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SHORT COMMUNICATION

Philip G. Oguntunde · Matthias Fosu ·
Ayodele E. Ajayi · Nick van de Giesen

Effects of charcoal production on maize yield, chemical properties and texture of soil

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Abstract The effects of charcoal production on soil textural and chemical properties were investigated in Ejura, Ghana. The aim was to study the effects of heating and charcoal residue on maize yield, soil texture and soil chemical properties. Composite samples were taken from the 0–10 cm layer of soil at charcoal-making sites and from adjacent fields (control). Twelve sites were randomly selected for the study across the range of the *Kotokosu* watershed. Maize was planted in four selected locations on charcoal site soils (CSS) and adjacent field soils (AFS) to assess the impact of charcoal production on crop yield. There was a significant increase in soil pH, base saturation, electrical conductivity, exchangeable Ca, Mg, K, Na and available P in the soil at the kiln sites as compared to the adjacent soils. A relative change of up to 329% was observed in K while organic C and total N decreased by 9.8% and 12.8%, respectively. Organic C and total N were highly correlated ($P < 0.01$) and both parameters significantly ($P < 0.05$) depended on clay minerals in the soils. Soil texture was also modified with a significantly higher sand content and lower clay fraction in the CSS. The grain and biomass yield of maize increased by 91% and 44%, respectively, on CSS as compared to AFS. Further research to ascertain the long-term effects of charcoal production on the soil environment and the fertility of tropical soils is needed.

Keywords Charcoal production · Soil heating · Soil fertility · Maize yield · Ghana

P. G. Oguntunde (✉) · A. E. Ajayi · N. van de Giesen
Centre for Development Research (ZEF),
University of Bonn,
Walter Flex Strasse 3, 53113 Bonn, Germany
e-mail: poguntun@uni-bonn.de
Tel.: +49-228-734973
Fax: +73-228-731889

M. Fosu
Savanna Agricultural Research Institute,
P.O. Box 52, Tamale, Ghana

Introduction

The production of wood charcoal is increasing in Ghana (Ofori-Nyarko 2001). The oldest system of carbonization, in which earth is used as a shield against O_2 and to insulate the carbonizing wood against the excessive loss of heat, is mostly used in charcoal making (FAO 1983). Heat released during pyrolysis can be more than that generated from slash and burn fires depending on the wood load in the piles, while an incorrectly managed charcoal fire can stimulate local bushfires. Hartford and Frandsen (1992) measured maximum surface temperatures of 400°C during a ground (litter and duff) fire. Temperatures of >500°C have been reported in shifting cultivation fires in Ethiopia (Sertsu and Sanchez 1978). According to Masson (1948), slash-and-burn fires in Senegal reached temperatures of >700°C. In a study conducted recently in Indonesia, severe burning was found to have drastic effects on soil texture and mineralogy (Ketterings et al. 2000). The effects of low, moderate and severe fires on soil physical and chemical properties have been reported (Sertsu and Sanchez 1978; Ulery and Graham 1993; Ketterings and Bigham 2000).

In addition to fire effects on soils, charcoal residues and charred biomass left on the kiln sites could serve to ameliorate and improve the fertility of tropical soils by direct nutrient addition and retention (Glaser et al. 2002). It has been reported that charcoal additions to soil have positive effects on soil properties and enhance soil fertility and productivity (Ketterings and Bigham 2000; Glaser et al. 2002). Increased pH, addition of free bases such as Ca, K, and Mg and enhancement of the cation-exchange capacity (CEC) have shown that added charcoal is not only a soil conditioner but also acts as a fertilizer (Glaser et al. 2002). Furthermore, the addition of charcoal to soil can positively affect seed germination, crop growth and yields (Ketterings and Bigham 2000). A recent review by Glaser et al. (2002) has demonstrated that crop yield can be increased upon charcoal additions to soil especially in the tropics. They presented the relationship between charcoal amendments to soil and crop response for a variety of crop and soil types and identified some research needs, e.g. field testing of charcoal production in tropical agroecosystems. Well-documented studies have been carried out both on fire effects and amelioration properties of charcoal on soils. But there is a need for further investigations on their combined effects especially under field conditions.

The aims of this study were to investigate the effect of charcoal production on the texture and chemical properties of soil and on maize yield in the field. The additional effect of fertilizer on maize yield was also studied.

Materials and methods

Study area

The study was carried out in Ejura (latitude 07°20′N, longitude 01°16′W), an area often referred to as the "food basket" of Ghana with agricultural practices ranging from subsistence to large commercial farming. Trees are usually left on farmlands as part of the traditional agroforestry practice to provide shade, fruits or to help conserve organic matter and nutrient status. The climate is wet semi-equatorial with a long wet season lasting from April to October, which alternates with a relatively short dry season that lasts from November to March. Total rainfall for the year 2002 was 1,375 mm but the long-term annual mean is 1,445 mm. The area lies in the Voltaian sandstone basin and is characterized by gently dipping or flat-bedded sandstones, shales, and mudstones, which are easily eroded. This has resulted in an almost flat and extensive plain, which is 60–300 m above mean sea level (Dickson and Benneh 1995).

Experimental plan and analyses

Twelve charcoal kiln sites were randomly selected for sampling purposes. The site information available revealed that charcoal production activity had occurred on the selected sites in the past 2–14 months as at the time of sampling. Soils within and outside charcoal sites were sampled so as to assess the effects of charcoal production on the texture and chemical properties of the soil. Soil of the surface layer (0–10 cm) was sampled by taking ten cores (composite) at each charcoal burning (earth kiln) site and ten cores (composite) from the adjacent field 5–10 m away from the edge of the charcoal site to ensure that the soils for comparison were of similar chemical and textural properties (Aweto and Iyanda 2003). Samples were air-dried, sieved (<2 mm) and analysed for texture (Bouyoucos 1926), total N (Bremner and Mulvaney 1982) and organic C (Allison 1965). Available P was determined by the Bray and Kurtz method (1945) while soil pH was determined with a pH meter in 0.01 M $CaCl_2$ solution using a soil:solution ratio of 1:2.5. Extracts of soil exchangeable cations were obtained by leaching the soil with 1 M neutral CH_3COONH_4. Soil exchangeable K and Na were determined using a flame photometer and Mg and Ca by an atomic absorption spectrophotometer. Soil CEC was determined as the sum of exchangeable cations and acidic cations. Electrical conductivity was measured with a 0.02 M KCl standardized conductivity meter using soil suspended in distilled water (1:5 soil:distilled water).

Maize was planted on four selected charcoal site soils (CSS) and their respective control soils (adjacent field soils; AFS). Four treatments with three replicates each were used to quantify the maize yield: CSS plots sown without fertilizer (C−), CSS plots sown with fertilizer (C+), AFS plots sown without fertilizer (A−) and AFS plots sown with fertilizer (A+). NPK (15–15–15) fertilizer was applied at a rate of 150 kg ha^{-1} based on the prevailing local management practice. The total maize aboveground dry matter and grain yields were determined at maturity.

Statistical analyses

The mean properties of soils within and outside the charcoal sites were compared by using Student's *t*-test. A simple relationship expressed in Eq. 1 was used to compute the relative change of the soil properties:

$$\mathrm{RC}(\%) = \frac{P_\mathrm{C} - P_\mathrm{A}}{P_\mathrm{A}} \times 100 \qquad (1)$$

where RC is the relative change in percent, P_C is the soil property measured on the charcoal soils and P_A is the soil property measured on the AFS. A test of mean differences between maize yield treatments was carried out using a least significant difference (LSD) post-hoc test.

Results and discussion

Charcoal-making effects on soil quality

The mean and the coefficient of variation (CV) of selected soil properties are shown in Table 1. The soils were generally loamy sand in texture and were characterized by low clay contents and a high sand content

Table 1 Mean and coefficient of variation (*CV*) of properties of the 0–10 cm layer of adjacent field soils (AFS) and charcoal site soils (CSS). *RC* Relative change, *CEC* cation exchange capacity

Soil characteristics	AFS		CSS		RC	*P*
	Mean	CV (%)	Mean	CV (%)		
pH	5.8	7.7	7.6	4.8	31.9	**
Organic C (%)	0.9	36.8	0.8	27.5	−9.8	NS
Total N (%)	0.07	30.4	0.06	27.5	−12.8	NS
Available P (mg kg^{-1})	9.1	83.6	22.8	76.4	151.8	*
Exchangeable K (mg kg^{-1})	39.4	45.1	169.1	71.3	329.2	**
Exchangeable Ca (mg kg^{-1})	188.9	27.8	282.2	13.1	49.4	**
Exchangeable Mg (mg kg^{-1})	93.3	9.8	106.7	6.9	14.3	**
Exchangeable Na (mg kg^{-1})	3.7	65.0	9.8	22.6	168.7	**
CEC (cmol kg^{-1})	4.5	45.1	4.8	25.8	6.0	NS
Electrical conductivity (mS cm^{-1})	26.5	17.2	59.5	38.1	124.6	**
Base saturation (%)	60.0	42.0	69.2	26.4	35.8	*
Sand (%)	78.4	4.9	82.8	3.4	5.6	**
Silt (%)	15.9	18.1	14.2	15.7	−10.5	NS
Clay (%)	5.7	45.9	3.1	41.2	−45.2	**

* $P<0.05$, ** $P<0.01$, *NS* not significant

resulting in a poor structure. Sand, the dominant inorganic mineral fraction accounted for >75% of the mineral fragments in the soils on both AFS and CSS. Sand was also the least variable of all the properties (CV of 3% in the CSS and 5% in the AFS). The mean clay proportion in AFS and CSS was 5.7% and 3.1%, respectively. The clay fraction was the most variable of the three soil textural components with CV>40% on both sites. The soils were of the same textural class (loamy sand) but there were significant differences between textural components of the soils on AFS and CSS with respect to their mean proportions of sand and clay ($P<0.01$), whereas silt fractions did not significantly differ between the two ($P>0.05$). The sand content increased while the silt and clay contents decreased as a result of charcoal making (Table 1). The observed trend may be related to the exposure of the soil to high temperatures resulting in the fusion of clay and silt particles into sand-sized particles (Sertsu and Sanchez 1978; Ketterings and Bigham 2000). The coarsening of severely heated surface soils may eventually lead to a poor water-holding capacity (Ulery and Graham 1993).

The mean organic C in the CSS was slightly lower than that of the AFS with a relative decrease of about 10%; however, the difference observed in this study was not significant ($P>0.05$) while previous studies (Sertsu and Sanchez 1978; FAO 1983) have reported significant changes in the organic C content of soils exposed to fire. Charcoal-C is highly condensed, inert and nearly elemental C, considered as part of the soil organic C (Skjemstad et al. 2002). The highest temperature normally attained by the heat-of-dilution reaction upon addition of H_2SO_4 in the Walkley-Black method is about 120°C. This is sufficient to oxidize the active forms of soil organic C, but not the more inert charcoal-C (Allison 1965). Hence, the contribution of charcoal-C was not measured in the analysis of organic C in this study. This means that CSS soils may in fact be shown to have more organic C if the Walkley-Black method is modified by applying heat immediately after the addition of the H_2SO_4 to bring the temperature to about 200°C. Total N decreased by about 13%, but the difference was not significant at the 5% level. A reduction in soil organic C and total N may depend on the effects of the severe fire as compared to the ameliorating effects of the remnants of charcoal. Soil pH was the least variable amongst the chemical properties with a mean CV of 8% in AFS and a mean CV of 5% in CSS. The mean difference is highly significant ($P<0.01$) and a relative change >30% was observed. The soil was slightly acidic originally but became alkaline after charcoal burning mainly because of the increase in the levels of basic cations. An increased pH has been found in studies related to slash-and-burn and soil amended by addition of charcoal (Glaser et al. 2002). Available P was significantly increased ($P<0.05$) and the relative change was as high as +150% (Table 1). It was the parameter showing the broadest variation in both AFS (CV=83.6%) and CSS (CV=76.4%). Similar results were obtained in a slash-and-burn experiment in Indonesia (Ketterings and Bigham 2000). Organic P constitutes the most important source of P because the sandstone parent material is not a source of soil P (Nye and Stephens 1962). Wood ash was the main source of the increased P due to its large concentration of P. The high increase in available P may also be due to the release of microbial P caused by the high temperatures with consequent soil sterilization. Singh (1994) reported the release of 12 kg available P ha^{-1} from microbial sources after tropical savanna fires. The high increase in total P (151%) suggests that P did not volatilize at the high temperature generated during the charcoal production.

The concentrations of Ca, Mg, K and Na were low probably due to over exploitation of the soil or as a result of the soil parent materials. All the exchangeable cations and electrical conductivity increased significantly ($P<0.01$) on the CSS (Table 1). The relative change varied from 14.3% for Na to 329.2% for K. Potassium was the most varied of all the cations with a CV of 45.1% on the AFS and 71.3% on the CSS. These high CVs are probably due to the variation in the ash content of different trees (wood and bark) used for charcoal production at each of the selected locations. The source of raw materials strongly affected the charcoal's properties and the direct effects of charcoal amendments on nutrient contents and their availability in soil (FAO 1983; Glaser et al. 2002). Ca, with a relative increase of 49.4%, was the dominant cation on both soils, being 188.9 mg kg^{-1} on AFS and 282.2 mg kg^{-1} on CSS. Ketterings and Bigham (2000) reported a significant increase in Ca, Mg and K while Na remained unaffected by exposure to fire. Furthermore, they observed that the exchangeable Ca, Mg, K and Na declined rapidly for 90 days. Our results suggest that the observed increase in these cations was due to their accumulation from wood ashes and/ or charred biomass. Similarly, increased levels of bases as a result of charcoal applications have been reported by Glaser et al. (2002). The increase in the exchangeable cations and pH may be attributed to the dominating effect of charcoal residues as compared to the effects of the severe burn. CEC was very low and the mean values were 4.53 cmol kg^{-1} and 4.80 cmol kg^{-1} on AFS and CSS, respectively. CEC is often low on African soils due to their clay mineralogy. Although CECs did not significantly differ ($P>0.05$) in this study, the observed increase agreed with results given by Glaser et al. (2002), who reported that charcoal made from hardwood increased the CEC of the amended soils.

Soil chemical properties and the textural fractions were inter-correlated for both soils. The highest significant correlation ($P<0.01$) was found between organic C and N ($r^2=0.84$) in AFS and the r^2 (0.64) was lower in CSS. Organic C and N were also significantly correlated ($P<0.05$) with clay contents ($r^2=0.49$ and 0.35, respectively, in AFS) thus confirming what was reported by Ladd et al. (1996). Base saturation and CEC were significantly correlated ($P<0.01$), both in AFS ($r^2=0.71$) and CSS ($r^2=0.74$).

Table 2 Yield and effects of yield components (*YC*) of CSS. *Ci*, *Cj* Paired combination for mean difference (*MD*) comparison and LSD, *MD(i−j)* MD of the respective combinations. *1* CSS plots sown without fertilizer, *2* CSS plots sown with fertilizer, *3* AFS plots sown without fertilizer, *4* AFS plots sown with fertilizer; for other abbreviations, see Table 1

YC (t ha^{-1})	*Ci*	*Cj*	MD(*i* −*j*)	Significance	*P*
Grain	1	2	−1.163	0.001	**
	1	3	0.594	0.050	*
	1	4	0.081	0.771	NS
	2	3	1.757	0.000	**
	2	4	1.244	0.001	**
	3	4	−0.513	0.084	NS
Cob	1	2	−0.106	0.011	*
	1	3	0.094	0.021	*
	1	4	0.003	0.931	NS
	2	3	0.200	0.000	**
	2	4	0.109	0.009	**
	3	4	−0.091	0.025	*
Stalk (root+stem+leaf)	1	2	−1.750	0.041	*
	1	3	1.041	0.199	NS
	1	4	0.109	0.889	NS
	2	3	2.791	0.003	**
	2	4	1.859	0.032	*
	3	4	−0.931	0.247	NS

* *P* <0.05, ** *P* <0.01 levels, *NS* not significant

Effects of charcoal production on maize yield

Mean maize grain yield was 2.36 t ha^{-1} in C+, 1.20 t ha^{-1} in C−, 0.63 t ha^{-1} in A− and 1.12 t ha^{-1} in A+. Yield on the C− treatment was the most variable (CV=31.8%) while the lowest variability of yield was found in the A− treatment. Grain yield increased by 91% in C−, 276% in C+, and 78% in A+ as compared to A− (control). Cob weight varied between 0.28 t ha^{-1} in A−, and 0.48 t ha^{-1} in C+. The increase in maize cob weight ranged from 32% in A+ to 71% in C+. The stalk produced increased by 44% in C−, 120% in C+, and 40% in A+ compared to A−. In related studies, Chidumayo (1994) reported an increase of about 13% in biomass production in some woody plants in Zambia, and Glaser et al. (2002) reported an increase of about 130% in *Cryptomeria japonica* following similar treatments.

Maize yield and yield components were compared using ANOVA and the LSD test (Table 2). There were significant differences in grain yield between C− and C+, at the 1% level. However, no significant difference was observed between C− and A+, whereas the difference between C− and A− was significant (*P* <0.05). There were no significant differences in maize stalk production between C− and A−, or between C− and A+. Ketterings et al. (2000) reported that farmers in Sumatra preferred low to medium burnt soils (darkened soils) to obtain higher crop yields and quicker crop establishment. Recent studies showed that crop yields can be further increased if charcoal is applied together with inorganic or organic fertilizers (Glaser et al. 2002).

In conclusion, charcoal making in an earth kiln increased the percent of sand and decreased the clay and silt contents of soil. In addition pH, available P, electrical conductivity, base saturation, exchangeable K, Ca, Mg, and Na were significantly higher in CSS than in a corresponding adjacent control field. The increase in some of the soil chemical properties, especially the exchangeable cations, may be attributed to the dominating effect of charcoal residues while a reduction in soil organic C and total N contents may depend on the effects of the severe fire during pyrolysis. The results showed an increased nutrient availability due to charcoal residues in the kiln sites. The improved nutrient contents, particularly in C+, resulted in a significant maize yield increase. We suggest that further field-testing of charcoal production should be continued for three or more growing seasons to see the trends in yield, so as to ascertain the long-term effects of charcoal production on the fertility of tropical soils.

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