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Vertical and lateral transport of biochar in light-textured tropical soils

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ABSTRACT

Field experiments were conducted in Arenosols (loamy fine sand) and Acrisols (sandy loam) in Zambia to quantify vertical and lateral transport of biochar (BC) using the BC and soil ^{13}C isotope signatures and total organic carbon contents. There were three experimental treatments composing of no BC, ≤0.5 and 0.5–1 mm BCs each with three replicates arranged in completely randomized design. The applied BCs were made from rice husk, except 0.5–1 mm BC in sandy loam, which was from maize cob. One year after mixing BC homogeneously in the 0–5 cm surface layer, soil down to 20 cm depth was sampled. The downward migration of BC was significant down to 8 cm depth in sandy loam and down to 6 cm in loamy fine sand. Below these depths, there was no significant difference in BC amounts between the BC amended and the reference plots. There was a general tendency for greater downward migration for the ≤0.5 mm than for 0.5–1 mm BC. Total BC recovery at 0–5 cm depth in the BC-treated soils amounted to 45–66% of the total applied amount of BC. As only 10–20% was recovered in the deeper soil layers, 24–45% of the applied BC could not be accounted for in the soil profile. Although, decomposition and downward migration to below 20 cm depth may contribute to the loss of BC from the surface soil, much can be attributed to lateral transfer through erosion. This is the first study that explicitly focuses on the theme of BC dispersion and shows that in Arenosols and Acrisols of the tropics, the downward migration of BC is limited.

1. Introduction

Biochar (BC), which is a biomass pyrolysis product has been reported to increase crop production with the co-benefit of sequestering carbon (C) (Glaser et al., 2002; Jeffery et al., 2011). Reported increases in crop production varied widely depending on soil and BC types, but there are indications that this effect of BC might be stronger in sandy and acidic soils (Glaser et al., 2002; Jeffery et al., 2011; Martinsen et al., 2014), which are widespread in tropical regions. Some of the mechanisms for the reported increase in crop production include increase in water holding capacity, liming effect and direct addition and retention of nutrients by BC (Cornelissen et al., 2013; Glaser et al., 2002). If these BC effects on soil properties are to benefit the crops for extended periods, then BC applied to top soils should remain within the top soil where root density is high. However, any transport of BC would not affect its C sequestration potential.

There are few studies, which indicate that BC, once applied to soil, might to a certain extent be mobile within the soil profile (Foereid et al., 2011; Haefele et al., 2011; Major et al., 2010). Such transport of BC within the soil profile could be exacerbated by physical disintegration of BC to nano- and micrometer sized particles, moving with infiltrating water (Spokas et al., 2014). Haefele et al. (2011) reported that as much as 50% of BC applied to 15 cm top soil, estimated based on total C changes in the soil profile, migrated to deeper soil horizons of structured humic Nitisols and gleyic Acrisols after one year. The migration of BC to deeper soil was fast in soils with high water infiltration rate (Nitisol and Acrisol), whereas no migration was found in soils with low water infiltration rate, as heavy paddy soil. In an experiment designed to measure the fate of BC from mango prunings applied at 0–10 cm in sandy clay loam Ferralsol using $\delta^{13}C$, Major et al. (2010) reported slow downward migration of BC at 15 cm depths at a rate of <0.5% of the BC applied to soil per year.

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An additional number of studies report downward migration of black C (Hockaday et al., 2006; Leifeld et al., 2007), which is similar to BC. Black C in the environment are organic products commonly derived from incomplete combustion without intentionally limiting oxygen (soot and charcoal). In drained peatland, black C from deposited combustion residues of household waste migrated to deeper soil layers (Leifeld et al., 2007). Leifeld et al. (2007) found between 21–69% of black C below plough depth of 30 cm, 50 years after the last deposition of black C. The migration rate of black C was estimated to be 0.6–1.2 cm year^{-1}. Similarly, Hockaday et al. (2006) found that black C can be mobile in fire-impacted forest soil (medium sand with poorly developed Podzol), particularly the soluble organic constituents resulting from decomposition, which leach with percolating soil water.

Based on a modeling study, Foereid et al. (2011) suggested that lateral transport of BC could be a very important transport pathway of BC in soils, but limited field data are available. In their modelling work, the authors predicted that erosional transport of BC decreased with time due to incorporation of BC into soil aggregates (Awad et al., 2013; Obia et al., 2016). Due to the scarcity of experimental data on both vertical and lateral transport of BC, more studies are warranted. In addition, no study has reported the influence of BC particle size on its lateral and vertical dispersion.

Acrisols and Arenosols, characterized by low agricultural productivity, dominate central and western regions of Zambia. The productivity of these soils, which are widespread globally, has been demonstrated to increase through the application of BC (Cornelissen et al., 2013; Martinsen et al., 2014). One of the main factors proposed to explain the BC-induced increase in productivity of these soils is the increase in water holding capacity in the root zone (Obia et al., 2016) leading to better-developed root systems (Abiven et al., 2015). Migration of large amounts of BC to deeper soil horizons with low density of roots might eliminate or reduce the effect of BC on soil productivity (Haefele et al., 2011).

In a controlled field experiment in two light-textured soils in Zambia, we determined BC transport rates and their dependence on BC particle size. We hypothesized that there would be greater downward migration of BC at Kaoma (loamy fine sand with higher saturated hydraulic conductivity ~5.2 cm h^{-1}) than at Mkushi (sandy loam soil with saturated hydraulic conductivity of ~1.7 cm h^{-1}) (Obia et al., unpublished data) and that this migration would be greater for finer BC fractions. Lateral transport of BC is also expected to be greater at Kaoma than at Mkushi and greater for finer than coarser BCs. The objective of the present study was therefore to quantify the downward and lateral transport of fine ($\leq$0.5 mm) and slightly coarser (0.5–1 mm) BC in loamy fine sand (Arenosol) and sandy loam (Acrisol). To this end, BCs with ^{13}C signals different from those of the soils were applied and recovered in a high-resolution depth profile by δ^{13}C and TOC analyses. This study is one of the few explicitly dedicated to studying BC mobility in soil and the first to consider the *in situ* mobility of different BC particle sizes.

2. Materials and methods

2.1. Biochars

The BCs used in this study were prepared from rice husk and maize cobs after shelling the grains. Rice husk is available in western Zambia, whereas maize cobs are available throughout Zambia. Pyrolysis of the feedstocks was carried out in a drum retort kiln at Chisamba, Zambia at a temperature of 350 °C and a retention time of one day. The drums were loaded with maize cob or rice husk and sealed with a lid before lighting wood; the startup fuel below the drums. Heat generated from the burning wood drove out moisture and other gases from the feedstock in the drums through an exhaust pipe in the non-retort mode. In retort mode, no more wood was added under the drums but instead, the combustible pyrolysis gases (e.g. methane and carbon monoxide) were directed under the drums, catching fire to generate the energy to sustain the pyrolysis, and reducing toxic gas emissions. Photographic illustrations can be found in Sparrevik et al. (2015). The maize cob BC was used in extensive field trials (Martinsen et al., 2014) and in mechanistic studies (Alling et al., 2014; Hale et al., 2013). The BCs were sieved to particle sizes of $\leq$0.5 and 0.5–1 mm before application to soil.

2.2. Experimental set up

Field experiments were established in sandy loam Acrisol at Mkushi, central Zambia (S13 44.839, E29 05.972) and in loamy fine sand Arenosol at Kaoma, western Zambia (S14 50.245, E25 02.150) in April 2013. The annual rainfall in Mkushi and Kaoma is 1220 and 930 mm and average temperature is 20.4 and 20.8 °C respectively (Martinsen et al., 2014). At each sites, there were three treatments, each with three replicates resulting in nine plots organized in a completely randomized design. Plot sizes were 50 × 50 cm, separated by 20 cm high hard plastic sheets, inserted approximately 10 cm vertically into the soil. Layout of the experimental design can be found in Supplementary information Fig. S1. In Kaoma loamy fine sand, treatments included $\leq$0.5 mm and 0.5–1 mm rice husk BC, both added at a rate of 3.4% w/w in addition to a reference without BC. In Mkushi sandy loam, the treatments included $\leq$0.5 mm rice husk BC, 0.5–1 mm maize cob BC and a reference. Here, BC addition rates were 4% w/w for both treatments. At Mkushi, the coarser (0.5–1 mm) fraction was maize cob BC (and not rice husk BC), due to shortage of coarser rice husk BC, caused by easy crumbling of rice husk BC during sieving to finer sizes. The same amount of BC was added per plot (625 g) to both Mkushi and Kaoma soils, but the BC contents (in%w/w) differed due to differences in soil bulk density between the two sites (Table 2).

Biochar was applied in the top 5 cm of the soil. To apply the BC, we removed the top 5 cm of the soil by hand hoe and spade and mixed it with BC in a bucket. The top soil was dry when the experiment was set up, so that mixing with BC was easy. The soil layers below 5 cm down to approx. 30 cm were loosened using a hand hoe to remove any compacted layer before placing back the soil-BC mixture at the surface. Loosening the compacted subsoil is a common farmer practice to increase root volume as recommended by the conservation farming unit (CFU) of Zambia for farmers practicing conservation farming (Cornelissen et al., 2013; Umar et al., 2011). The reference plots were treated in the same way as the BC amended plots. The soil was left to naturally settle after the establishment of the experiment.

The experiment was set up at the end of the growing period followed by a long dry period from April to October 2013. Maize was planted at the onset of rainy season in November 2013 in the middle of each plot after application of NPK fertilizer (10:20:10) at a rate of 140:280:140 kg ha^{-1} with a top dressing of urea at 140 kg ha^{-1}. The plots were hand weeded without any traffic.

2.3. Soil sampling and sample preparation

Soil samples were taken at the end of March 2014, one year after BC application, to determine the amount of BC recoverable in the soil profile down to 20 cm depth. Two samples were taken from each of eight depth intervals per plot: 0–5 cm (depth of BC application), 5–6 cm, 6–7 cm, 7–8 cm, 8–9 cm, 9–10 cm, 10–15 cm, and 15–20 cm. Each sample was taken by cutting 1 cm thick vertical slices of soil across the plot through the entire layer of each