Potential of Pyrolyzed Organic Matter in Soil Amelioration

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Abstract: To secure food supply for the increasing population there is an urgent need to intensify the agricultural production especially in less developed countries of the tropics. There, soils are frequently poor and not suitable for intensive sustainable agriculture because low organic matter contents and minerals with low cation exchange capacity favor nutrient leaching. Under such circumstances, mineral fertilizers such as NPK have shown to be of low value. Recent investigations gave evidence that carbonized materials from incomplete combustion of organic substances (pyrogenic carbon, C_{pyr}) are a key factor for maintaining high levels of soil organic matter in Chernozems of North America and Germany. Also anthropogenic soils of the Brazilian Amazon region (Terra Preta *do Indio*) contain high amounts of C_{pyr}. They contain high amounts of nutrients, whereas the surrounding Ferralsols and Acrisols are less fertile. In this paper we inform about the C_{pyr} contents in Chernozems and in Terra Preta soils, secondly we present some experimental results, carried out to test the hypothesis that pyrolyzed organic matter stabilizes inorganic nutrients such as N, P, and K via cation exchange and sorption and contributes in combination with inorganic fertilizers such as NPK and/or organic manure sustainably to plant production.
Keywords: Soil amelioration, pyrogenic carbon

1 Introduction

There is an urgent need to intensify agricultural production to secure food supply for the increasing population especially in less developed countries of the tropics. There, sustainable agriculture faces large constraints due to low nutrient contents and accelerated mineralization of soil organic matter (SOM). However, SOM is of particular importance for sustainable agricultural use of the heavily weathered tropical soils (Tiessen *et al*., 1994; Zech, 1997). It contributes substantially to nutrient supply, cation exchange capacity (CEC) and to a favorable soil structure (Ross, 1993). A loss of SOM after slash-and-burn, agricultural and pastoral land-use progresses the soil degradation of many tropical soils resulting in unfertile soils after a few years of cultivation. Soil amelioration by application of mineral fertilizers or compost is often unaffordable for poor smallholder farmers or remains ineffective due to the low CEC of the soils or the lack of knowledge about the nutrient release from organic fertilizers (Tiessen *et al*., 1994).

2 C_{pyr} sequestration in chernozems and anthropogenic dark earths

Chernozems contain high amounts of organic matter with a higher contribution of aromatic compounds (e.g. Amelung *et al*., 1997; Zech *et al*., 1997), thus they could be more efficient in sequestering atmospheric CO_2 than other soil types. In former publications it was proposed that polyphenols and condensation reactions, e.g. of lignin degradation products, contributed the major part of aromatic compounds in SOM (Stevenson, 1994). Recent investigations, however, revealed that at least a part of aromatic carbon in these soils is of pyrogenic origin. Recently, the sources of the highly aromatic organic matter in Chernozems have been identified to derive to a major part from incomplete combustion of organic matter (pyrogenic carbon, C_{pyr}) which is assumed to be a key factor for maintaining high levels of stable soil organic matter in these soils (Glaser and Amelung, 2002; Schmidt *et al*., 1998; Schmidt *et* *al*., 1999). An overview on C_{pyr} contents in Chernozems and archaeological soils is given in Table 1. Glaser and Amelung (2002) investigated the accumulation of C_{pyr} in surface soils across the native North American prairies. These soils contain between 2 and 23 Mg C_{pyr} ha^{-1} in the top 10 cm contributing between 3 and 25 % to the total organic carbon, the major proportions of C_{pyr} being mostly found in the clay and silt fractions. (Brodowski *et al*., 2001) found similar values between 10 and 20% in the top 10 cm of German chernozemic soils, whereas according to (Schmidt *et al*., 1999), C_{pyr} in Axh horizons of German Mollisols represented up to 45% of organic C (Table 1).

Even in anthropogenic dark earths, C_{pyr} seems to be responsible for high organic carbon levels (Table 1). For instance, Neolithic Cultures in Central Germany have distinctly favored Chernozems over less fertile soils as settling grounds (Kleber *et al*., 2002). There is ample reason to suppose that large contributions of charred organic carbon to the soil have resulted from such activities and that the strangely patchy distribution of chernozemic soils in Central Germany might be related to such practice. Carbon stocks were elevated by a factor of 2.5, and large contributions of C_{pyr} to the archaeological soil formed about 700 BC confirmed that organic matter aromaticity was higher in the archaeological soil (Kleber *et al*., 2002). (Schmid *et al*., 2002) reported on a large contribution of C_{pyr} to an archeological site in Southern Germany which was occupied during the whole Neolithic period (5,500 to 2,700 BC).

Also in the humid tropics, ancient human activities lead to organic matter rich soils despite the high mineralization rates. For instance, anthropogenic dark earths of the Brazilian Amazon region (Terra Preta do indio or Terra Preta, 0 to 1,000 AD) contain about three times more total organic carbon per hectare (mean 250 $Mg \cdot ha^{-1}$ m^{-1}) compared to the surrounding Ferralsols and Acrisols (mean 100 $Mg \cdot ha^{-1}$ m^{-1}). In Terra Preta soils, pyrogenic carbon contents exceeded those of the surrounding soils by a factor of up to about 70 (Glaser *et al*., 2001b).

Table 1 C_{pyr} sequestration in Chernozems and anthropogenic dark earths

Region	Soil type	C_{pyr} age	C_{pyr} [$g \cdot kg^{-1}$]	C_{pyr} [$Mg \cdot ha^{-1} \cdot m^{-1}$]	C_{pyr} [% TOC]	Reference
North America	Chernozem	unknown	1-15	2—23 (0—10 cm)	5—25	(Glaser and Amelung, 2002)
Germany	Chernozem	unknown	-	-	up to 45	(Schmidt *et al*., 1999)
Germany	Chernozem	unknown	-	-	10—20	(Brodowski *et al*., 2001)
Germany	Anthrosol	5,500—2,700 BC	0.1-25	-	2—35	(Schmid *et al*., 2002)
Germany	Anthrosol	700 BC	0.2-2.4	23	7—13	(Kleber *et al*., 2002)
Brazil	Anthrosol	150AD—500BC	4-24	40-60	up to 35	(Glaser *et al*., 2001b)

3 The potential of C_{pyr} to sequester nutrients

Under the high leaching conditions in upland soils of Central Amazonia, reduction of nutrient losses by leaching is an important aim in order to improve nutrient availability for plants. In a pot experiment, (Lehmann *et al*., 2002a) studied the adsorption of different nutrients by charcoal produced from secondary forest sites of central Amazonia. Immediately after fertilizer application, nutrient contents significantly increased as shown for ammonium (Fig. 1) and leveled off to background levels only 21 days after fertilization. This was also the case with K, Ca, and Mg (data not shown). Leaching from the unfertilized Ferralsol was reduced when charcoal was applied and resembled the low values found in an Anthrosol (Terra Preta) with a high C_{pyr} content (Fig. 1). These results indicate that ammonium was adsorbed by the charcoal and elevated N uptake by rice after the combined application of charcoal and fertilizer (Lehmann *et al*., 2002a) was partly an effect of ammonium retention. This retention could not be found for other cations or anions, because K, Ca, and Mg were in higher supply with charcoal additions (Lehmann *et al*., 2002a).

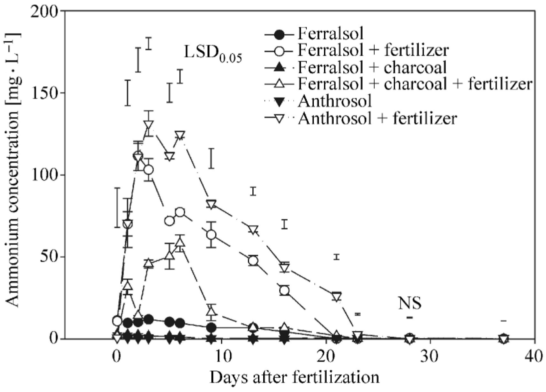


Fig.1 Ammonium concentration in the leachate of a Xanthic Ferralsol amended with charcoal and fertilizer compared to a Fimic Anthrosol; main effects significant at $P <$ 0.001 apart from one (NS not significant $P > 0.05$) (means and standard errors; N=4; Lehmann *et al*., 2002a)

Generally, upland Amazonian soils are poor in nutrients due to prolonged leaching and because the weathering front of the geological substrate is too deep to provide nutrients for plants. Compared to the surrounding Ferralsol, the topsoil of anthropogenic dark earths (Terra Preta) is characterized by a significantly higher cation exchange capacity (CEC) and base saturation (BS) showing a predominance of Ca (Glaser *et al*., 2002). The clay mineralogy, besides SOM the main factor determining the CEC, is predominated by kaolinite in both soils. Due to the low CEC of this clay mineral of 3—15 $cmol_c\ kg^{-1}$ (AG Boden, 1994), the differences in CEC must be related to the SOM. Assuming a mean CEC of SOM of about 200 $cmol_c\ kg^{-1}$ (AG Boden, 1994), it is obvious that SOM in Terra Preta soils contributes more to the CEC than the mineral fraction. In particular, as it is known that a considerable part of the SOM in Terra Preta soils consists of aromatic structures from pyrogenic processes (Glaser *et al*., 2000a; Glaser *et al*., 2000b; Glaser *et al*., 2001a; Glaser *et al*., 2001b; Glaser *et al*., 2002) it is assumed that this imposingly high CEC is caused by partly oxidized pyrogenic carbon forming carboxylic groups on the edges of the aromatic backbone. This assumption is corroborated by the highly significant ($P < 0.001$) correlation between the CEC and the amounts of pyrogenic carbon (Fig.2a) and TOC (Fig.2b). Moreover, from this relationships it can be calculated that one gram of pyrogenic carbon contributes 2.11 $cmol_c$ to the CEC. Compared to the “average” SOM, the contribution of pyrogenic carbon to the CEC is by a factor of 4 higher at least in the soils investigated by (Glaser *et al*., 2002). From this study, it can be concluded that in highly weathered tropical soils, SOM and especially C_{pyr} plays a key role in maintaining soil fertility.

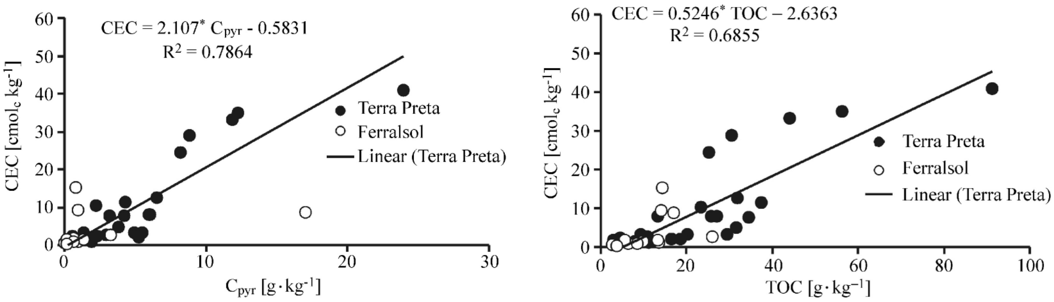


Fig.2 Relation between the effective cation exchange capacity (CEC) and the amounts of A) pyrogenic carbon (C_{pyr}) and B) total organic carbon (TOC) in Terra Preta soils and surrounding Ferralsols in Central Amazonia (N=24, $P < 0.001$)

4 The potential of C_{pyr} to increase crop yields

We investigated whether charcoal additions to highly weathered Ferralsols could increase plant growth. For this aim, three bioassays were done using cowpea (*Vigna unguiculata*), rice (*Oryza sativa*) and oats (*Avena sativa*) as test plants. For the first experiment, mineral fertilizer was compared to manure and charcoal applications on a Xanthic Ferralsol and a Fimic Anthrosol (Terra Preta) in Central Amazonia. The Anthrosol was a relict soil from pre-Columbian settlements with high organic C containing large proportions of black carbon. Only the Ferralsol received 10 % and 20 % (w/w) charcoal (67.6 and 135.2 Mg C ha^{-1}, respectively), which was produced by local farmers originating from secondary forests. The applied amounts of charcoal at 10 % were in the range of projected charcoal yields from the wood biomass of Amazonian forests (Fearnside *et al*., 1999; Fearnside *et al*., 1993) which calculate to 57—66 Mg C ha^{-1} for the topsoil (0m—0.1m) with an estimated mass loss of 70 % during charcoal production 74.8 % from (Correa, 1988). Charcoal additions increased biomass production of a rice crop by 17% in comparison to a control on a Xanthic Ferralsol (Fig. 3) which was shown to be largely an effect of improved P, K, and possibly Cu nutrition (Lehmann *et al*., 2002b). Increasing the amount of charcoal further increased above-and belowground biomass production (Fig. 4).

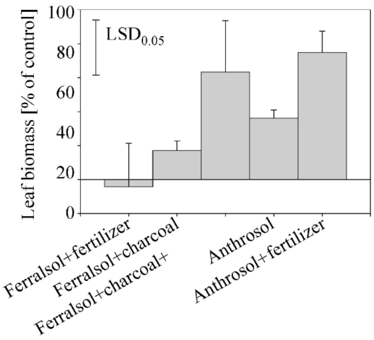


Fig.3 Biomass production of rice (*Oryza sativa*) after additions of charcoal and fertilizer to a Xanthic Ferralsol or a Fimic Anthrosol after 37 days in a greenhouse experiment at 28°C—32°C and 2,500 mm precipitation per year (means and standard errors; N=4; Lehmann *et al*., 2002a)

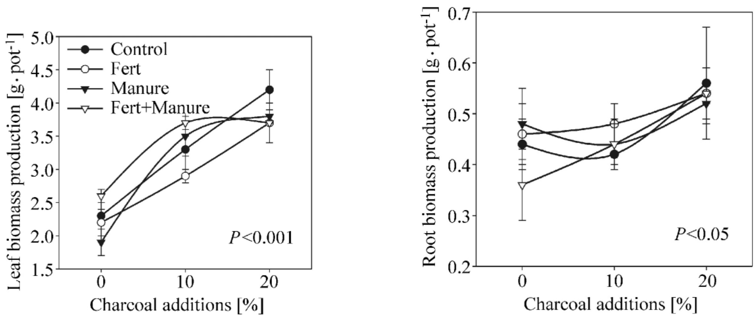


Fig.4 Yields of biomass upon increasing amounts of charcoal applications

For the second bioassay, a pot experiment (N=5) was conducted on a sandy soils (100% sand). The potential of pyrolyzed organic matter alone and in combination with inorganic and conventional organic fertilisers was tested with respect to plant growth of oats (*Avena sativa*) and soil characteristics (EC, pH, CEC, pyrogenic carbon, N, P, and K). The following 6 treatments were investigated: Sand (Control); Sand + charcoal (5%); Sand + charcoal (5%) + NPK; Sand + charcoal (2.5%) + compost (2.5%); Sand + NPK; Sand + compost (5%). Oats were grown during two growing seasons in a greenhouse simulating humid tropical conditions (30°C, 2,000 mm precipitation). Fertilizers were applied only once to study sustainability aspects. Charcoal amendments to sand increased the total biomass production of oats significantly compared to sand alone during the two growing seasons and only after the second growing season for sand fertilized with NPK (Fig.5). During the first growing season, the organic manure treatment was superior to charcoal and charcoal plus organic manure (Fig.5). However, during the second growing season plant height and yields of oats amended with organic manure decreased more dramatically than thosee amended with charcoal and organic manure (Fig.5). This indicates that charcoal additions have positive effects on growth on the long term, although it is clear from these experiments that charcoal alone is not capable of maintaining high crop yields.

The third experiment was a field-trial on Xanthic Ferralsols on the *Terra Firme* north of Manaus. In a randomized complete block design with five replicates 15 treatments were tested (Fig.6). The first crop (rice, *Oryza sativa*) did not show a significant effect of charcoal amendments probably due to masking effects of sufficient nutrient supply on all plots (data not shown). However, during the second growing period (sorghum, *Sorghum bicolor*), the charcoal amendments caused a significant increase in plant growth. There are no plant biomass and harvest data available yet, but plant size measurements 55 days after planting are shown in Fig. 6. Plots treated with charcoal only show the same biomass production as the controls. On these plots (control and charcoal), there was no biomass production at all during the second cropping period. However, a highly significant difference ($P < 0.001$) between NPK plus lime-fertilized plots and plots that received NPK, lime, and charcoal amendments was observed (Fig.6). This confirms the assumption that charcoal has nutrient retention capacities.

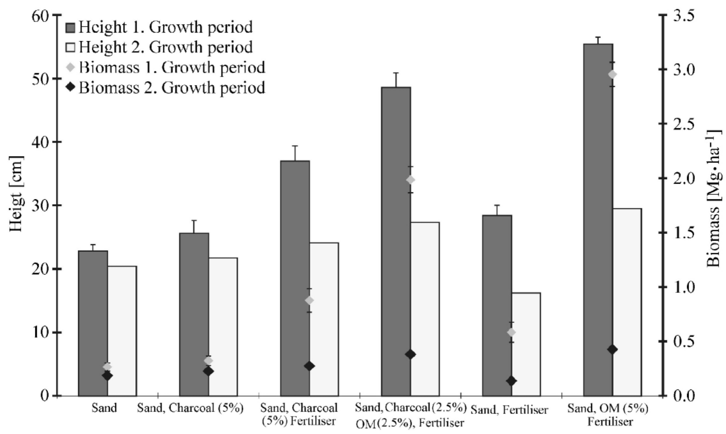
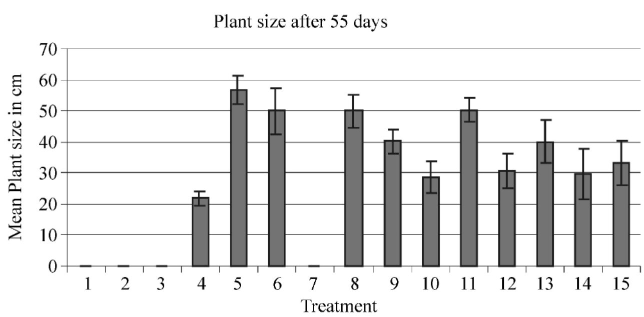


Fig.5 Effect of different fertilizers on plant height and above ground biomass yield of oats (*Avena sativa*) grown during two growing seasons on pure sand in a greenhouse bioassay under humid tropical conditions (28°C—32°C and 2,000 mm precipipation per year, means and standard errors, N=5)



1 control 2 litter
3 burned litter 4 NPK
5 chicken manure 6 OS 25%
7 charcoal 25% 8 OS 25% + NPK
9 charcoal 25% + NPK
10 OS 12,5% + charcoal 12.5%
11 OS 12,5% + charcoal 12.5% + NPK
12 OS 12,5% + charcoal 25%
13 OS 12,5% + charcoal 25% + NPK
14&15 charcoal in pieces + OS

Fig.6 Effect of different fertilizers added prior to the first growing season with rice (*Oryza sativa*) on plant growth of sorghum (*Sorghum bicolor*) variety BR 304, grown during the second growing period on a *Terra Firme* soil (Xanthic Ferralsol), Manaus, Brazil, under natural conditions (28°C—32°C and 2,400 mm precipitation per year, means and standard errors, N=5)

5 Conclusions

The accumulation of C_{pyr} in SOM is favored especially in Chernozems and anthropogenic dark earths, i.e., in soils of highest soil fertility. This gives support to the assumption that similar to fertile soils in the tropics (Glaser *et al*., 2001b), soil fertility might be causally linked to C_{pyr} accumulation. There might even be a positive feed-back loop: High primary productivity of the Chernozems and anthropogenic dark earths promotes C_{pyr} accumulation upon vegetation burning, thus functioning as an effective CO_2 sink in terrestrial environments. The high C_{pyr} contents in the soil, however, are slowly abiotically oxidized, which elevates cation exchange capacity and thus, soil fertility. This again promotes primary plant productivity if nutrients do not limit plant growth.

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