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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 (≤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 $\delta^{13}$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 ≤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 ≤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 ≤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

of the eight depth intervals. Samples were sealed in sampling bags prior to analysis.

The field-moist soil samples were dried at 40 °C for 3 days before passing through a 2 mm sieve. Sub-samples of the sieved homogenous soils were milled for analysis of $\delta^{13}C$ and TOC. Milled samples were prepared in 8 × 5 mm tin capsules and sent to Stable Isotope Facility, University of California, Davis for analysis using isotope ratio mass spectrometry.

Core ring samples (100 $cm^3$) were taken to determine the bulk density of the soil to allow calculation of TOC stocks in each of the depth intervals and thus establishment of BC mass balances relative to the amount applied to the plots in April 2013. The bulk density (Table 2) was determined at two depths (0–5 cm and 6–10 cm) for each plot. The bulk density at 6–10 cm depth was used for calculation of TOC stocks in all depths from 6 to 20 cm. This is reasonable because the soils from 6 to 20 cm were homogenized during plot establishment (see above).

### 2.4. Calculation of biochar amounts and mass balance

The TOC stock (g) per soil depth interval at each 50 × 50 cm plot was calculated according to:

$$TOC(g) = 50 * 50 * Depth * Bulkdensity * \frac{TOC(\%)}{100} \quad (1)$$

Where Depth and Bulk density are in cm and g $cm^{-3}$, respectively.

The fraction $f$ of TOC contributed by BC was calculated according to Eq. (2), adapted from Kocyigit (2006):

$$f = \frac{\delta^{13}C_{mixture} - \delta^{13}C_{ref.soil}}{\delta^{13}C_{biochar} - \delta^{13}C_{ref.soil}} \quad (2)$$

Where $\delta^{13}C_{mixture} = \delta^{13}C$ of the soil-BC mixture, one year after BC application, $\delta^{13}C_{biochar} = \delta^{13}C$ of the BC and $\delta^{13}C_{ref.soil} = \delta^{13}C$ of the reference soil. The reference $\delta^{13}C$ of the 0–5 cm was determined at the time of experimental set up in April 2013 while the 5–20 cm was determined in the reference plots as average value at depth of 5–20 cm in April 2014. The $\delta^{13}C$ of the reference plots was constant with depth at the interval of 5–20 cm (Fig. 1).

The amount of BC recovered (g) from each depth interval in each plot was calculated according to:

$$BCrecovered = TOC * f * \frac{100}{\%CofBC} \quad (3)$$

The two measurement values of $\delta^{13}C$ (‰), TOC (%) and BC (g) recovered per plot for each depth interval were averaged prior to statistical analysis.

### 2.5. Analysis of other basic soil and biochar properties

The soil and BCs were characterized for TOC, total nitrogen, total hydrogen after milling using a CHN analyzer (CHN-1000, LECO USA). Biochar was acidified to remove carbonates before determination of TOC. Loss on ignition of BC was determined by heating the milled samples in an oven (Carbolite Bamford, Sheffield, England) at 550 °C. pH was measured in water at a ratio of 1 to 2.5 (soil or BC to water) using a pH meter (Orion 2 Star, Thermo Fisher Scientific, Fort Collins, CO). Soil texture was measured using the pipette method. The surface area of BC was measured using standard BET method with nitrogen adsorption at 77.4 K. Easily soluble constituents of the BCs were determined by mixing 2 g of BC in 100 ml deionized water (1:50) followed by overnight shaking. The BCs were then filtered and oven dried at 105 °C overnight. Loss in

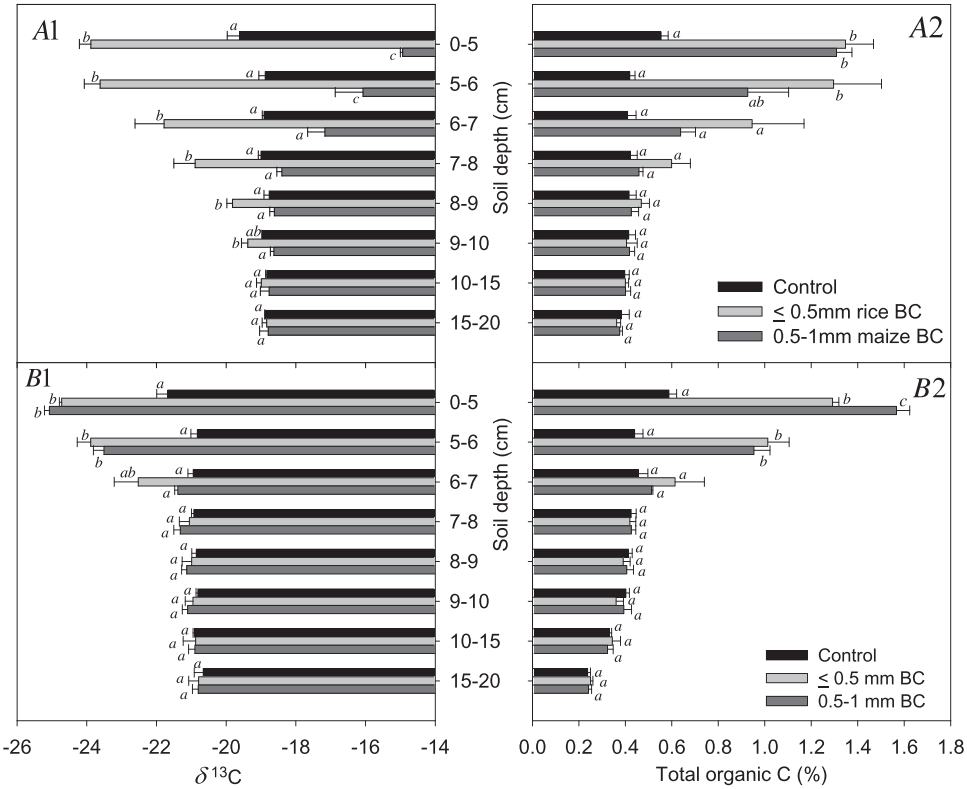


**Fig. 1.** Distribution of $\delta^{13}C$ and TOC in the soil profile one year after BC was applied to the surface soil (0–5 cm depth). *A1* and *A2* indicate the $\delta^{13}C$ and TOC for Mkushi soil amended with rice husk BC (with $\delta^{13}C = 27.3 \pm 0.03$) and maize cob BC (with $\delta^{13}C = 12.3 \pm 0.3$), whereas *B1* and *B2* indicate the $\delta^{13}C$ and TOC for the Kaoma soil (only rice BC was added). For significant differences, each depth at each site for either $\delta^{13}C$ or TOC were considered separately. Different letters indicate significant difference, Tukey's test at $p < 0.05$. Error bar is SE.

**Table 1**
Soil and biochar (BC) properties.[a]

| Properties | Kaoma soil | Mkushi soil | Rice husk BC | | | Maize cob BC | |
|---|---|---|---|---|---|---|---|
| | | | ≤0.5 mm | 0.5–1 mm | Unsorted | ≤0.5 mm | Unsorted |
| Sand (%) | 85.4 | 75.1 | – | – | – | – | – |
| Silt (%) | 10.2 | 15.9 | – | – | – | – | – |
| Clay (%) | 4.4 | 9.0 | – | – | – | – | – |
| Texture class | Loamy fine sand | Sandy loam | – | – | – | – | – |
| Total organic C (%) | 0.62 | 0.74 | 39.3 | 42.8 | 47.8 | 44.8 | 53.8 |
| Total nitrogen (%) | 0.00 | 0.01 | 0.61 | 0.52 | 0.82 | 0.79 | 0.65 |
| Total hydrogen (%) | – | – | 2.33 | 2.41 | 2.37 | 2.09 | 2.36 |
| H/C (molar ratio) | – | – | 0.71 | 0.68 | 0.60 | 0.56 | 0.53 |
| pH | 5.8 | 5.8 | 8.3 | 8.3 | 8.3 | 9.0 | 8.8 |
| Loss on ignition (%) | – | – | 48.8 | 54.9 | – | 52.1 | – |
| Soluble constituents (%) | – | – | 2.1 | 0.6 | 2.0 | 2.6 | 2.4 |
| BET surface area ($m^2\,g^{-1}$) | – | – | 2.4 | 2.3 | – | 10.5 | – |
| CEC ($cmol_c\,kg^{-1}$) | 2.8 | 1.7 | – | – | 14.0 | – | 22.2 |
| $K^+$ ($cmol_c\,kg^{-1}$) | 0.1 | 0.3 | – | – | 10.4 | – | 16.5 |
| $Ca^{2+}$ ($cmol_c\,kg^{-1}$) | 1.2 | 1.1 | – | – | 2.4 | – | 4.3 |
| $Mg^{2+}$ ($cmol_c\,kg^{-1}$) | 0.2 | 0.3 | – | – | 0.9 | – | 1.2 |
| $\delta^{13}C$ (‰) | −20.78 | −18.86 | −27.05 | −27.05 | −27.05 | −12.27 | −12.27 |

[a] Maize cob BC with particle size 0.5–1 mm was not characterized in the lab because it was exhausted in the field. Calculation of mass balance of 0.5–1 mm maize cob BC in the soil layers was based on C content of the ≤0.5 mm BC. This could have resulted in a slight overestimation (<7.6% of 284 g of the total BC recovered). The $\delta^{13}C$ of the soil presented here is the average of the bulk soil at 5–20 cm depth measured in April 2014.

weight of BC after drying was considered as the soluble constituents. The soil and BC properties are presented in Table 1.

The 0.5–1 mm maize cob BC was not characterized in the laboratory because its stock was exhausted in the field. Calculation of mass balance of 0.5–1 mm maize cob BC recovered in the soil layers was based on C content of the ≤0.5 mm maize cob BC. The C content of the 0.5–1 mm maize cob BC is expected to be only slightly higher than that of the ≤0.5 mm particle size and less than that of unsorted BC analogous to the trends of rice husk BC in Table 1. Apparently, a higher percentage of ashes relative to the unsorted BC was still found in the 0.5–1 mm size fraction (not only in the ≤0.5 mm one). Total recovery of 0.5–1 mm maize cob BC calculated using Eq. (3) was 45.5% based on C content (44.8%) of ≤0.5 mm BC but it would be 37.9% based on C content of unsorted BC of 53.8% resulting in a difference in recovery of 7.6%. Therefore use of C content of ≤0.5 mm maize cob BC to calculate recovery of 0.5–1 mm maize BC resulted in a slight overestimation by <7.6%.

### 2.6. Statistical analysis

The data were analyzed using the software package R (R Core Team, 2014) . In order to display the distribution of BC along the soil profile, $\delta^{13}C$ and TOC (%) were plotted along the soil depth profile. The amount of BC recovered at each depth interval and total amount of BC recovered were analyzed using two-way analysis of variance (ANOVA). In this analysis, BC treatments (no BC, ≤0.5 mm BC, and 0.5–1 mm BC) and sites (Mkushi and Kaoma) were considered as the explanatory factors for the differences in BC recovered at each depth. This allowed comparison among treatments within each site and comparison of treatments between sites. Since the number of replicates in Mkushi and Kaoma were the same, only a single standard error was reported for amount of BC recovered at each depth. Such single standard error was preferred as opposed to the individual standard error of each treatment mean based on three replicates that could be erroneous (Webster, 2007). Differences between mean values were assessed using Tukey's test at 5% level of significance. All numbers presented in tables are mean values ± standard errors.

## 3. Results

The $\delta^{13}C$ signal and the TOC contents of the BC amended plots changed along the depth profile in both Mkushi and Kaoma soils (Fig. 1). The $\delta^{13}C$ of the rice husk BC (−27.1 ± 0.04‰) and maize cob BC (−12.3 ± 0.1‰) (Table 1), which are from C3 and C4 plants respectively, were different from those of the two soils and therefore allowed tracing of the BCs in the soils. Maize cob BC (0.5–1 mm particle size) was applied only in Mkushi soil. The reference value of $\delta^{13}C$ of Mkushi and Kaoma soil were −18.1 ± 0.3‰ and −20.2 ± 0.1‰, respectively, for the 0–5 cm depth and −18.9 ± 0.03 ‰ and −20.8 ± 0.03‰, respectively, for the 5–20 cm (Table 1). One year after BC application, the surface soil layer (0–5 cm) of the neighboring reference plots received BC transported laterally from the BC amended plots as indicated by their $\delta^{13}C$ values (−19.6 ± 0.3‰ and −21.7 ± 0.3‰, in Mkushi and Kaoma soil, respectively; Fig. 1 and Table 3).

In Kaoma loamy fine sand where only rice husk BC ($\delta^{13}C$ = −27.1‰) was applied, the $\delta^{13}C$ in the top soil (0–5 cm) was −24.7 ± 0.1‰ for the ≤0.5 mm BC and −25.1 ± 0.1‰ for the 0.5–1 mm BC, respectively. Both values were significantly smaller than the soil reference value of −20.2 ± 0.05‰ prior to BC addition in 2013 (Fig. 1B1). With increasing soil depth, the $\delta^{13}C$ increased to values not significantly different from the soil's reference value of 20.8 ± 0.03‰ below 7 cm soil depth for both ≤0.5 mm BC and 0.5–

**Table 2**
Bulk density ($g\,cm^{-3}$) of the soil from biochar experiments in Zambia.[a]

| Site | BC particle size | BC dose (%) | Soil depth | |
|---|---|---|---|---|
| | | | 0–5 cm | 5–10 cm |
| Mkushi | Ref. soil | 0 | 1.26 ± 0.01 | 1.28 ± 0.02 |
| | ≤0.5 mm | 4 | 1.17 ± 0.03 | 1.25 ± 0.02 |
| | 0.5–1 mm | 4 | 1.16 ± 0.05 | 1.34 ± 0.04 |
| Kaoma | Ref. soil | 0 | 1.40 ± 0.02 | 1.40 ± 0.04 |
| | ≤0.5 mm | 3.4 | 1.28 ± 0.01 | 1.38 ± 0.01 |
| | 0.5–1 mm | 3.4 | 1.27 ± 0.02 | 1.46 ± 0.03 |

[a] The bulk density of 0–5 cm soil depth was presented in our earlier work (Obia et al., 2016). The BCs were from rice husk except 0.5–1 mm BC in Mkushi, which was from maize cob. Values are means ± standard error (n = 3).

1 mm BC. The TOC of 0–5 cm soil depth interval was significantly larger for the 0.5–1 mm BC (1.57 ± 0.05%) than for the ≤0.5 mm BC (1.29 ± 0.02%) amended plots (Fig. 1B2). However, for both treatments, TOC decreased with depth and was no longer significantly different from that of the reference soil (0.46 ± 0.03%) at 6–7 cm soil depth interval.

In the sandy loam at Mkushi, the addition of ≤0.5 mm rice husk BC with $\delta^{13}C$ of −27.1‰ significantly reduced $\delta^{13}C$ of the 0–5 cm soil from reference value of −18.1 ± 0.3‰ (prior to BC addition in 2013) to −23.9 ± 0.3‰ measured in April 2014 ($p < 0.05$) (Fig. 1A1). For deeper soil layers below the application depth, the $\delta^{13}C$ of the soil in April 2014 increased gradually with depth reaching the reference soil value of −18.9 ± 0.03‰ at the depth of 10 cm (Fig. 1). On the other hand, the 0.5–1 mm maize cob BC with $\delta^{13}C$ of −12.3‰ increased $\delta^{13}C$ of the soil from reference value prior to BC addition of −18.1 ± 0.3‰ to −14.9 ± 0.1‰ in the 0–5 cm soil (Fig. 1A1). Below 5 cm depth, $\delta^{13}C$ decreased reaching the soil reference value at 7 cm soil depth. The TOC content of the soil followed a similar pattern with soil depth as $\delta^{13}C$ (Fig. 1A2). However, the treatments with ≤0.5 mm rice husk BC and 0.5–1 mm maize cob BC reached the reference soil's TOC level at 7 cm soil depth, 3 cm depth short of that estimated using $\delta^{13}C$ for ≤0.5 mm rice husk BC (Fig. 1A2). The TOC contents of the soil in the 5–8 cm depth interval were larger for ≤0.5 mm rice husk BC than for 0.5–1 mm maize cob BC amended plots.

We recovered greater amounts of BC of the ≤0.5 mm fraction below the application depth compared to the 0.5–1 mm fraction in Mkushi (19% vs 10%) (Table 3 and S1). Likewise, there were also greater amounts of fine BC below the application depth in Kaoma. However, the difference between the two BC particle sizes was not significant ($p = 0.41$) (13% vs 9%). Overall, the downward transport of BC was greater in Mkushi sandy loam than in Kaoma loamy fine sand. The recovered BC in the top 0–5 cm of the Kaoma soil based on eq. 3 after one year was 56% and 67% for ≤0.5 mm and 0.5–1 mm BCs, respectively (Table 3 and S1). In Mkushi, since the two BCs used had different $\delta^{13}C$ signals and there was cross-transportation of BCs between the surface layers of the plots, no accurate estimate of the recovery of BC in the 0–5 cm layer, based on $\delta^{13}C$ (Table 3 and S1) was possible. Use of TOC changes alone to calculate BC recovery indicated a recovery of 53% and 45% for ≤0.5 mm rice husk and 0.5–1 mm maize cob BCs, respectively (Table S2). The overall BC recovery in the 0–5 cm at both sites after one year were therefore between 45–67%. The total recovery in the soil profile down to the 20 cm soil depth was 55–76% of the BC applied. Below the depth of 8 cm, less than 2% of added BC was found with no significant difference between BC content in amended and reference plots based on Eq. (3) ($p > 0.05$) (Table 3 and S1). The recovery of BC based on Eq. (3) and based on TOC alone were similar, especially for Kaoma where only rice husk BC was used. The only difference was below the depth of 8 cm where $\delta^{13}C$ signal allowed detection of small amounts of BC. The total recovery of 0.5–1 mm maize cob BC in Mkushi soil was small (55%) (Table S2) compared to other BC treatments (69–76%) at Mkushi and Kaoma (Table 3 and S1) ($p < 0.05$).

## 4. Discussion

The changes in both $\delta^{13}C$ signal and TOC content of the soil with depth in the 5–10 cm interval at both Mkushi and Kaoma (Fig. 1) showed that BC migrated to deeper soil horizons. The downward migration of BC one year after the application was confined to less than 3 cm below the application depth, i.e., the 5–8 cm depth interval (Fig. 1 and Table 3). The downward migration of the BCs down to 5–20 cm was in the range of 9–19% of the applied BC and was generally greater for fine BC of ≤0.5 mm than for coarser BC of 0.5–1 mm (e.g. 19% vs 10% in Mkushi). There was greater downward migration of BC in sandy loam (Mkushi) than in loamy fine sand (Kaoma) (e.g. 19% vs 13% for ≤0.5 mm BC). Migration of BC in the Zambian sandy loam Acrisol and loamy fine sand Arenosol differed in magnitude from that reported by Haefele et al. (2011) who found annual downward migration rates of up to 50% of the applied rice husk BC in humic Nitisol and gleyic Acrisol in the Philippines and Thailand, respectively. Major et al. (2010) on the other hand found a very low annual downward migration rate of <1% of the applied BC in sandy clay loam Ferralsol in Colombia.

Several factors may influence migration rates of BC to lower horizons including BC particle size, tillage practice, soil texture, soil structure/aggregation, hydraulic conductivity and rainfall amount. Our results suggest that the finer the BC, the faster it will migrate to deeper horizons (TOC in Fig. 1 and recovered BC in Table 3). The TOC content of the 0–5 cm depth interval was smaller for ≤0.5 mm than 0.5–1 mm BC amended plots in Kaoma (TOC = 1.29 ± 0.02% for the ≤0.5 mm BC vs 1.57 ± 0.05% for 0.5–1 mm BC plots). This was not just because of smaller TOC content of ≤0.5 mm BC (Table 1) but also because of greater downward migration (Fig. 1 and Table 3). Tillage practice using planting basins, as common in conservation agriculture, may aid the increased migration rate of BC in soil by creating big soil-packing voids that may be filled, due to subsequent preferential colloidal and particle transport with percolating water to deeper soil horizon. In this study, we suspect that such packing voids were the main factor responsible for the slightly greater downward migration of BC in Mkushi sandy loam compared to Kaoma loamy fine sand. The Kaoma soil lacks packing voids as the sandy soil (85% sand) does not exhibit any significant

**Table 3**
Amount of biochar recovered in the 0–20 cm soil depth, one year after establishing the experiment, of a total of 625 g of biochar applied. Computations based on $\delta^{13}C$ and TOC contents (Eq. (3)).

| Soil depth (cm) | Mkushi sandy loam | | | Kaoma loamy fine sand | | | SE |
|---|---|---|---|---|---|---|---|
| | Reference plot BC (g) | ≤0.5 mm rice husk BC (g) | 0.5–1 mm maize cob BC (g) | Reference plot BC (g) | ≤0.5 mm rice husk BC (g) | 0.5–1 mm rice husk BC (g) | |
| 0–5 | 40.2a | 326.8bc | 223.1b | 56.5a | 350.3c | 416.9c | 34.0 |
| 5–6 | 0.5a | 62.9b | 32.6ab | 0.8a | 46.4b | 41.4ab | 12.7 |
| 6–7 | 0.1a | 30.2a | 13.8a | 1.2a | 17.8a | 4.4a | 9.3 |
| 7–8 | 0.5a | 13.4b | 2.5a | 0.8a | 2.0a | 3.2ab | 3.2 |
| 8–9 | 0.1a | 4.4a | 1.4a | 0.8a | 1.5a | 2.0a | 1.0 |
| 9–10 | 0.3a | 2.0a | 1.3a | 0.2a | 1.2a | 1.9a | 0.7 |
| 10–15 | 0.0a | 2.5a | 5.3a | 2.4a | 7.0a | 4.4a | 3.3 |
| 15–20 | 0.0a | 1.2a | 4.2a | 2.3a | 3.6a | 1.9a | 2.5 |
| Total BC recovered | 41.6a | 446.4c | 284.2b | 64.9a | 429.8c | 476.2c | 35.1 |

Amount of BC are mean values (n = 3) recovered in each depth of soil with a single standard error (SE) for the three BC treatments at the two sites. Different letters following means for each soil depth indicate significant difference between BC treatments and between sites, Tukey's test, $p < 0.05$.

extent of aggregation, as shown in our previous work on the same sites (Obia et al., 2016). The slightly greater migration depth in the sandy loam at Mkushi can also be explained by its higher rainfall (1220 mm $yr^{-1}$) compared with Kaoma (930 mm $yr^{-1}$). The importance of water percolation for BC movement has been reported previously for sandy clay loam Ferralsol (Major et al., 2010). The water flow rate in the soil, as emphasized by Haefele et al. (2011), appeared less important in the present study in determining migration rate of BC. This was shown by the smaller migration rate in Kaoma, which had higher saturated hydraulic conductivity than Mkushi (5.2 vs 1.7 cm $h^{-1}$ measured using tension disc infiltrometers; Obia et al., unpublished data).

Although the downward migration of BC was mainly within a few cm below the application depth, the total BC recovery for the 0–20 cm depth interval sampled was less than the amount of BC applied. The amount of maize cob BC recovered in the application layer (0–5 cm soil depth) at Mkushi (based on the change in TOC content) was smaller (55%) than that of rice husk BC treatments (69–76%) in both Mkushi and Kaoma ($p < 0.05$) (Table 3 and S1). However, the amount of maize cob BC recovered in the 5–20 cm depth profile, i.e., below the application layer, was of the same order of magnitude as that of the other treatments at both sites. For example, there was similar pattern in the recovery of maize cob BC and rice husk BC of 0.5–1 mm at Mkushi and Kaoma, respectively in 5–20 cm depth (Table 3). The TOC contents corroborated the similarity of the trends in the distribution of maize cob and rice husk BCs below application depth at both sites (Table S2). Maize cob BC had higher TOC contents than rice husk BC (Table 1) and the similar TOC contents of these two BCs in the application layer (0–5 cm) (Fig. 1) indicated that more maize cob BC must have moved out of the plots. The total recovery of BC at 0–20 cm depth was 55–76%, leaving between 24 and 45% of the applied BC unaccounted.

The unrecovered BC of at least 24% in the top 20 cm of soil can be attributed to (i) loss due to decomposition, (ii) migration as solid BC or dissolved organic matter to soil layers below 20 cm depth, which were not sampled, and (iii) lateral loss due to both water and wind erosion of the surface soil. The decomposition rate of BC produced within the same temperature range as our BCs has been reported to be small, with values in the range of ≤1% $yr^{-1}$ within the first year of application (Carlsson et al., 2012; Kuzyakov et al., 2009; Luo et al., 2011). Some of the studies e.g. Kuzyakov et al. (2009) were conducted under optimal condition of temperature and moisture throughout the year, implying that under non-continuous optimal conditions in the field, the decomposition rate is expected to be smaller. This might especially be true under Zambian conditions where hardly any rainfall occurs for seven months per year. Decomposition losses are therefore expected to be <5%. Migration of BC to soil layers below 20 cm depth mainly as dissolved organic C was most likely small as well. In Table 1, the water soluble constituents of BC were ~2%, and in our earlier rice husk BC washing experiment (Obia et al., 2015), dissolved organic C consisted of only 2.4% of the total constituents of BC leachate. In the soil depth interval of 15–20 cm, the accumulated BC was as little as 0.2–0.7% (Table 3 and S1). Thus, BC transfer to below the 20 cm soil depth is at most of the same order of magnitude ( < 1.4% of total BC). Also Haefele et al. (2011), despite observing high extents of BC leaching, found no indication of rice husk BC migration beyond 30 cm soil depth, four years after BC application. Major et al. (2010) found very small amounts (<1%) of BC moving with percolating water in intact subsoil below the application depth (10 cm) at 15 cm depth both as dissolved and particulate organic C. Thus, overall at least 20% of the BC added to the Mkushi and Kaoma soils was not accounted for and could not be attributed to leaching to deeper soil layers or to decomposition.

Black C, which is similar to BC with respect to for example their low density relative to soil, has been shown to undergo preferential water erosion (Rumpel et al., 2006). Lateral losses of BC through erosion by water and wind, could account for the non-recovered BC in the present study as well. The importance of lateral transport at the Mkushi and Kaoma sites is supported by the change in $\delta^{13}C$ of the reference plots adjacent to the BC-treated ones. The BC in the reference plots is part of the BC not recovered in the 0–20 cm depth of the amended plots. This BC in the reference plots was probably brought by wind and water erosion from amended plots and indicate that much of the missing BC (24–45%) may have been transported outside the experiment. Transport and some exchange of BC also likely occurred between BC treatments. However, the insignificant difference between the recovered BC from ≤0.5 plots and that from 0.5–1 mm BC plots in the top 0–5 cm soil depth of the two sites indicates that net transport between treatment plots was not significant.

There was greater lateral transport of BC in loamy fine sand at Kaoma than in aggregating sandy loam at Mkushi (Table 3). The opposite was true for downward transport where there was smaller downward transport in loamy fine sand than in sandy loam. Since we work with fine BCs with sizes less than 1 mm, the lateral transport through erosion and downward migration of particulate BC observed here is most likely the upper limits. Usually much coarser, hand-crushed BC will be applied, which is less vulnerable to downward migration and erosional lateral transport.

## 5. Conclusions

In this study, we showed that significant downward migration of fine size fractions of BC (≤0.5 mm and 0.5–1 mm) once applied to soil was mainly limited to ~3 cm below the application depth. There was a tendency for somewhat greater downward migration of the finer BC size fraction. Slightly greater downward migration of BC in the Mkushi sandy loam compared to the Kaoma loamy fine sand was likely caused by more rainfall and the presence of packing voids through which BC could move downward with percolating water. In Kaoma loamy fine sand, with its single-grain structure devoid of aggregates, formation of packing void does not happen. In this study, between 45 and 66% of BC was found within the application depth after one year. A further 10–20% moved below the application depth. This means that between 24 and 45% of the BC was not recovered in the upper 20 cm of the soil profile. Transportation of BC to adjacent reference plots indicates that a large part of the unrecovered BC was transported laterally through erosion.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.still.2016.07.016.

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