J. Plant Nutr. Soil Sci. 2008, *171,* 591–596 **DOI:** 10.1002/jpln.200625185 591

Effects of charcoal production on soil physical properties in Ghana

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Abstract

Charcoal production, widespread in Ghana like in other W African countries, is a major driver of land-cover change. Effects of charcoal production on soil physical, including hydrological, properties, were studied in the forest–savannah transition zone of Ghana. Core and composite samples from 12 randomly selected sites across the width of Kotokosu watershed were taken from 0–10 cm layer at charcoal-site soils and adjacent field soils (control). These were used to determine saturated hydraulic conductivity (K_{sat}), bulk density, total porosity, soil texture, and color. Infiltration rates, surface albedo, and soil-surface temperature were also measured on both sites.

The results showed that the saturated hydraulic conductivity of soils under charcoal kilns increased significantly ($p < 0.01$) from 6.1 ± 2.0 cm h^{-1} to 11.4 ± 5.0 cm h^{-1}, resulting to a relative increase of 88%. Soil color became darkened under charcoal kilns with hue, value, and chroma decreasing by 8%, 20%, and 20%, respectively. Bulk density on charcoal-site soils reduced by 9% compared to adjacent field soils. Total porosity increased from 45.7% on adjacent field soils to 50.6% on earth kilns. Surface albedo reduced by 37% on charcoal-site soils while soil-surface temperature increased up to 4°C on average. Higher infiltration rates were measured on charcoal-site soils, which suggest a possible decrease in overland flow and less erosion on those kiln sites.

Key words: charcoal production / soil physical properties / K_{sat} / infiltration rates / reflection coefficient / watershed hydrology

Accepted August 4, 2007

1 Introduction

Charcoal (CC) production is widespread in Ghana in general and around Ejura in particular. Structured survey conducted shows that this activity attracts especially socio-economically weaker groups, such as immigrants, and traditional social controls on resource management tend to be less efficient. Apart from farming, approx. 63% of the respondents were involved in CC making and/or fire-wood selling and that CC production was primarily motivated by the quest for additional income, insurance in case of crop failure, procurement of farm inputs, and at times, to meet up with other socio-cultural needs.

In Ghana, CC is produced by using earth as a shield against oxygen and to insulate the carbonizing wood against excessive loss of heat (*FAO*, 1983). Thermal decomposition of the wood starts when the wood is raised to a temperature of about 300°C. This pyrolysis process, once started, continues by itself and gives off considerable heat with a maximum temperature of approx. 500°C for high efficiency and product quality (*FAO*, 1983). However, higher temperatures may occur due to inefficiency. The amount of heat released during pyrolysis is similar to that from bushfires or shifting-cultivation (slash and burn) fires, depending on period and wood load in the piles. Charcoal production has both heating and amelioration effects on soils (*Glaser* et al., 2002; *Oguntunde* et al., 2004) and hence influences soil properties.

Hartford and *Frandsen* (1992) measured surface temperatures up to 400°C in a ground fire (litter and duff) while temperatures >500°C have been reported in shifting-cultivation fires (*Sertsu* and *Sanchez*, 1978). Studies have shown that severe burning has drastic effects on soil texture, color, mineralogy, and other soil properties (*Sertsu* and *Sanchez*, 1978; *Ketterings* et al., 2000; *Oguntunde* et al., 2004). A significant decrease in clay fraction and a corresponding increase in sand fraction of severely burnt soils (*Oguntunde* et al., 2004) may eventually lead to poor water-holding capacity (*Ulery* and *Graham*, 1993). Low to medium fire severity resulted in darkening of the topsoil while high-severity burns (>600°C) caused pronounced reddening of the topsoil, accompanied by an increase in both Munsell value and chroma (*Ulery* and *Graham*, 1993; *Ketterings* and *Bigham*, 2000).

Fires have been reported to cause increased runoff and erosion losses due to removal of vegetation and water repel-

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lency resulting in reduced infiltration and increased sediment loads in rivers (*Inbar* et al., 1998). *Scott* and *van Wyk* (1990) showed a 200% increase in annual runoff and about 300% for the peak discharges during the year following a forest fire in S Africa. However, *Ueckert* et al. (1978) found that soil bulk density, porosity, and hence rainfall infiltration were not significantly affected by fire in a tobosagrass community. Similarly, the significant impact of fires on surface albedo and soil temperatures has been reported. According to *Scholes* and *Walker* (1993) and *Beringer* et al. (2003), approx. 50% reductions of albedo between pre-fire and post-fire sites have been observed.

Charcoal amendments may affect soil water retention and aggregate stability, leading to enhanced crop water availability and reduced erosion (*Piccolo* and *Mbagwu*, 1990; *Piccolo* et al., 1997). *Tryon* (1948) studied the effect of CC additions on the available moisture in soils with different textures. A positive effect of 18% increase in soil water retention was observed upon addition of 45% (by volume) charcoal to a sandy soil while a decrease of approx. 20% was noted for a clay soil, whereas no change was recorded for a loamy soil, given the same charcoal treatment. Therefore, improvements of soil water retention by CC ameliorations may only be expected in coarse-textured soils or soils with large amounts of macropores (*Glaser* et al., 2002). Evidently, well-documented studies have been carried out on the different fire effects and the ameliorating effects of CC. However, field-testing of the combined effects is still lacking. The aims of this study were to determine the impact of CC-making fires and charred residue on soil physical properties in Ghana where CC production, in addition to bush-fires, is widespread and is a major driver of land-cover change (*e.g., Braimoh* and *Vlek*, 2004a).

2 Materials and methods

2.1 Study Area

The study area is a watershed located near Ejura town, a densely populated rural district approx. 90 km to the NE of Kumasi, Ghana, and lies in the forest–savannah transition zone (07°20′ N, 01°16′ W). 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. Mean total rainfall and temperature, from 1973 to 1993, are 1264 mm and 26.6°C, respectively (*Oguntunde* et al., 2004). The geological formation consists of Voltaian sandstone basin and is characterized by gently dipping or flat-bedded sandstones, shales, and mudstones that are easily eroded. This has resulted in an almost flat and extensive plain, which is 60–300 m asl. The soils in the area, generally Haplic Acrisols, have a high sand content with mean values of about 72% in the topsoil (0–15 cm) and approx. 69% in the subsoil (30–45 cm) (*Agyare*, 2004).

2.2 Experimental measurements and analyses

Based on a reconnaissance survey of Kotokosu watershed, 12 CC kiln sites were randomly selected for sampling purposes. The background information revealed that the selected sites were 2 to 14 months old at the time of sampling. Soils under CC kilns (hereafter refers to as charcoal-site soil, CCS) and soils from the adjacent fields or control (hereafter refers to as adjacent field soil, AFS), 5–10 m away from the edge of the CC kiln, were sampled to assess the effects of charcoal production on selected soil physical and hydrological properties, which include saturated hydraulic conductivity, bulk density, soil color, soil texture, infiltration rates, surface temperature, and albedo.

Saturated hydraulic conductivity, K_{sat}, was determined in the laboratory using the falling-head method (*Klute* and *Dirksen*, 1986); bulk density was determined with the core method (*Blake* and *Hartge*, 1986); total porosity was estimated from particle and bulk densities (*Danielson* and *Sutherland*, 1986); soil color (hue, value, and chroma components) was measured with a Munsell color chart (*Munsell Color Company*, 2000). Composite samples were air-dried, sieved (<2 mm), and analyzed for percent sand, silt, and clay using the hydrometer method (*Bouyoucos*, 1962). Other parameters measured include: surface albedo and soil-surface temperature (T_s) on wet and dry charcoal-site soil and adjacent field soil using an albedometer and a handheld infrared thermometer, respectively. Both parameters were measured at sun elevation angles 20°, 30°, 40°, 50°, 60°, and 70° on cloudless hours of the days Dec. 5, 2002 and Dec. 8, 2002. Infiltration rates were measured on each plot using a 0.5 cm–suction mini-disc infiltrometer having approx. 3.2 cm internal diameter (Decagon Devices, Inc., Washington, USA). A simple relationship was used to compute the relative change of the soil properties between soils under CC kilns and the adjacent fields (control):

$$RC(\%) = \frac{P_C - P_A}{P_A} 100 . \tag{1}$$

Where RC is the relative change (increase or decrease), P_C is the soil property measured on the soils under charcoal kilns, and P_A is the soil property measured on the adjacent field soils. The mean properties of soils within and outside the charcoal sites were compared using Student's t-test. Soil hues were coded as 2.5 YR = 1; 5YR = 2; 7.5 YR = 3, and 10 YR = 4 (*Braimoh* and *Vlek*, 2004b).

3 Results and discussion

3.1 Effects of charcoal making on soil physical properties

The summary of the dataset, showing the mean, minimum, maximum, coefficient of variation (CV), and relative change in selected soil physical properties, is presented in Tab. 1. The statistical analysis for mean and variance-difference comparison of soil properties of AFS and CCS is shown in Tab. 2.

Soils in the control plot have the reddest hue (the dominant spectral color) with a mean of 3.2, the highest value (lightness of color) with a mean of 3.1, and the highest chroma (strength of color) with a mean of 2.1. Among these soil-color variables, values significantly differ between AFS and CSS at

Table 1: Summary statistics for selected soil physical properties on charcoal-site soils (CSS) and adjacent field soils (AFS) in Ejura, Ghana.

Soil parameters	**Minimum**		**Maximum**		**Mean**		**SD**		***CV* (%)**		***RC* (%)**
	AFS	CSS	AFS	CSS	AFS	CSS	AFS	CSS	AFS	CSS	
Hydraulic conductivity (cm h^{-1})	2.7	4.7	9.6	20.6	6.1	11.4	2.0	5.0	33.3	43.9	87.9
Bulk density (g cm^{3})	1.2	1.1	1.6	1.5	1.4	1.3	0.1	0.1	8.5	9.2	–9.0
Total porosity (%)	41.1	44.6	54.6	57.0	45.7	50.6	4.6	4.5	10.1	9.0	10.7
Hue	3.0	1.0	4.0	4.0	3.2	2.9	0.4	1.2	12.3	39.9	–7.9
Value	2.5	2.0	4.0	3.0	3.1	2.5	0.6	0.4	18.2	16.1	–21.3
Chroma	1.0	1.0	3.0	2.0	2.1	1.7	0.5	0.5	24.7	29.5	–20.0
Sand (%)	71.0	80.0	83.0	89.0	78.4	82.8	3.8	2.8	4.9	3.4	5.6
Silt (%)	12.1	10.1	20.1	17.1	15.9	14.2	2.9	2.2	18.0	15.7	–10.5
Clay (%)	2.9	0.9	10.9	4.9	5.7	3.0	2.6	1.3	45.9	44.3	–48.1

Table 2: Summary of statistical tests for selected soil-physical parameters.

Soil parameters	**Levene's test**[a]		**Student's t-test**[b]	
	F-statistic	V_d	t-statistic	M_d
Hydraulic conductivity (cm h^{-1})	7.91	***	–3.42	***
Bulk density (g cm^{-3})	0.08	NS	2.62	**
Total porosity (%)	0.11	NS	–2.61	**
Hue	11.84	***	0.71	NS
Value	1.23	NS	3.33	***
Chroma	1.22	NS	2.03	*
Sand (%)	2.04	NS	–3.23	***
Silt (%)	1.53	NS	1.59	NS
Clay (%)	3.35	*	3.25	***

[a] Levene's test for equality of variances
[b] Student's t-test for equality of means
V_d = variance difference, M_d = mean difference, * = significant at 10%, ** = significant at 5%, *** = significant at 1%, and NS = not significant

1% and chroma at 5% levels, respectively. Mean hue was not significantly different between both soils, but a higher coefficient of variation in CSS (CV = 40%) as compared to AFS (CV =12%) coupled with a highly significant ($p < 0.01$) variance difference (using Levene's test for equality of variance) showed a considerable spatial variation in Munsell hues due to charcoal-production effects. This observation was further supported by computing the redness rating RR ([RR = (10 – YR hue) × chroma] / value) according to *Ulery* and *Graham* (1993). The mean of RR was not significantly different between AFS and CSS whereas its CV is 52% and 98% on both treatments, respectively. This result was similar to previous studies reported on slash-and-burn site in Indonesia (*Ketterings* and *Bigham*, 2000). They found a decrease in Munsell values and chromas of topsoil to increasing temperature up to 600°C and explain, in agreement with *Ulery* and *Graham* (1993), the darkening of the soil to be caused by charring of the organic matter. Other studies also showed a relationship between a deep black soil color and the presence of charred organic matter (*Schmidt* and *Noack*, 2000).

The bulk density of the CSS was generally lower than that of the AFS ranging from 1.1 to 1.5 g cm^{-3} and from 1.2 to 1.6 g cm^{-3}. Average bulk density of soils under charcoal kiln decreased significantly ($p < 0.05$) by 9% as compared to the control. Similar reduction in bulk density following charcoal addition to soil has been reported (*Glaser* et al., 2002), whereas *Ueckert* et al. (1978) found no significant change in bulk density due to soil heating. Generally, the soils were loamy sand–textured. The sand fraction in AFS and CSS ranged from 71% to 83% and from 80% to 89%, respectively. Both sand and clay components of the texture were significantly different in AFS compared to CSS. Both clay and silt particles, on exposure to high temperatures, aggregated to form sand-sized particles leading to a loosely structured soil. The coarsening of severely heated surface soils may eventually lead to poor water-holding capacity (*Ulery* and *Graham*, 1993). *Oguntunde* et al. (2004) discussed in detail the effect of CC production on soil texture in the study area.

Significant increase ($p < 0.01$) of total porosity from 45.7% in AFS to 50.6% in CSS was observed. Porosity showed low variability in both AFS (CV = 10%) and CSS (CV = 9%). Charcoal amendments have been reported to increase macroporosity and total porosity (*Piccolo* et al., 1996), whereas no significant effect was observed from soil burning (*Ueckert* et al., 1978). The observed increase in porosity may be responsible for the reduction in bulk density observed above. Bulk density is often used as a measure of soil structure or compaction as it varies with structural condition of soil related to packing (*Blake* and *Hartge*, 1986).

Saturated–hydraulic conductivity values ranged from 2.7 cm h^{-1} to 9.6 cm h^{-1} (mean = 6.1 cm h^{-1}) in AFS but varied between 4.7 cm h^{-1} and 20.6 cm h^{-1} (mean = 11.4 cm h^{-1}) in CC-kiln soils. Saturated hydraulic conductivity is a spatially highly varied parameter. Its coefficients of variation in CSS and AFS were 44% and 33%, respectively. Under AFS, K_{sat} was significantly ($p < 0.01$) lower than under CSS with the highest relative change (increase) of 88% among all the soil properties reported in this study. According to the classification of *Landon* (1991), the K_{sat} of soils in AFS showed moderate values as compared to high values (rapid-flow characteristics) observed in soils under CC kilns. However, K_{sat} values reported for both AFS and CSS are comparable to those reported from other studies in Ghana (*Agyare*, 2004).

3.2 Surface albedo, soil temperature, and infiltration

Albedo values at six sun-elevation angles are shown in Fig. 1 for soils under charcoal kilns and the adjacent fields. The graph shows a gradual decrease in surface albedo with corresponding increase in sun elevation. Highest albedo values were observed on AFS (dry) and lowest values on CSS (wet). The average for the six sun angles with dry-surface conditions was 0.18 (AFS) and 0.10 (CSS), yielding a 37% decrease, while the values reduced on the wet surfaces to 0.11 (AFS) and 0.07 (CSS), yielding a 30% decrease, respectively. Albedo values were compared using analysis-of-variance test (ANOVA) and least–significance difference (LSD) test (Tab. 3). There were significant differences in albedo values measured on AFS and CSS for both wet- and dry-surface conditions at the 1% level. Among all the paired combinations, albedo of AFS (wet) was not different ($p > 0.05$) from that of CSS (dry). The observed reduction in albedo on CSS as compared to AFS may be directly linked to changes in optical properties of the soils under charcoal kilns. Although pronounced reddening would be expected to characterize the fused soil material (*Ketterings* and *Bigham*, 2000), charred organic matter left on earth kilns seems to dominantly affect the overall appearance of soils under charcoal sites. Similarly, *Scholes* and *Walker* (1993) reported a post-fire reduction of albedo by approx. 50% for the African savanna whereas *Bremer* and *Ham* (1999) found an average of a 43% lower albedo value on burnt sites compared to unburnt sites.

Table 3: LSD test for soil-surface albedo. 1—CSS (wet), 2—AFS (wet), 3—CSS (dry), 4—AFS (dry).

i	*j*	MD(*i-j*)	*p*	Remark
1	2	–0.032	0.003	**
	3	–0.041	0.000	**
	4	–0.103	0.000	**
2	3	–0.009	0.338	*NS*
	4	–0.071	0.000	**
3	4	–0.062	0.000	**

*$p < 0.01$ level, *NS* = not significant

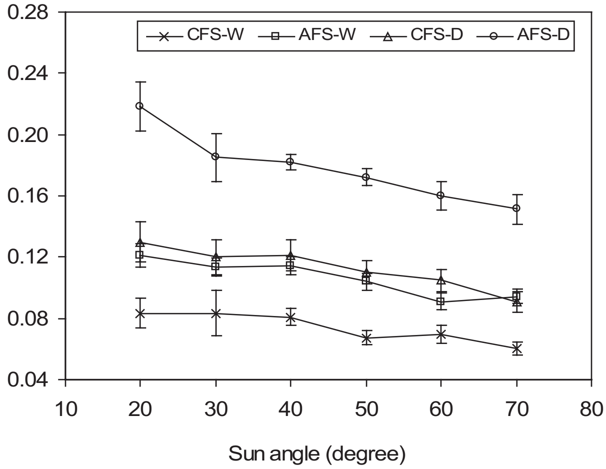

Figure 1: Surface albedo of CSS and AFS under wet and dry moisture conditions and five sun angles. Each data point and the vertical spike are mean and one standard deviation, respectively, computed from five replicates.

Soil surface temperatures and the corresponding ambient air temperature are presented in Tab. 4. Temperature difference (*TD*), between CSS and AFS for wet- and dry-surface conditions (not shown), generally increased with increasing sun angle. Temperature difference ranged from 0.6°C to 4.1°C and from 0.7°C to 8.3°C on wet and dry surfaces, respectively. Higher soil-surface temperature was measured on the CSS relative to AFS. Average air temperatures on the two days were 25.3°C and 26.2°C. These values seem to be low despite the fact that December is a dry period in the study area. The observation may be linked to the prevailing harmattan situation that attenuates the global incoming radiation during this period (*Oguntunde*, 2004). Decrease in albedo, due to the presence of charred matter from CC production, has implications for radiation budget at soil surface. The amount of incoming solar radiation absorbed at CSS increased, leading to increased soil heating and higher soil-surface temperature. This elevated soil temperature may affect soil biophysical processes, such as seed germination, root growth, plant development, and microbial activity (*Potter* et al., 1987).

A plot of cumulative infiltration, from the disc infiltrometer, for both CSS and AFS is exemplarily shown in Fig. 2. The CSS consistently records higher values of cumulative infiltration than the AFS at all times during the experiments. This could be attributed to changes in soil structure: decreased bulk density, increased porosity, sand fraction, and K_{sat} of soils under CC kilns. Previous studies have indicated that CC addition to soil leads to increased infiltration capacity and decreased erosion effects (*Piccolo* et al., 1997; *Glaser* et al., 2002). However, many studies have shown very significant fire-induced increases of runoff and erosion due to loss of vegetal cover and development of water repellency (*Scott*

Table 4: Soil-surface temperature (°C) on charcoal-site soils (CSS) and adjacent field soils (AFS) at six sun angles. Each value is a mean of five spatial measurements within a plot. Standard deviation is in parentheses.

Sun angle (°)	**Date: 2002-12-05**			**Date: 2002-12-08**		
	CSS (wet)	**AFS (wet)**	**T_{air}**	**CSS (dry)**	**AFS (dry)**	**T_{air}**
20	23.5 (1.5)	22.9 (0.5)	21.1 (0.9)	23.8 (0.9)	23.1 (0.5)	22.7 (0.9)
30	27.4 (1.0)	25.8 (0.9)	23.0 (0.9)	26.4 (1.0)	26.0 (0.6)	24.1 (0.7)
40	29.2 (1.4)	27.9 (0.8)	24.5 (1.0)	30.8 (1.2)	28.1 (1.4)	25.3 (0.8)
50	31.8 (1.3)	28.6 (1.6)	27.0 (0.8)	33.9 (1.6)	29.8 (1.4)	28.0 (0.7)
60	32.0 (1.9)	29.1 (1.4)	27.7 (0.8)	36.4 (1.7)	30.5 (1.0)	27.8 (1.0)
70	36.6 (2.3)	32.5 (1.0)	28.6 (1.0)	41.3 (1.9)	33.0 (1.9)	29.2 (1.2)
Mean	30.1(4.5)	27.8 (3.2)	25.3 (2.9)	32.1 (6.5)	28.4 (3.5)	26.2 (2.5)

and *van Wyk*, 1990; *Inbar*, 1998; *Lane* et al., 2004). Apparently, the combined effects investigated in this study showed the dominance of hydrological response of charcoal amelioration of soils over the fire-induced effects.

Following the demonstrated positive impacts of CC additions on soil properties and productivity, *Glaser* et al. (2002) proposed the use of a slash-and-char technique as an alternative to the slash-and-burn system. Higher infiltration rates observed here suggest possible reduction of overland flow and hence erosion, if the slash-and-char technique is widely adopted in the study area. However, care should be taken to draw conclusions from this plot-level study as the overall watershed response may differ. Interviews with the CC producers showed that an average ratio of 5:1 of cleared land area to area occupied by kiln is common. Hence, a combination of this result and data at watershed level would be required to access detail hydrological response of charcoal production, which is currently widespread in the study area.

4 Conclusions

The study investigated the impact of soil heating and deposited residue from CC production on soils in a tropical agroecosystem of W Africa. Most of the soil properties investigated were affected by CC production. Decrease in bulk density and increased sand fraction influenced total porosity, infiltration rates, and K_{sat} of the soils under CC kilns. Darkening of soil color changed the optical properties of the CSS leading to lower surface albedo and increased soil heating as evidenced by higher soil-surface temperature. Measured infiltration rates, which increased on the CC site soils, may lead to increasing water retention and decreasing soil erosion. This has implication for higher productivity of soils under CC kilns compared to AFS. The results presented here, in addition to watershed-scale measurements when available, are expected to enhance our understanding of hydrological responses of ecosystems to indiscriminate CC making. Further research is needed to evaluate the effects of CC amendments on surface hydrological processes under field conditions.

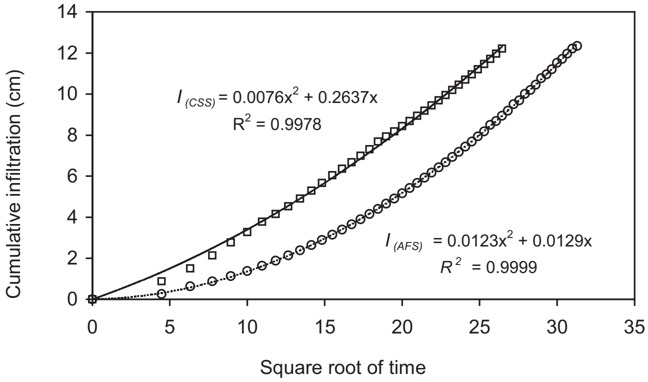

Figure 2: Typical cumulative infiltration curves of CSS (circle) and AFS (rectangle) measured with min-disc infiltrometers (time is in seconds).

Acknowledgments

The authors thank Dr. *Wilson Agyare* for his assistance during sampling and laboratory determination of K_{sat}. This research was partially supported by the *GLOWA Volta project*, funded by the *German Federal Ministry of Education and Research (BMBF)* under *grant 07GWK01*.

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