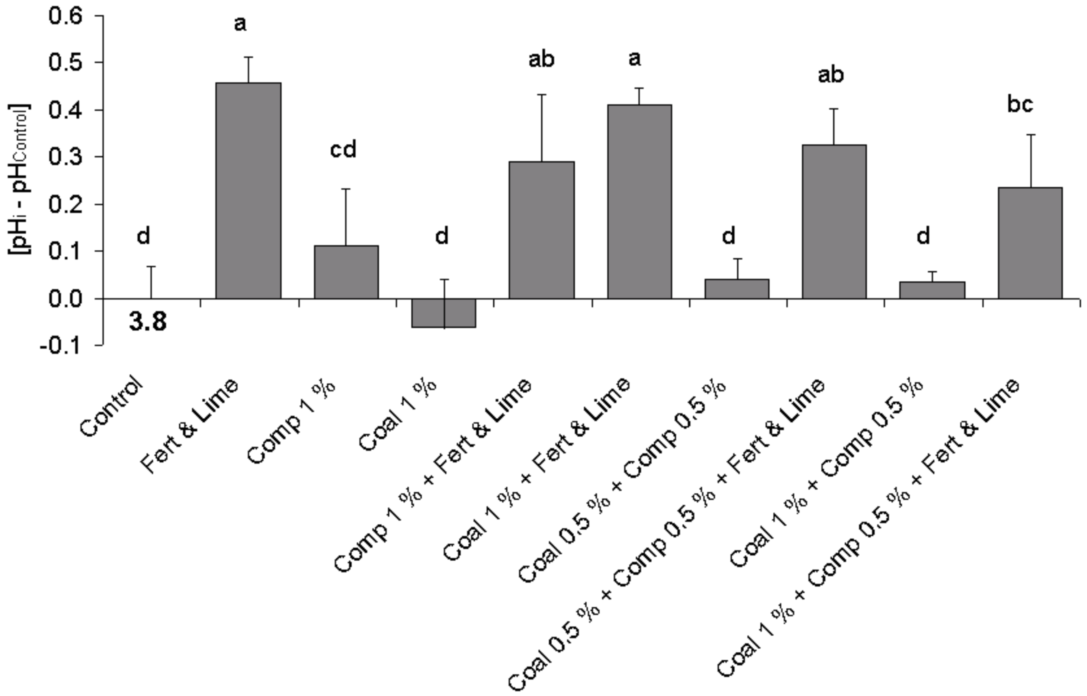


Figure 4: pH Values (KCl) at the end of the experiment in the top 0.1 m in difference to control; error bars show standard errors; bars labelled by the same letter are not significantly different at P<0.05 (N=5)

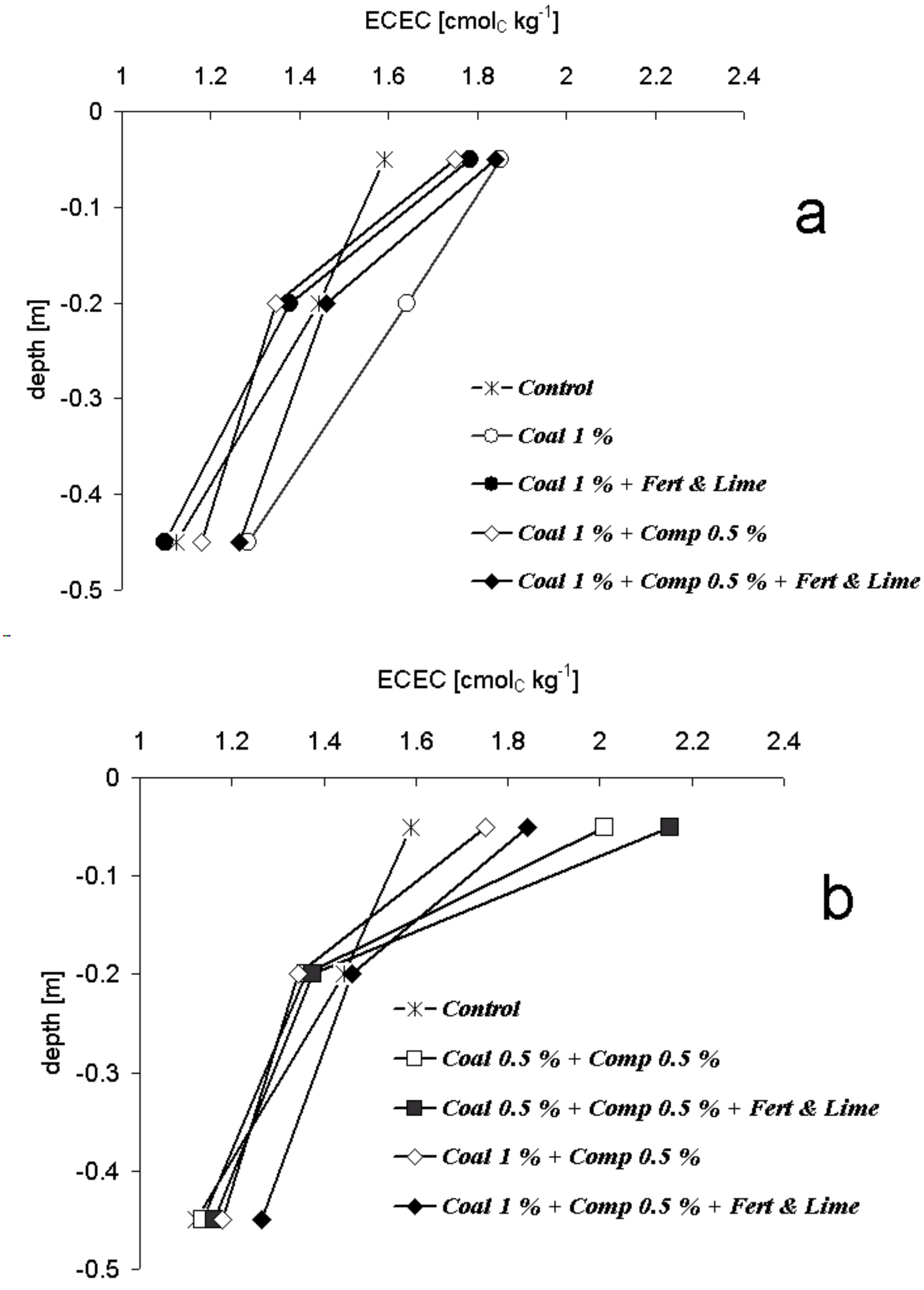


Figure 5: Depth profiles of ECEC of a) charcoal amended and b) charcoal and compost amended treatments;
all treatments are not significantly different at P<0.05 (N=4); error bars are not shown in order to keep a better clearness

The cation exchange capacity was determined as the effective CEC (ECEC). There were no significant differences between the treatments at the 5 % significance level (Table 7).

The comparison of the treatments in Figure 5 clearly demonstrates that application of charcoal or compost or of different combinations of it did not result in increased ECEC regardless of the amount of added material and the addition of mineral fertiliser and lime.
Base saturation and exchangeable acidity were determined as measures for the composition of the elements at cation exchange sites of the soil (Table 7).
The treatments ***Control*** and ***Coal 1 %*** showed the significantly lowest values for BS and the significantly highest values for exchangeable acidity. All other treatments form a homogenous group with significantly lower levels of exchangeable acidity. The ***Coal 1 %*** treatment did not show significantly higher BS compared to the control. The comparison of the solely charcoal amended treatment (***Coal 1 %***) with the two charcoal and compost amended treatments show different results: while the treatment ***Coal 1 % + Comp 0.5 %*** is not significantly different compared to it, the treatment with the smaller charcoal amount (***Coal 0.5 % + Comp 0.5 %***) showed a significantly higher value for BS. In the direct comparison of both treatments (***Coal 0.5 % + Comp 0.5 %*** and ***Coal 1 % + Comp 0.5 %***) no significantly differences can be found. All treatments including mineral fertiliser and lime are in one homogenous group and showed BS from 63 % to 82 %, which are the significantly highest values in the experiment.

3.2.4 Nutrient Availability

For testing the availability of added nutrients, investigation of the relation between added nutrient amounts and foliar nutrient contents (at early flowering) is an adequate measure (Figure 6).
In case of N and Ca the relationships for added N and Ca amounts and responding foliar concentrations are not proportional. The correlation coefficients R^2 of the correlations for both nutrients are less than 0.5. In case of P, increased amounts of added nutrients lead to increased amounts of foliar P concentrations. The only two exceptions are charcoal amount increase steps on the compost-amended treatments (***Coal 1 % +Comp 0.5 %*** and ***Coal 1 % + Comp 0.5 % + Fert & Lime***). The foliar P-concentration is significantly lower in these treatments. Furthermore, P shows the highest correlation coefficient of all investigated nutrients (R^2 = 0.72).

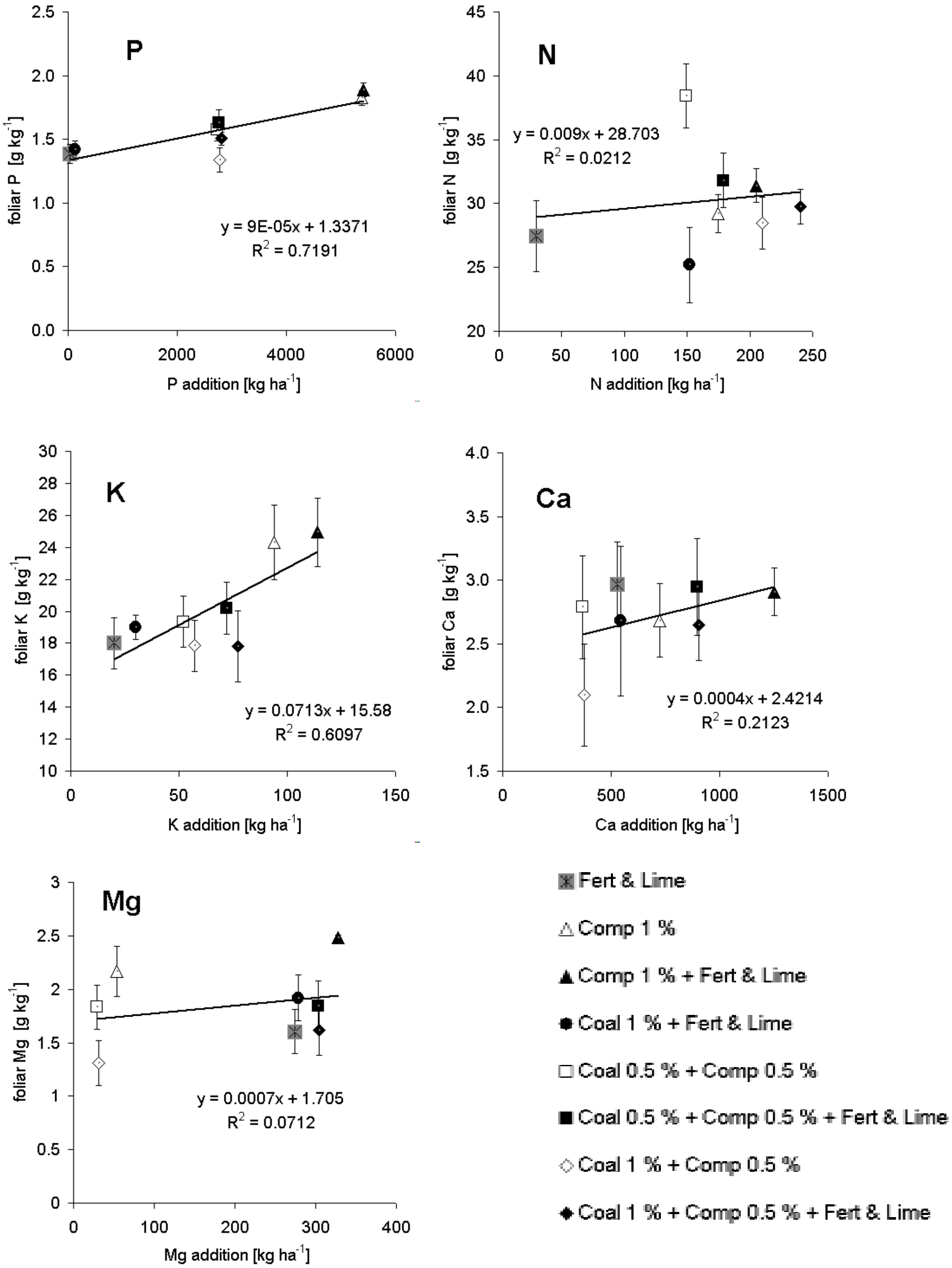


Figure 6: P, N, K, Ca and Mg addition to soil and corresponding foliar contents of upland rice (*Oryza sativa* L.) at early flowering grown with different combinations of charcoal, mineral and organic fertiliser applications on a Xanthic Ferralsol; error bars show standard errors (N=5)

For K, higher nutrient additions were reflected in higher foliar K contents. The trend is distinct, but with 0.6 the correlation coefficient R^2 is not very high. At the ***Coal 1 % + Comp 0.5 % -*** treatments further K addition did not lead to higher foliar K contents.
The relationship for added Mg and foliar Mg contents shows similar behaviour like that for N. Increasing the added amount did not lead to proportional increase of the foliar contents. Especially for Mg, the increase of added amounts by fertiliser application was without response. The mineral fertilised and limed and the not fertilised treatments are sharply separated on the category axis by the added amounts range, but showed the similar level of foliar contents.

3.4 Nutrient Uptake

The nutrient uptakes were computed using the foliar nutrient contents and the leaf biomass data from the end of the experiment. There are no uptake data available for Ca, because of missing data for foliar contents of Ca (Figure 7).

3.4.1 Phosphorus Uptake

The solely charcoal amended treatment (***Coal 1 %***) showed the lowest P uptake which is not significantly different to the uptake of mineral fertilised and limed treatments without the full amount of compost (***Fert & Lime*** and ***Coal 1 % + Fert & Lime*** and ***Coal 0.5 % + Comp 0.5 % + Fert &*** **Lime** and ***Coal 1 % + Comp 0.5 % + Fert & Lime***). The treatments ***Control*** and ***Fert & Lime*** and ***Coal 1 % + Fert & Lime*** and ***Coal 1 %*** were not significantly different at the 5 % significance level.
The charcoal increase step on the additionally compost amended treatments and the additionally compost amended and fertilised and limed treatments lead not to higher P uptake rates.
Fertilisation showed no beneficial effects on the P uptake rates, which had lead to significant differences compared to apart from fertilisation similar treatments.
The addition of fertiliser lead not to the same high uptake rates as the addition of the full dose of compost. At the compost-amended treatments with only 0.5 % compost, additional mineral fertilisation and liming lead to uptake rates comparable to the highest uptake rate of the ***Comp 1 % + Fert & Lime*** treatment. Without fertilisation, the P uptake decreased below the highest level.

3.4.2 Nitrogen Uptake

Nitrogen uptake generally showed the similar pattern of the distribution of high and low uptake rates at the different treatments. In contrast to P, N uptake rates are more differentiated.

Exclusive charcoal application (***Coal 1 %***) did not lead to higher values for N uptake compared to the control treatment. Furthermore, the exclusively charcoal amended treatments show the lowest N uptake rate. The combination of charcoal and fertiliser and lime (***Coal 1 % + Fert & Lime***) did not increase the N uptake rate compared to the treatments ***Coal 1 %*** and ***Control***. The application of mineral fertiliser and lime alone (***Fert & Lime***), without charcoal, showed significantly higher uptake rates than ***Control*** and ***Coal 1 %***.

The highest N uptake rates were found at all compost-amended and mineral fertilised and limed treatments and on the solely mineral fertilised and limed treatment. The highest uptake was found at the treatment ***Comp 1 % + Fert & Lime***.

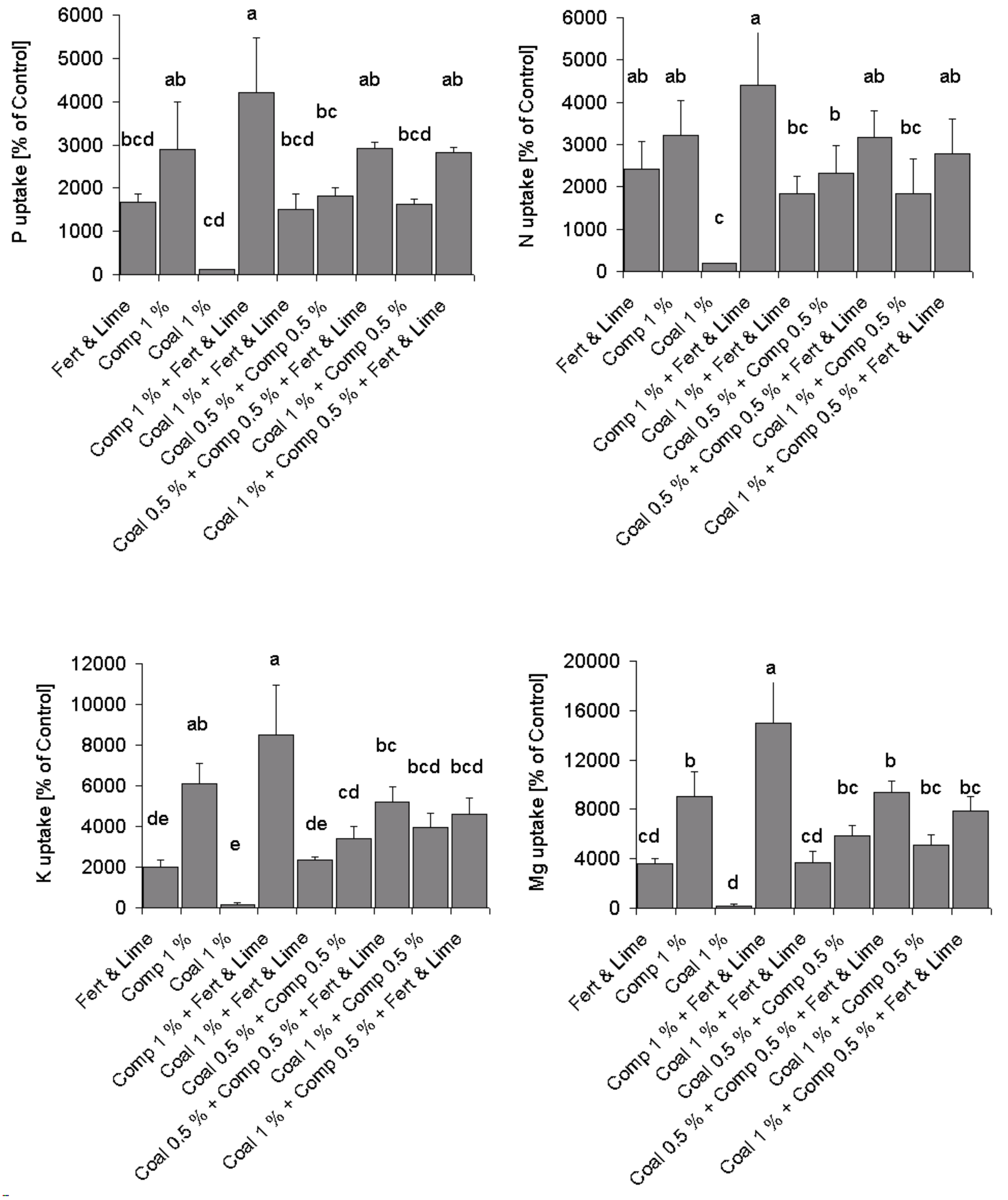


Figure 7: P, N, K and Mg uptake of upland rice (*Oryza sativa* L.) grown with different combinations of charcoal, mineral and organic fertilisers on a Xanthic Ferralsol in relation to uptake of the solely fertilised and limed treatment;
bars with the same letter are not significantly different at P<0.05 (N=5); error bars show standard errors

3.4.3 Potassium Uptake

Charcoal application without any other amendment did not lead to increased K uptake rates compared to the control. The combined application of mineral fertiliser, lime and charcoal did also not increase the K uptake significantly compared to the control treatment. Furthermore, there is no significant difference between the treatments ***Fert & Lime*** and ***Coal 1 % + Fert & Lime***.

The combination of compost and fertiliser and lime (***Comp 1 % + Fert & Lime***) showed the significantly highest uptake rate in the experiment. All other compost amended treatments showed similar uptake rates except the treatment ***Coal 0.5 % + Comp 0.5 %***, which showed a significantly lower K uptake. The charcoal amount increase step did not result in increased K uptake rates of the compost amended and the compost amended and mineral fertilised and limed treatments.

3.4.4 Magnesium Uptake

The Mg uptake showed the same pattern of distribution of high and low uptake rates like the K uptake rates (Figure 7) except, that the uptake rates of the treatments ***Comp 1 %*** and ***Comp 1 %*** + ***Fert & Lime*** are significantly different. As for the other nutrients, the fully compost amended and fertilised treatment showed the highest Mg uptake rate of the experiment.

3.5 Financial Benefits of Charcoal Application

The market prices for the amendments were very high compared to the gross incomes through rice production. Countable positive net benefits could only be yielded without use of mineral fertiliser and lime in the scenario "autarky". The charcoal and compost amended treatments showed comparatively high net benefits, which were only exceeded by the fully compost amended treatment.

All net benefits calculated in the scenario "market" are negative.

Table 8: Cost-benefit approximation for the production of upland rice (*Oryza sativa* L.) on a Xanthic Ferralsol in Central Amazonia amended with charcoal, mineral and organic fertilisers

treatment	rice yield	gross income	costs	net benefit
			Scenario market ***Scenario autarky***	
	[kg ha^{-1}]	--------------[R$ ha^{-1}]--------------		
Control	15	2	0 ***0***	2 ***2***
Fert & Lime	1360	204	941 ***941***	-737 ***-737***
Comp 1 %	5328	799	17369 ***0***	-16570 ***799***
Coal 1 %	100	15	3670 ***0***	-3655 ***15***
Comp 1 % + Fert & Lime	7261	1089	18310 ***941***	-17220 ***148***
Coal 1 % + Fert & Lime	1778	266	4611 ***941***	-4344 ***-674***
Coal 0.5 % + Comp 0.5 %	2874	431	10519 ***0***	-10088 ***431***
Coal 0.5 % + Comp 0.5 % + Fert & Lime	5208	781	11460 ***941***	-10679 ***-160***
Coal 1 % + Comp 0.5 %	3720	558	12354 ***0***	-11796 ***558***
Coal 1 % + Comp 0.5 % + Fert & Lime	4762	714	13295 ***941***	-12581 ***-226***

4. Discussion

4.1 Short-Term Effects of Combined Application of Charcoal, Mineral and Organic Fertilisers on Rice Yield and Crop Nutrition

Plant nutrition and rice yields in the first cropping period are first clues for the success of charcoal application for soil fertility improvement. The financial success in the first cropping period after slash-and-char is of great importance for the acceptance and realisation of slash-charring as a soil fertility improving soil preparation method. Especially smallholders depend on fast financial return of investment. The yields of the first cropping season are of limited value for the assessment of the long-term benefit. Therefore, only the short-term benefit can be discussed here.

The solely addition of charcoal resulted in a 7 times higher yield compared to the control. This cannot be the effect of an increased nutrient supply of the investigated exchangeable nutrients, because there were no significant differences between both treatments (Table 5). It can be an effect of other increased macronutrients like N, P or of micronutrients. The yield improvement can also be the result of indirectly nutritive effects. One example for such effects is the increased water retention in the topsoil. This effect was already described by TRYON (1948) for clayey and sandy forest soils, which showed decreased evaporation losses of water after charcoal addition. The appearance of droughts seems to be absurd in regard to the intensive rainfall of the region. Due to high evaporation and fast infiltration rates of the well-drained soils, this is partly a serious problem, as experienced during this experiment. A second benefit of charcoal is its potential for the adsorption of allelopathic substances, which can be phytotoxic and thereby inhibit seeds from germination. Adsorption of such substances at charcoal surfaces would inactivate it (NILSSON, 1994).

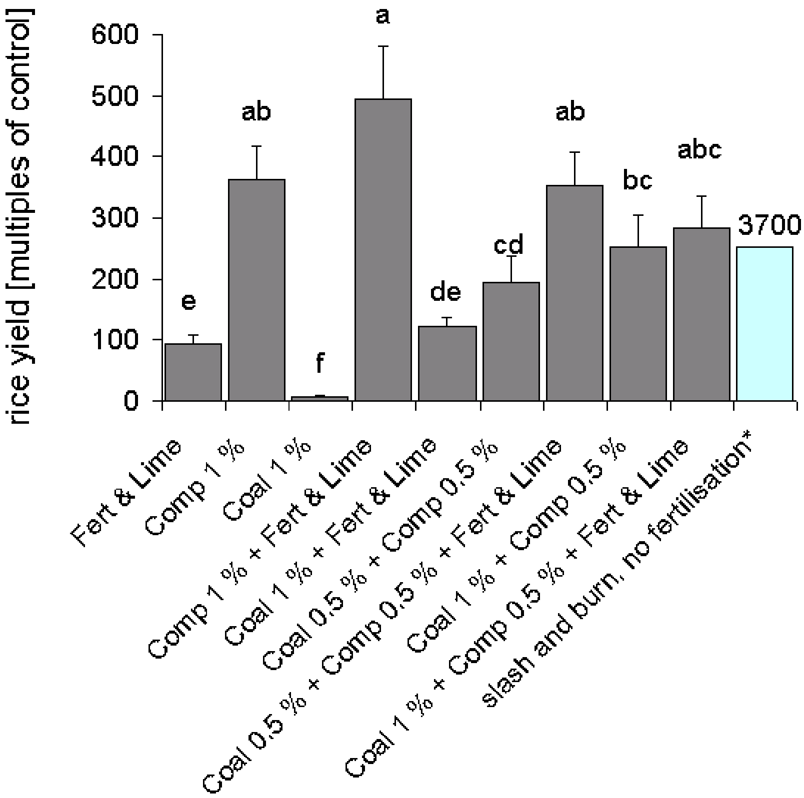


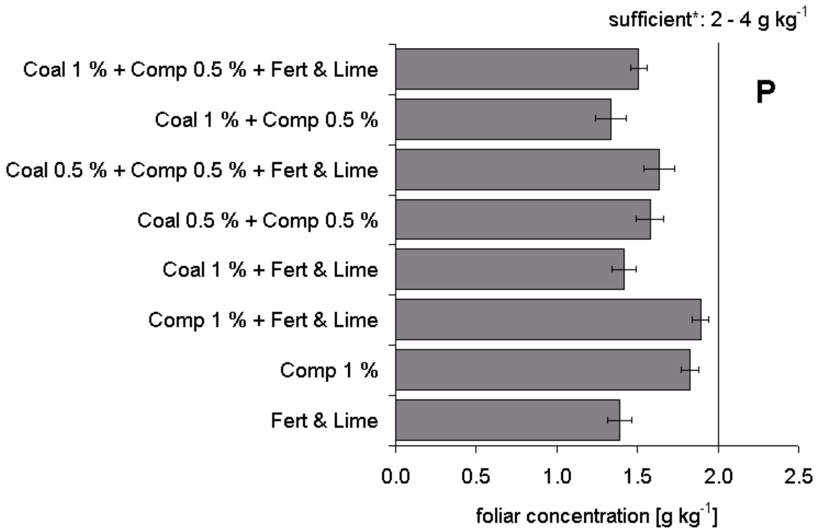
Figure 8: Yield of upland rice grown on a Xanthic Ferralsol in Central Amazonia amended with mineral and organic fertilisers in relation to control and compared to rice yield of a common slash-and-burn site;
Heights of the bars indicate the quotient of the individual treatment and the control; bars with the same letter are not significantly different at $P<0.05$ (N=5); * yield of upland rice on an Ultisol in Yurimaguas, Peru from a slash-and-burn site without fertilisation; the value at the top of the bar indicates the absolute yield in [kg ha^{-1}] (SANCHEZ, 1976)

With 100 kg ha^{-1} the total yield of the exclusively charcoal amended treatments is very small and not acceptable for practical use (Figure 8). The reason for that low yield improvement is that charcoal addition itself was not an appropriate addition of immediately available nutrients at the required amount (Table 2). The delayed maturity of both treatments, the control and the solely charcoal amended plots, indicates substantial deficiencies in nutrition.

The ash content of charcoal determines the amount of immediately available nutrients. The commercial charcoal production process is optimised in terms of the reduction of burning and ash production, which is contrary for the charcoal production efficiency. Therefore, the ash content of commercially available charcoal is certainly much lower than the content in char, which is produced in the field using more simple charring technologies. The potential of such charcoal to act as an immediate inorganic fertiliser could be higher than that of the commercial charcoal, which was employed in this experiment. The characteristic impact of commercial charcoal on soil is more like a conditioner than like a fertiliser.

Application of mineral fertiliser and lime was tested as a conventional option for improving the immediately available nutrient supply. In terms of yield improvement, the additional application of mineral fertiliser and lime to charcoal amended plots (***Coal 1 % + Fert & Lime***) is without response compared to the ***Fert & Lime*** treatment. With 1788 and 1360 kg ha^{-1} respectively, both treatments show disappointing yields compared to the average rice yield in South America of 3000 kg ha^{-1} (FAO, 1995 cited in REDDY AND HODGES, 2000). According to LANDON (1991), these yields are just between "typical unimproved smallholder yields" (500-1500 kg ha^{-1}) and "average farmers yield: rainfed" (1500-2500 kg ha^{-1}). The low yields of the treatments ***Coal 1 % + Fert & Lime*** and ***Fert & Lime*** can be explained at least by, according to, significant deficiencies in P, N, Ca and Mg nutrition (BERGMANN, 1986) (Figure 9). The yields of these treatments are also very small in contrast to compost-amended treatments.

All treatments including charcoal and compost are nearly equal to the average yield of 3000 kg ha^{-1} in South America (FAO, 1995 cited in REDDY AND HODGES, 2000) even without the use of mineral fertilisers. This can be the result of the high nutrient doses applied through compost (Table 2) and the slow but continual release of it during the cropping season. It can also be a result of the increased water retention of the topsoil due to higher contents of humic substances (SCHEFFER AND SCHACHTSCHABEL, 1998). However, rice from the compost and charcoal amended treatments showed nutrition deficiencies in P, Mg and Ca. Especially the treatment ***Coal 1 % + Comp 0.5 %***, which was amended with the full charcoal amount, showed the lowest foliar concentrations and total uptakes of P, N, Mg and Ca of all compost including treatments. The nutrient deficiencies did not reduce the yield compared to the treatment ***Coal 0.5 % + Comp 0.5 %***. At the same time, the yield of this treatment was satisfying according to the South American average yield, even without use of expensive mineral fertilisers (Figure 8). Increased charcoal addition brings no advantages for yield and nutrition of rice.



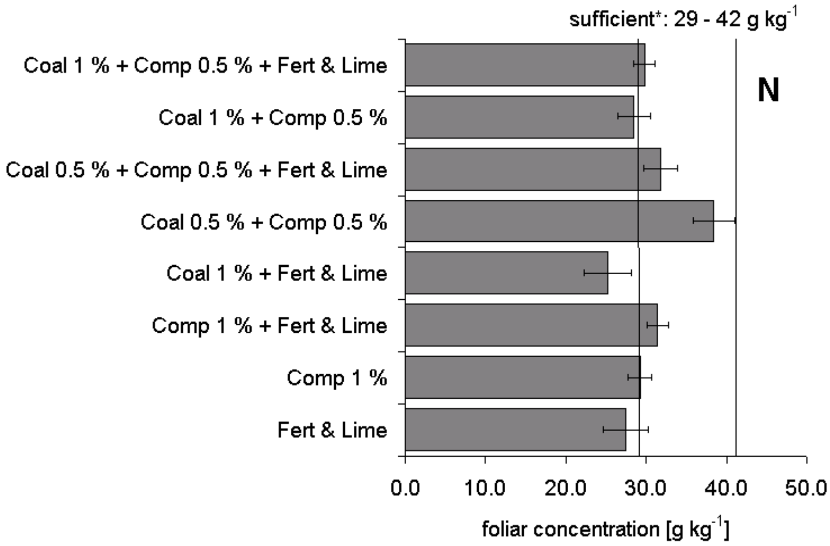
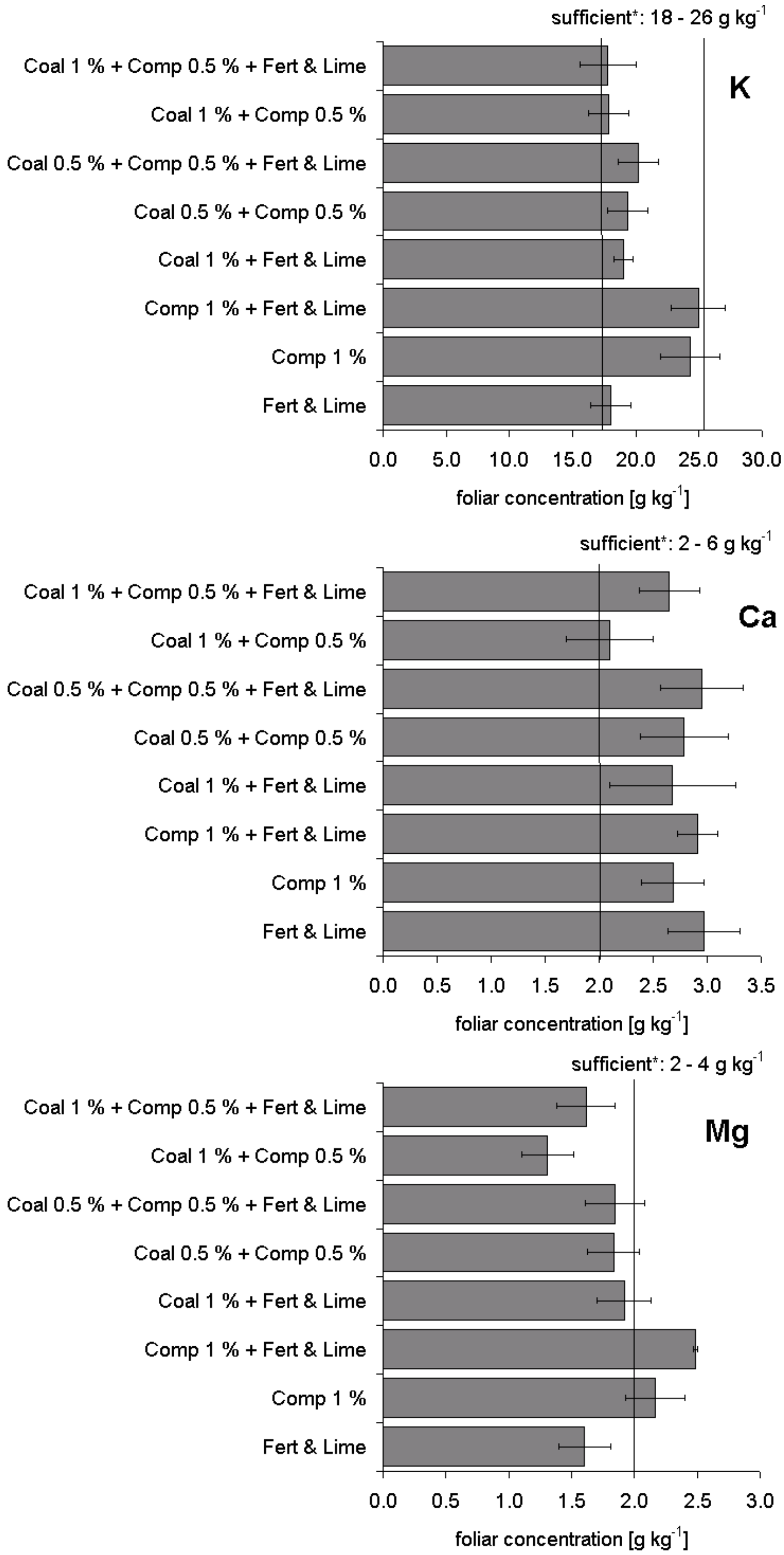


Figure 9: Foliar contents of P, N, K, Ca and Mg of upland rice (*Oryza sativa* L.) at early flowering grown with applications of charcoal, mineral and organic fertilisers on a Xanthic Ferralsol in Central Amazonia compared to sufficient nutrient contents (BERGMANN (1986); error bars show standard errors (N=5)



Continuation of Figure 9: Foliar contents of K, Ca and Mg of upland rice (*Oryza sativa* L.) at early flowering grown with applications of charcoal, mineral and organic fertilisers on a Xanthic Ferralsol in Central Amazonia compared to sufficient nutrient contents (BERGMANN, 1986); error bars show standard errors (N=5)

The ***Coal 1 % + Comp 0.5 %*** treatment shows a very similar rice yield as it was found for a common not mineral fertilised slash-and-burn agriculture for Amazonia practised on an Ultisol in Yurimaguas, Peru (SANCHEZ 1976). Thus, the application of compost and charcoal is an alternative to slash-and-burn concerning the rice production of the first year. In contrast to mineral fertiliser, compost can be gained directly from the slash-and-char site without further capital demand as it is needed for mineral fertiliser. Furthermore nearly every kind of organic waste can be used for on-site production of compost. Besides its character as a source of slow releasing nutrients, compost application was an addition of easy degradable organic material, which is needed for the microbial co-metabolic oxidation of BC, which would be necessary for the development of long-term beneficial characteristics of charcoal in the soil (GLASER et al. 2001).

In the first cropping period, farmers would not have to cope with smaller yields if they would change to charring and composting the biomass of a slashed site. Further investigation is needed to assess the long-term benefit of combined charcoal and compost application.

Because of too small yield improvement, the additional application of mineral fertiliser and lime to charcoal and compost amended treatments would result in a financial loss according to market prices for rice (BRESEGHELLO AND STONE, 1998) (Table 8). Furthermore, the additional mineral fertiliser and lime application was not reflected in a better plant nutrition. The same deficiencies in P, Mg and Ca were found for rice from these plots.

The yield improvement through fertilisation and liming of compost including treatments compared to the not mineral fertilised ones, could have two reasons: the pH-increasing effect of lime and the further nutrient addition by Nitrogen, Phosphorus, Potassium fertiliser (NPK). Apart from Mg, the recommended doses for all macronutrients were exceeded (BRESEGHELLO AND STONE, 1998) by application of compost. The nutrient addition through NPK fertilisation is small compared to the nutrient content of compost (Table 2). The mineral fertiliser and lime addition results in a yield increase of 1345 kg ha^{-1} compared to the control plots. The additional application of mineral fertiliser and lime to the treatments ***Comp 1 %*** and ***Coal 0.5 % + Comp 0.5 %*** and ***Coal 1 % + Comp 0.5 %*** increases the yields by 1933, 2334 and 457 kg ha^{-1} respectively. Apart from the latter case, the improvements are not only additive but synergistic. The yield improvement seems to be rather an effect of lime application than of additional nutrient supply (see section 4.2). This is remarkable especially considering the fact that also the limed treatments showed lower soil pH values, than recommended for rice growing (LANDON, 1991). Thus, a further increase of the added lime amount is still possible and might result in further yield improvement. This is very important especially in regard to the comparatively low dolomite prices. Beneficial aspects of liming with dolomite would be the addition of Mg and Ca, which were deficiently in all compost and charcoal amended plots. Compared to $CaCO_3$, dolomite is more sustaining, because of slower release and of lower leaching losses. Nevertheless which form will be applied, there is the serious risk of overliming (see section 4.2).

According to recommended sufficient foliar nutrient concentrations for rice at the highest nutrient demand at early flowering (BERGMANN 1986, p.25) rice had P deficiencies at all treatments (Figure 9). One reason is the low pH of all treatments. At pH values smaller than 5.5, formation of Fe- and Al-phosphates leads to not readily plant available, fixed P. For charcoal amended treatments the adsorption of P at the surface of charcoal and the absorption of solved P in pores of the charcoal are other possible processes, which can explain P deficiencies. Absorption in that case means storage of dissolved nutrients in micro-pores of charcoal pieces, which have no or only a limited exchange with the surrounded soil solution. Natural charcoal has pores with maximal diameters of 20 µm (ZACKRISSON et al. 1996). In pot experiments in Bayreuth, the author found the roots of Oat grown directly into pores of charcoal pieces. But not all pores are accessable for fine roots, which have diameters of 10 µm. An amount of 1460 kg charcoal on 1 ha Swedish forest soil had a surface area of 360000 ha (MEYER, 1997). For comparison, approximately 11000 kg charcoal ha^{-1} was applied (Table 3) in this experiment.

Increasing the charcoal amount of charcoal and compost amended treatments, with or without fertilisation, leads to lower foliar P concentrations and lower P uptake while the added amounts of P were similar for both treatments. In Figure 6, that compares the various P applications, the phenomenon of reduced foliar P at treatments with the doubled charcoal amount is clearly demonstrated.

The pH cannot be determining for the differentiation of the treatments by foliar P contents. The ***Coal 0.5 % + Comp 0.5 %*** treatment showed the same low pH value like the treatment ***Coal 1 % + Comp 0.5 %***, but higher foliar P concentrations. Especially the treatment ***Coal 1 % + Comp 0.5 % + Fert & Lime*** showed a significantly higher pH value than the treatment ***Coal 0.5 % + Comp 0.5 %*** but a lower P uptake.

Lehmann et al. (2002, submitted) described a similar trend for a pot experiment. Increased P additions in connection with charcoal also did not result in higher yields or higher foliar P contents. Phosphorus is the limiting nutrient in acidic tropical soils similar than in this experiment. Further worsening of P supply for crops due to charcoal application and resulting crop yield decline is not acceptable for smallholders. The described phenomenon was found for the first cropping season but the behaviour of P in connection with charcoal during further cropping seasons is not known. There may be the opinion of a slow release of plant available P from the charcoal in the next cropping seasons.

In the first cropping season, compost application is the determining step for rice yield improvement. The compost-amended treatments are the most successful treatments. The combined application of charcoal together with organic or organic and mineral fertilisers is also very successful, especially because of the good yields from treatments with lower compost applications. In regard to financial success of rice production, application of mineral fertiliser cannot be recommended. The charcoal increase step was not reflected in higher yields in the first cropping period.

4.2 Charcoal Effects on Available Nutrients and Nutrient Losses

In general, with pH values (KCl) below 4.5 all treatments of this experiment must be classified as extremely acidic (LANDON, 1991). For the Ferralsol investigated in this experiment, the influence of charcoal on soil reaction, also in combination of lime, is of great interest.

Charcoal shows no beneficial influences for the soil reaction (Figure 4) because the content of bases in charcoal was too low. For an immediately increasing of the pH only the ash content of charcoal can be held responsible. Commercially available charcoal consists of only 1 % of ash (FALBE AND ROEMMP, 1996). Perhaps the ash content of more unimproved on-site produced charcoal is much higher. Assuming an ash content of 20 % and that ash only consists of Ca this dose would be only about 4 % of the Ca dose added by lime and fertiliser. This is negligible. Liming is much more effective. Addition of charcoal to ***Fert & Lime*** plots did not result in beneficial effects for the pH. Increasing the added charcoal amount of plots already amended with charcoal, compost and lime amended plots is also not effecting the pH.

Table 9: Decrease of the soil pH (H_2O) during production (134 days) of upland rice (*Oryza sativa* L.) on a Xanthic Ferralsol in Central Amazonia amended with charcoal, mineral and organic fertilisers;
values in the column followed by the same letter are not significantly different at P<0.05; N=5

treatment	[Δ pH 134 d^{-1}]
Control	-0.70 d
Fert & Lime	-0.24 a
Comp 1 %	-0.58 cd
Coal 1 %	-0.71 d
Comp 1 % + Fert & Lime	-0.41 ab
Coal 1 % + Fert & Lime	-0.29 a
Coal 0.5 % + Comp 0.5 %	-0.66 d
Coal 0.5 % + Comp 0.5 % + Fert & Lime	-0.37 ab
Coal 1 % + Comp 0.5 %	-0.66 d
Coal 1 % + Comp 0.5 % + Fert & Lime	-0.46 bc

The decrease of the pH value during the cropping season is significantly higher in plots without lime application than in limed plots (Table 9). For the first cropping season, addition of charcoal brings neither benefits nor disadvantages for soil reaction. Besides that, there might be long-term effects for the soil reaction connected to the effects of charcoal application for the CEC of the topsoil. Theoretically, an increased CEC prevents bases from leaching. Thus, they lead to an increased pH value of the topsoil or at least to a slower acidification.

All treatments strongly require liming after the first cropping season. The low pH value theoretically causes a lack of some nutrients (P, N, K, Mg, Ca, S, Mo) because of fixation in unavailable forms. At the same time, there is an oversupply of Al, which is toxic and leads to root damages for many crops (Al-toxicity). Therefore, increasing the pH value to at least pH 5.5 is a very important measure to enhance soil nutrients availability and to avoid Al-toxicity in tropical acidic soils (LANDON, 1991, SANCHEZ, 1976). Furthermore, liming increases the microbial activity and the decomposition of organic material, which accelerates the further release of mineralised nutrients from SOM (SANCHEZ, 1976). This is the most important reason for the synergistic yield improvement effect of additionally limed compost-amended treatments compared to those without liming. In regard to soil acidifying effect, the application of Ammonium sulphate is - 3 kg CaO per kg N, but it increases the biological activity. The acidifying effect of KCl is negligible and that of OSP is very variable (Landon, 1991).

The risk of soil structure deterioration by excessive liming to values higher than pH 5.5, is serious. In clayey Oxisols and Ultisols the clay component is highly aggregated to stable sand sized aggregates, forming the so-called pseudo-sand structure, which leads to an excellent soil structure regarding the high clay content. The stable granules are formed by clay and amorphous Fe-III-oxides and Al-oxides, which have cementing functions in the tertiary connected structure. Due to overdoses of lime, Fe and Al are exchanged by Ca^{2+}, which cannot serve this function because of one lacking charge. Consequently the aggregates are destroyed, which results in deterioration of the soil structure (SANCHEZ, 1976). A further negative consequence of overliming would be the decreased availability of the micronutrients Fe, Mn, Zn and Cu (LANDON, 1991).

Charcoal application is not accompanied by an increase of ECEC especially not at such low pH. The meaning of an assumed increase of CEC due to charcoal is negligible for yield improvement compared to the effect of the high nutrient supply through compost application. Compost itself perhaps exceeded the number of cation exchange sites of charcoal. By measuring the CEC at the low soil pH, this is not observable because the functional groups of the organic substances are protonated. Their potential for cation exchange is a function of the soil reaction. The analysis for the potential CEC in contrast to the effective CEC would have yielded more valuable hints, especially in the context of further liming and its positive effects, but it was not possible at the *Embrapa* due to technical problems in the laboratory. While the number of variable charged sites of compost decreases with time due to decomposition of humic substances the number of charcoal derived exchange sites theoretically increases due to oxidation of BC

(GLASER, 2001). This is the option for the future. The long-term study, in which this experiment is continued will answer that question.

The changing of available soil nutrient contents during and the remaining available nutrients at the end of the first cropping period are important clues for the sustainability of the slash-and-char system. Changes of the available soil nutrients may have several reasons. Besides of leaching into the subsoil, where crop roots are sparse, losses due to runoff, erosion and lateral flow are thinkable as well as nutrient fixation in unavailable forms. Cross contamination of the treatments due to runoff was prevented by several selective measures (see section 2.2). Erosion due to wind was not a serious problem at the small field, which was bordered by secondary forest (Figure 1). At the actual pH of the soil the fixation of Mg and K e.g. as carbonate is not very realistic. Therefore, leaching is the most relevant process for nutrient losses, especially because of the abundant intense rainfall in Central Amazonia.

Input of nutrients, that means negative losses in Table 6, are possible due to dry and wet deposition from the air, lateral flow and from release of nutrients from unavailable forms to available forms. Nutrient input from the air is relevant only in periods of intensive slash-burning in Amazonia, when metals can be transported in the air as aerosols. This transport is of local relevance and can be excluded, because in the neighbourhood of the experimental field, burning was not observed during the experiment course. The releasing of nutrients from unavailable forms to available forms is the most important process, especially considering the added OSP, dolomite and compost amounts because the amount of primary minerals is very low. Lateral flow cannot be excepted as source or as a sink especially for K, which is very mobile. The uniform values for exchangeable K at the end of the experiment outgoing from significant different levels at the beginning of the experiment may be the result of that lateral flow between the different treatments (Table 5). The exclusively charcoal amended treatment also showed wins for Mg and K (Table 6). The negative losses of that treatment are not the result of increased exchangeable contents of K and Mg at the end of the experiment (Table 5, Table 6) but of the nutrients stored in rice and leaf biomass. The source of these taken up nutrients can be lateral flow as well as nutrient release from the soil. Without further investigation, the source cannot be determined. Because of the low nutrient level of the treatment for both nutrients, the effect of lateral flow is more distinct for this treatment than for others.

Consequently the same effect is registered at the control. Although the barriers for runoff worked properly, which could be evaluated in the field, there might have been cross contaminations at heavy rain events like at the 19 March 2001, when 45 mm rainfall were registered in 3 hours (own observations).

At the ***Coal 0.5 % + Comp 0.5 %*** treatment, the losses of K and Mg are also negative. Because of the much higher starting amounts and the high amount of degradable material, the nutrient win seems to be the effect of nutrient release from organically fixed forms. Charcoal in the soil brings advantages for microbial life. The darker colour of the soil due to the charcoal increases the soil temperature and the charcoal itself contributes a very good living space for microbes where they are save from microbe devouring nematodes (MEYER, 1997). This effect was also observable for the other charcoal and compost amended treatment (***Coal 1 % + Comp 0.5 %***), which shows no significantly different nutrient losses compared to the ***Coal 0.5 % + Comp 0.5 %*** treatment. Both treatments have exchangeable nutrient levels at the end of the experiment, which are among the highest of the experiment.

The charcoal in the treatment ***Coal 1 % + Fert & Lime*** did not prevent it from the highest proportional unproductive Mg loss and also from high K loss (Table 6). As it was shown for the ECEC, charcoal did obvious not develop features, which can retard nutrients from leaching during the first cropping period. On the other hand, the nutrient losses were not measured directly in the soil leachates and so the nutrient losses can also be virtual nutrient losses, to explain by nutrient absorption in micro pores of charcoal. How these nutrients behave in long term is not yet investigated. However, at the end of the cropping season, the ***Coal 1 % + Fert & Lime*** treatment show the same nutrient contents for K, Ca and Mg as the treatment ***Fert & Lime***. Thus, exclusive application of charcoal shows no beneficial effects for the stock of available nutrients for the second crop.

Combined application of charcoal and compost reduces the proportional nutrient losses compared to solely compost amended and compared to only mineral fertilised and limed treatments.

5. Conclusions and Implications for Future Research

Charcoal application without any other amendment like compost, cannot be recommended, although it significantly improves the rice yield of first cropping period. Compared to common slash-and-burn practice this yield is much to low. With application of charcoal alone, no beneficial effects for soil fertility can be gained during the first cropping season. Further investigation is needed to validate the predicted long-term benefit of charcoal application.

The combined application of charcoal and mineral fertiliser is useless compared to the small yield improvement and regarding the lacking beneficial effects on nutrient stocks for future crops and is not improving the farmers income. The plant nutrition concerning micronutrients should be an objective of further research in order to get recommendations for micronutrient application. In that context, mineral fertilisers could be important for future yield improvement.

Application of charred and composted material instead of mineral fertiliser is a successful soil fertility improving strategy in terms of yield improvement, reduction of unproductive nutrient losses from the soil and nutrient resource saving for future crops. The yields of the first cropping season were comparable to common slash-and-burn practise. The introduction of the slash-char-and-compost technique would not reduce the financial benefit through the first crop. The long-term benefit of this land use technique should be investigated in order to get recommendations for the optimal amounts of compost. Further application of mineral fertiliser is a measure for further yield improvement but results in financial loss in case of rice. For cash crops, the additional fertilisation with mineral fertilisers might be recommendable.

The highest rice yields of this experiment were shown by the treatments ***Comp 1 %*** and ***Comp 1 % + Fert & Lime***. Apart from P, these treatments showed no nutrition deficiencies for the other investigated nutrients. The application of mineral fertiliser would also not lead to economic success. The costs of fertiliser and lime exceed the benefit of higher yields and almost the income of the whole yield (Table 8). For cash crops the situation might be different. Compost as organic matter is affected by the fast decomposition rates in the tropics. From that point of view there is no sustaining effect and compost application cannot explain the formation of Terra preta. From the practical point of view, compost application is highly recommended for yield improvement.

The added charcoal amounts are realistic proceeding from the charrable biomass data of secondary forests. Assuming that only the not charrable components of the secondary forest vegetation like twigs, branches, leafs and annual plants are composted, the compost amounts are not realistic without biomass import. For practice the broad, unspecific application of compost and charcoal is not economic but a wasting of resources especially because of composts character as an organic fertiliser. The effective charcoal and compost amounts for plants can be increased by specific application into planting holes or into planting grooves, especially for cash crops like banana, pepper or passion fruit. With increased charcoal amounts, the charcoal might serve also as a source of nutrients. Fixation phenomenons, especially for P, related to charcoal amount increase must be investigated in column experiments in the laboratory using different forms of nutrients, different charcoal amounts and different soils. The analysis of the breakthrough characteristics for different nutrients would be of interest in this connection.

The predicted improvement of the CEC by charcoal application is not observable after the first cropping period. The hypothesis of BC oxidation and the connected development of carboxylic groups should be prooved in the following cropping seasons. A comparison of the different contents of carboxylic groups of different aged charcoal is recommended. The use of solid phase ^{13}C NMR (nuclear magnetic resonance) spectroscopy can provide valuable information about the process of oxidation and about the time needed therefore. Without this proof it is hardly possible to justify charcoal application to soil instead of selling the charcoal. In the *Terra preta* the carboxylic groups might have developed over centuries. For smallholders this is not an alternative. In that context the application of powdered charcoal waste from commercial charcoal production should be promoted, because this is gratis.

The simple nutrient balance showed in this study should be sophisticated by considering the additional nutrients Ca, P and N and by employing soil solution data connected to a respective water balance model. Chemical analyses of charcoal (pieces or after density separation) would deliver further hints for the fate of lost nutrients.

Organic farming is possible and profitable even in highly weathered, acidic soils like Oxisols in Central Amazonia. Mineral fertilisers can be substituted by on-site produced charcoal and compost without any yield depletions compared to yields of mineral fertilised rice. For moderate pH increasing, the application of lime is highly recommended. Besides compost, other forms of organic matter, like chicken manure[5], can be applied in order to gain beneficial effects concerning the soil acidity.

The pest and disease problem was not an objective of this experiment but might be serious. Further investigation is needed concerning beneficial effects of charcoal for crop disease control.

[5] analysed chicken manure from a commercial chicken farm contained around 25 g kg-1 of Ca (own unpublished data)

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Appendix

Table A: Applied amounts and nutrient loads of charcoal and compost

amendment	amounts	price	C	N	P	K	Ca	Mg
	[kg ha^{-1}]	[R$ ha^{-1}]	----------------------------	----------------------------	[kg ha^{-1}]	----------------------------	----------------------------	----------------------------
charcoal 25 %	11121	3760	7500	122	81.5	9.89	14.24	3.56
charcoal 12.5 %	5561	1880	3750	61.2	40.8	4.95	7.12	1.78
compost 25 %	99251	17369	7500	175	5377	94.3	722	53.6
compost 12.5 %	49625	8685	3750	87.7	2689	47.2	361	26.8

Table B: Applied amounts of mineral fertiliser and lime

element	fertilisation as recommended*					fertilisation as employed in this experiment					
	quantity	form	elemental content	elemental dose		form	quantity		elemental dose		price
	[kg ha^{-1}]		[%]	[kg ha^{-1}]	[g 4m^{-2}]		[kg ha^{-1}]	[g 4m^{-2}]	[kg ha^{-1}]	[g 4m^{-2}]	[R$ ha^{-1}]
N	142.9	$(NH_4)_2SO_4$	21	**30.00**	12.00	$(NH4)_2SO_4$	142.9	**57**	30.00	12.00	83.09
P	**80**	P_2O_5	43.6	34.88	13.95						
		OSP	8			OSP	436	**174**	34.88	13.95	273.37
K	**60**	K_2O	83	49.80	19.92						
		KCl	52.4			KCl	95	**38**	49.80	19.92	80.33
Mg	**2100**	**Lime**	13	273.84	109.54	Lime	2100	**840**	273.84	109.54	504
Ca	**2100**	**Lime**	21.7	456.52	182.61	Lime	2100	**840**	456.54	182.62	
		OSP	16.5			OSP	436	**174**	71.94	28.78	

* Breseghello and Stone, 1998

Rain data was estimated daily by using a HELLMANN-pluviometer.

Table C: Measured rain data in the experiment course

date	quantity [mm]	date	quantity [mm]
31-Jan-01	30.02	29-Mar-01	39.69
01-Feb-01	0.21	30-Mar-01	10.60
02-Feb-01	13.60	31-Mar-01	0
03-Feb-01	1.67	01-Apr-01	0
04-Feb-01	5.21	02-Apr-01	33.02
05-Feb-01	8.51	03-Apr-01	23.33
06-Feb-01	0	04-Apr-01	5.45
07-Feb-01	0.85	05-Apr-01	0
08-Feb-01	21.51	06-Apr-01	45.75
09-Feb-01	2.79	07-Apr-01	0
10-Feb-01	6.39	08-Apr-01	0
11-Feb-01	0.33	09-Apr-01	9.09
12-Feb-01	6.64	10-Apr-01	2.12
13-Feb-01	11.42	11-Apr-01	0
14-Feb-01	5.15	12-Apr-01	41.20
15-Feb-01	8.30	13-Apr-01	2.73
16-Feb-01	0	14-Apr-01	4.85
17-Feb-01	2.94	15-Apr-01	0
18-Feb-01	29.69	16-Apr-01	6.67
19-Feb-01	3.88	17-Apr-01	28.78
20-Feb-01	6.91	18-Apr-01	0
21-Feb-01	2.42	19-Apr-01	10.30
22-Feb-01	2.73	20-Apr-01	0
23-Feb-01	2.73	21-Apr-01	
24-Feb-01	2.12	22-Apr-01	
25-Feb-01		23-Apr-01	5.76
26-Feb-01	1.21	24-Apr-01	29.99
27-Feb-01	31.21	25-Apr-01	6.67
28-Feb-01		26-Apr-01	4.24
01-Mar-01	21.81	27-Apr-01	6.36
02-Mar-01	7.73	28-Apr-01	30.60
03-Mar-01		29-Apr-01	
04-Mar-01		30-Apr-01	13.33
05-Mar-01		01-May-01	
06-Mar-01	37.42	02-May-01	16.66
07-Mar-01	0.61	03-May-01	29.09
08-Mar-01		04-May-01	0
09-Mar-01	16.06	05-May-01	0
10-Mar-01	5.91	06-May-01	0
11-Mar-01	0	07-May-01	20.60
12-Mar-01	0	08-May-01	20.00
13-Mar-01	0	09-May-01	3.94
14-Mar-01	0	10-May-01	0
15-Mar-01	0	11-May-01	6.06
16-Mar-01	0	12-May-01	
17-Mar-01	7.73	13-May-01	0
18-Mar-01	2.42	14-May-01	17.57
19-Mar-01	44.84	15-May-01	10.60
20-Mar-01	6.67	16-May-01	0
21-Mar-01	13.94	17-May-01	0.27
22-Mar-01	4.39	18-May-01	0
23-Mar-01	0	19-May-01	
24-Mar-01	20.91	20-May-01	
25-Mar-01	2.58	21-May-01	10.91
26-Mar-01	41.51	22-May-01	4.39

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Erklärung

Hiermit versichere ich, diese vorgelegte Arbeit selbst verfaßt und keine anderen als die angebenen Hilfsmittel und Quellen verwendet zu haben.

Thomas Nehls