Farmer-led maize biochar trials: Effect on crop yield and soil nutrients under conservation farming

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Abstract

In extensive farmer-led trials practicing conservation farming (CF) in three regions of Zambia (Mongu: sandy soils; Kaoma: sandy or loamy sand soils; Mkushi: sandy loam or loamy soils), we studied the effects of biochar made of maize cobs (0, 2, and 6 t ha^{-1} corresponding to 0, 0.8, and 2.5% per basin) at different fertilizer rates of NPK and urea on crop yield of maize (*Zea mays*) and groundnuts (*Arachis hypogaea*). Conservation farming in this case combines minimum tillage (how basins), crop rotation and residue retention. For the first time, the effect of biochar on *in situ* soil nutrient supply rates [determined by buried Plant Root Simulator (PRS™) exchange resins] was studied, as well as the effects of biochar on elemental composition of maize. Effects of 0–10% (w:w) biochar addition on soil physical and soil chemical properties were determined in the laboratory. At all sites there was a consistent positive response in crop yield upon the addition of biochar. However, due to a great variability between farms there were no significant differences in absolute yields between the treatments. In the sandy soils at Mongu, relative yields (*i.e.*, percentage yield with biochar relative to the same fertilizer rate without biochar) of maize grains and maize stover were significantly increased at recommended fertilizer rates (232 ± 60%) and at half the recommended rate (128 ± 6%), respectively. In addition, biochar significantly increased concentrations of K and P in maize stover. *In situ* soil nutrient supply rates as measured by PRS™-probes were highly spatially variable with no consistent effects of the different treatments in the three regions. By contrast, the fraction of plant available water (Vol.-%) significantly increased upon the addition of biochar in all three soils. The increase caused by 10% biochar addition was of factor 2.5 in Mongu (from 4.5% to 11.2%) and 1.2 in both Kaoma (from 14.7% to 18.2%) and Mkushi (from 18.2% to 22.7%). Cation exchange capacity, pH, and exchangeable K significantly increased upon the addition of 10% (w:w) biochar in all three regions with a subsequent increase in base saturation and decrease of available Al^{3+}. Our findings suggest that the addition of biochar in combination with CF might have a positive impact on crop growth and that this positive effect is mainly caused by increases in plant-available water and decreased available Al.

Key words: biochar / crop yield / crop elemental composition / soil nutrients / Plant Root Simulator (PRS™) / water holding capacity

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1 Introduction

The agricultural sector in Zambia, particularly smallholder farmers, face serious challenges related to low production and productivity (*Goverment of Zambia*, 2011). Changes in climate may further exacerbate the conditions for smallholder farmers under rain-fed agriculture. Conservation agriculture (CA) is based on the integrated management of soil, water and agricultural resources in order to achieve sustainable and profitable agriculture (*Jat* et al., 2012). In Zambia it has been promoted since the 1980s in the form of conservation farming (CF) including planting basins [*i.e.*, preparation of rows of permanent basins each with a length of 30 cm and a spacing of 90 cm between rows and 70 cm between basins within rows (*CFU*, 2011)] and dry season land preparation (*Arslan* et al., 2013) increasing yields as a result of timely planting, improved soil fertility and soil moisture regime, in addition to reduced soil erosion, and thus, increased nutrient availability (*Giller* et al., 2009; *Jat* et al., 2012). While the average yield of maize (*Zea mays*) in Zambia was 2.4 t ha^{-1} in 2011 (*FAOSTAT*, 2013), the average yield on smallholder farms was found to be < 2 t ha^{-1} (*Xu* et al., 2009). In a survey including 129 farmers practicing CA, *Umar* et al., 2011 reported yields of 5.2 t ha^{-1} at farms with planting basins. Yet, the effect of CA on crop yield and soil physical and chemical properties is the subject of debate due to substantial variations in results between different studies (*Chivenge* et al., 2007; *Hobbs* et al., 2008; *Giller* et al., 2009; *Umar* et al., 2011; *Jat* et al., 2012; *Thierfelder* et al., 2012; *Thierfelder* et al., 2013).

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Biochar may serve as an attractive soil amendment especially for acidic and sandy soils (*Jeffery* et al., 2011). Previous studies have attributed the effect of biochar on crop yield to greater amounts of plant-available water (*Glaser* et al., 2002; *Jeffery* et al., 2011; *Novak* et al., 2012; *Cornelissen* et al., 2013a), increased cation exchange capacity (CEC) and associated nutrient retention (*Glaser* et al., 2002; *Lehmann* et al., 2003; *Yamato* et al., 2006; *Hale* et al., 2013), greater pH and base saturation (*Glaser* et al., 2002; *Lehmann* et al., 2003; *Yamato* et al., 2006; *Major* et al., 2010), increased available P (*Chidumayo*, 1994; *Yamato* et al., 2006), and biological factors like increased mycorrhiza development (*Lehmann* et al., 2011). The effectiveness of biochar on soil properties and crop yield depends on the feedstock and the production procedure used for biochar generation (*Chen* et al., 2008; *Brewer* et al., 2011), which largely affect important factors like the liming ability and pH of the biochar (*Yuan* and *Xu*, 2011; *Yuan* et al., 2011; *Manya*, 2012) as well as its stability (*Harvey* et al., 2012). In addition, biochar supplied in combination with fertilizer has been reported to increase (*Steiner* et al., 2007; *Chan* et al., 2007; *Asai* et al., 2009) or have no effect on yield (*Jeffery* et al., 2011) reflecting interactions between biochar and fertilizer on crop yield.

In contrast to other organic material, biochar is probably stable for hundreds to thousands of years and, thus, represents C that is actively removed from the short-lived C cycle (*Lehmann*, 2007; *Renner*, 2007; *Fraser*, 2010; *Sohi* et al., 2010; *Schmidt* et al., 2011). Using retort technologies (*i.e.*, recirculation and combustion of the pyrolysis gases so that CO_2 is emitted rather than CO, CH_4, and H_2) for production with low gas emissions (*Sparrevik* et al., 2013), the addition of biochar is a potential tool to mitigate climate change.

The positive elements of CA, including minimum tillage, crop rotation, residue retention, timely sowing, water harvesting in planting basins, and efficient utilization of fertilizers (*CFU*, 2011), may be further improved if combined with biochar addition (*Cornelissen* et al., 2013a). The combination of CA minimum tillage with biochar allows the biochar to be applied in low dosages to the area where the maize is grown (*i.e.*, in the plant basins representing 10–12% of the soil), which could reduce the amount of biochar needed. An earlier study found strong positive effects on maize yields in a sandy soil of Kaoma, with smaller effects in a sandy loam soil of Mkushi, and no effects in three other soils. While the study conducted by *Cornelissen* et al., 2013a focused on effects of biochar addition on maize yield and soil characteristics at five farms in five locations in Zambia, the present study includes 12 farmers at three locations and both maize and groundnuts, which makes it one of the most extensive farmer-led scientific biochar trials published so far.

Innovative elements of the present study included the following aspects: (1) for the first time, *in situ* nutrient status upon biochar addition has been monitored with plant-root simulators; (2) the effect of biochar amendment on crop elemental composition has been studied; (3) mechanistic understanding of changes in soil chemical and physical properties upon the addition of biochar was gained; and (4) the effect of biochar under various fertilizer rates was studied. We hypothesized an increase in maize yield and plant available nutrients without influencing concentrations of macro-nutrients in maize upon the addition of biochar. In addition, we hypothesized increased amounts of plant available water, CEC, and pH upon addition of biochar.

2 Material and methods

2.1 Experimental setup

The farmer-led field trials were conducted at twelve farms in Zambia: four farms in Mongu (annual rainfall ≈ 750 mm), three farms in Kaoma (annual rainfall ≈ 930 mm), and five farms in Mkushi (annual rainfall ≈ 1220 mm). An overview of the experimental setup including coordinates, type of measurements, and number of samples for the measured variables is given in Table 1.

In Zambia, the Conservation Farming Unit (CFU) uses the terms minimum tillage (MT, minimum tillage or zero tillage), conservation tillage (CT, as MT *plus* the retention of crop residues), conservation farming (CF, as CT *plus* the incorporation of legumes in crop rotation), and conservation agriculture (CA, as CF *plus* the establishment of *Faidherbia albida* trees over CF) (*CFU*, 2011; *Aune* et al., 2012). In this study, all trials were conducted at farms practicing conservation farming (CF) with dry season preparation of basins (minimum tillage method, ≈16,000 basins ha^{-1}) and addition of fertilizer to basins only. A detailed description of the practice, including sowing and weed control (herbicides and hand weeding), is given by *Cornelissen* et al., 2013a.

In Mongu, the effect of biochar made of maize cobs (0 and 6 t ha^{-1}) was tested at different fertilizer application rates [0, 70+70, 140+140, and 280+280 kg (ha · y)$^{-1}$], applied as one part basal fertilizer (NPK, 10:20:10) before planting and one part top dressing (urea, 46:0:0), on yield and elemental composition of maize (*Zea mays*) and soil nutrient supply rates (adsorbed on PRS™-probes) (Table 1, Fig. 1). The amounts of added NPK fertilizer (10:20:10) and urea (46:0:0) are reported on elemental basis, *i.e.*, 10% and 46% N, 20% P and 10% K. Fertilizer application rates of 0, 70+70, 140+140, and 280+280 kg (ha · y)$^{-1}$ corresponded to an application of 0, 39, 78 and 156 kg N (ha · y)$^{-1}$, 0, 14, 28 and 56 kg P (ha · y)$^{-1}$, and 0, 7, 14 and 28 kg K (ha · y)$^{-1}$. Amounts of added fertilizer represented a fraction of 0, 25, 50 and 100% of the recommended application for CF farmers which is 280 kg NPK (10:20:10) ha^{-1} and 280 kg urea ha^{-1} applied as top dressing. In Kaoma and Mkushi, effects of different amounts (0, 2, and 6 t ha^{-1}) of maize cob biochar at a constant fertilizer rate [140+140 kg (ha · y)$^{-1}$] on yields of maize and groundnuts (*Arachis hypogaea*) and soil nutrient supply rates were studied (Table 1, Fig. 1). No lime was applied to the fields. The total size of each trial was around 300 m^2 per farm. Each treatment consisted of an area of around 50 m^2, three rows of 15 basins separated by one control row of 15 basins (Fig. 1, Table 1).

The biochar and fertilizers were applied to the basins one week before sowing. Thereafter, the soil was back-filled and

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Table 1: Setup and replication of the farmer-led field trials in Mongu, Kaoma, and Mkushi, Zambia, for the field season 2011–2012.

Region	GPS coordinates	No. of farms[a]	Total size of trials	Planting date	Harvesting date	Biochar / t ha^{-1}	Fertilizer / kg ha^{-1}	Crop	No. of samples for the measured variables				
									Crop yield weight[b]	Elemental composition of crop[c]	Plant Root Simulators (PRS™)	Soil characteristics	PAW[d]
Mongu	S 15°06.527–15°27.717 E 23°09.033–23°14.107	4	300 m^2, 345 basins	20.11.2011	25.04.–30.04.2012	0	0	Maize	11	11	11	12	1
							70+70		5	5	12	–	–
							140+140		5	5	12	–	–
							280+280		6	6	12	–	–
						6	70+70		6	6	12	–	–
							140+140		6	6	12	–	–
							280+280		6	6	12	–	–
Kaoma	S 14°49.571–14°50.464 E 24°52.970–25°05.220	3	300 m^2, 345 basins	23.11.2011	20.04.2012	0	0	Ground nuts	6	–	12	11	1
								Maize	4	–	4		
							140+140	Maize	4	–	8	–	–
						2	0	Ground nuts	3	–	12	–	–
							140+140	Maize	4	–	8	–	–
						6	0	Ground nuts	3	–	12	–	–
							140+140	Maize	4	–	8	–	–
Mkushi	S 13°36.264–13°48.007 E 29°03.349–29°32.571	5 (6)	300 m^2, 345 basins	21.11.2011	10.05.2012	0	0	Ground nuts	8	–	16	15 (16)	1
								Maize	–	–	2		
							140+140	Maize	10	–	12	–	–
							280+280	Maize	6	–	–	–	–
						2	0	Ground nuts	8	–	12	–	–
							140+140	Maize	10	–	12	–	–
						6	0	Ground nuts	8	–	12	–	–
							140+140	Maize	10	–	12	–	–

[a]Farmer involved in a related study (in brackets). This farmer was included only for determining effects of biochar addition on PAW, CEC and pH.
[b]Yield of maize (grain and stover) or ground nuts (nuts and pods).
[c]Elemental composition of maize grain and stover.
[d]Plant available water determined in pure soils and soil + 2.5%, 5% or 10% (w:w) maize cob biochar.

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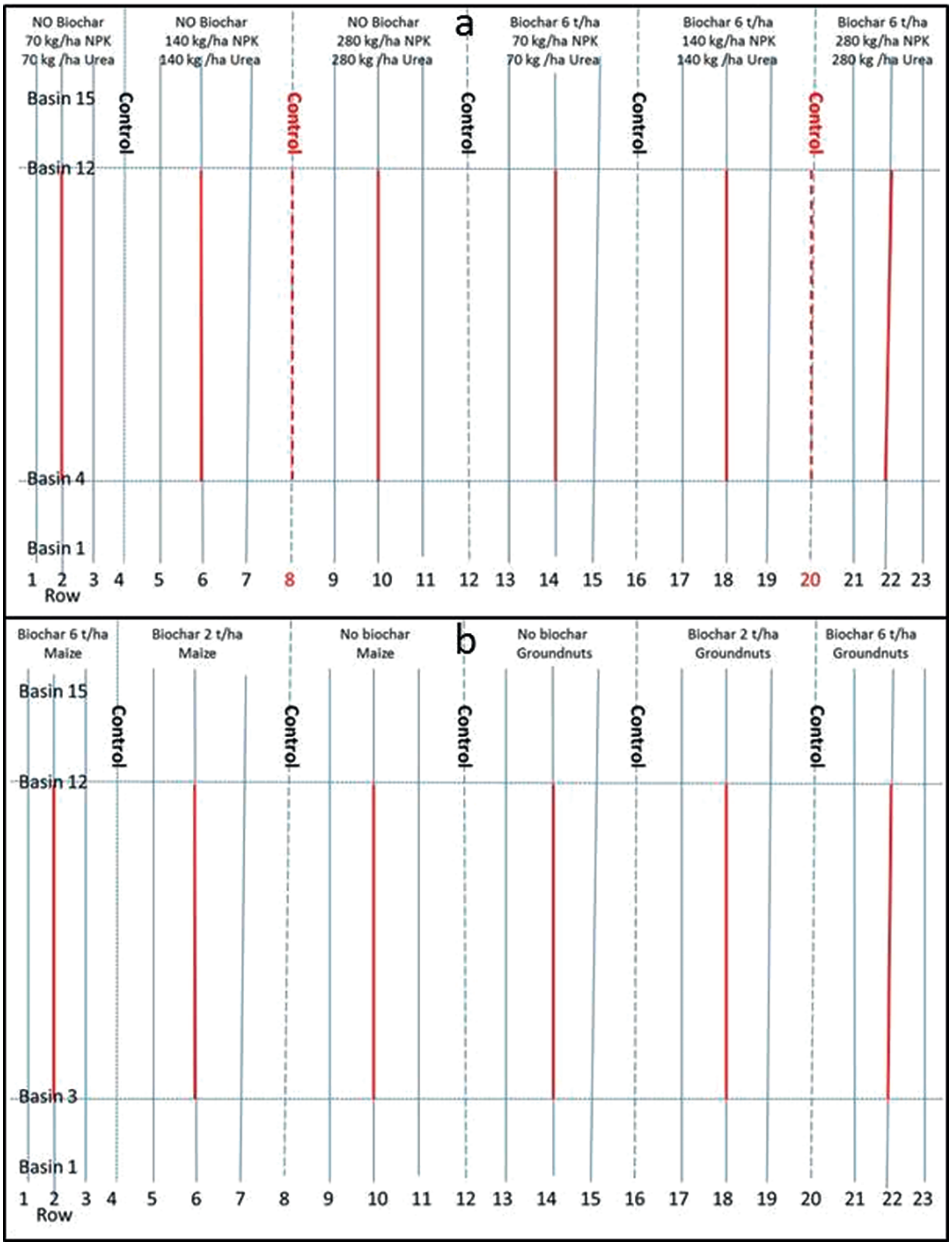

Figure 1: Experimental setup used in Mongu (a) and Kaoma and Mkushi (b) for the season 2011–2012. Rows with basins used for yield determination are highlighted in red. Rows marked as controls did not receive biochar or fertilizer. Fertilizer application for rows with maize in Kaoma and Mkushi was 140 kg NPK ha^{-1} and 140 kg urea ha^{-1}. No fertilizer was added in rows with groundnuts.

mixed thoroughly using a hoe. The amounts of added biochar (2 t ha^{-1} = 125 g $basin^{-1}$ and 6 t ha^{-1} = 375 g $basin^{-1}$) corresponded to approximately 0.8 % and 2.5 % biochar in the basins with a volume of ≈10 L (corresponding to 15 kg soil $basin^{-1}$ with 20 cm depth, 30 cm length, 16.7 cm width and a bulk density of 1.5 g cm^{-3}). In the laboratory, a range of 0, 2.5, 5, and 10% biochar addition was used to determine changes in amounts of plant available water (PAW; defined as the volumetric water content between pF 2 and pF 4.2, *i.e.*, the amount of water at field capacity and permanent wilting point, respectively), pH, and CEC.

2.2 Biochar production and properties

The biochar was produced from maize cobs using an earth-mound kiln (produced in Chisamba, Zambia, and applied in Mongu and Kaoma) and a brick kiln (produced and applied in Mkushi). The charring temperature was around 350°C in both cases, as measured by a digital thermocouple, and the pyrolysis time was 7 d. The charred maize cobs were crushed to a coarse powder before application in the field. The crushed biochar was further sieved at 2 mm prior to laboratory measurements. Characteristics of the two BCs are given in Table 2.

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Table 2: Characteristics of the maize cob biochars used in the farmer-led trials in Mongu and Kaoma (produced in an earth mound kiln) and Mkushi (produced in a brick kiln), Zambia. The table presents cation exhange capacity (CEC), exchangeable base cations[a] and extractable acidity (H^+) for unwashed and washed biochar (*cf.* section 2.6). Numbers for total C and N are based on two replicates. Exchangeable base cations and CEC for the biochar "wash procedure II" are based on three replicates in the laboratory. $n = 1$ for pH, exchangeable base cations, and CEC of the unwashed and "wash procedure I" biochars[b] (no SD). "–" = below detection limit.

Biochar	$pH_{(H_2O)}$	$pH_{(CaCl_2)}$	H^+		Mg^{2+}		Ca^{2+}		K^+		CEC		Total C		Total N	
							/ $cmol_c$ kg^{-1}								/ %	
			mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd
Earth mound kiln biochar	7.6	7.1	0.4		2.3		2.8		27.0		32.5		69.7	5.32	0.6	0.02
Brick kiln biochar	9.7	8.8	–		0.8		0.9		56.1		57.8		81.1	4.53	0.7	0.02
Earth mound kiln biochar: *Wash. Proced. I*	na	7.0	2.5		1.7		2.0		17.5		23.7		na		na	
Brick kiln biochar: *Wash. Proced. I*	na	8.9	–		0.8		0.9		19.5		21.1		na		na	
Earth mound kiln biochar: *Wash. Proced. II*	7.6		–	–	1.3	0.05	1.6	0.05	13.7	1.07	16.6	1.16	na		na	
Brick kiln biochar: *Wash. Proced. II*	9.2		–	–	0.4	0.08	0.3	0.04	16.1	0.44	16.8	0.50	na		na	

[a]Na^+ < detection limit, thus not included in the table. The Mg^{2+} and Ca^{2+} contents were lower and the K^+ content higher in the brick kiln biochar than in the earth-mound kiln biochar. Since the biochars were produced from identical feedstock, the only explanation could be some inclusion of soil particles containing more Ca^{2+} and Mg^{2+} than K^+ in the earth-mound kiln char.
[b]Washing procedure I: 20 mL of distilled water was added to 5 g biochar, and gently shaken overnight prior to filtration and further washing with 30 mL water (biochar : water ratio of 5 g : 50 mL). Washing procedure II: 50 mL of distilled water was added to 0.5 g of biochar, and gently shaken prior to centrifugation. After centrifugation the wet biochars were washed and filtered (0.45 μm) five times with 20 mL distilled water.

2.3 Harvest, yield, and elemental analysis

Air-dried grains as well as air-dried stover (stems and leaves) of maize and nuts, as well as pods and nuts of groundnuts were used to determine yield. The moisture content was 10–15%, as measured by drying overnight at 110°C, and not corrected for in the yield data reported. This led to uncertainties of up to 5% in the absolute harvest data but not in the relative biochar *vs.* non-BC comparisons. All plant material was sampled from the middle row (to avoid edge effects) of each three rows of a certain treatment (Fig. 1). Ten basins (20 to 30 plants) were sampled. Plant material from the mixed 10-basin samples was pooled into one sample and weighed at every farm, resulting in one sample (consisting of 20–30 plants) per treatment and farm. Maize stover and grains in Mongu and maize stover, grains and groundnuts in Kaoma and Mkushi were sampled in April and May 2012 (simultaneously with the harvest date, Table 1). All samples were dried at 60°C and milled prior to analysis of elemental composition (Ca, Fe, K, Mg, P, C, H, and N). Each sample was analyzed in triplicate in the laboratory. Total C and N in the biomass and grains were determined by dry combustion (*Nelson* and *Sommers*, 1982) and the Dumas method (combustion at > 900°C) (*Bremmer* and *Mulvaney*, 1982), respectively, using a CHN analyzer (Leco CHN-1000; Leco Corporation, Sollentuna, Sweden). Total C and N concentrations were used to calculate the C/N ratio. Between 0.2 and 0.3 g plant material was decomposed with ultrapure HNO_3 (69%) and 2 mL distilled water in an Ultraclave (Milestone) at a maximum temperature of 250°C for 15 min. Concentrations of Ca, Fe, K, Mg, and P were determined using ICP-OES (Perkin Elmer Optima 5300 DV). Wheat flour (1567a, standard reference material), hay (V-10, International Atomic Energy Agency analytical control service) and bush branches and leaves (NCS DC 73348, standard reference material) were used as reference material.

2.4 In situ soil nutrient supply rates

Plant root simulators (PRS™; Western Ag Innovations Inc., Saskatoon, Canada) are ion exchange membranes that mimic plant roots with respect to nutrient uptake, and thus serve as a sink for both cationic and anionic nutrients in soil solution. PRS™-probes were buried in the soil for one month (end of February to the end of March 2012) to estimate *in situ* nutrient availability, which is affected by both release from mineralization or dissolution (*Qian* and *Schoenau*, 2002) and immobilization by plants and microorganisms. As the PRS™-probes were inserted directly in the soil, the amount of adsorbed cations and anions represents nutrient surplus rather than net mineralization (*Western AG Innovations Inc.*, 2009). The PRS™-probes were inserted under a 45° angle at various depths (between 5 and 15 cm, since the biochar and fertilizer were present at this depth) in order to get an integrated estimate of mobile ions in the basins. Four pairs of cation and anion PRS™-probes were inserted in four basins (*i.e.*, one pair per basin) along each of the three rows of each treatment combination at each farm (Fig. 1). In addition, one extra set of four PRS™-pairs was inserted in the middle row of each treatment combination at each farm to increase the number of replications. For each row, the four cation and four anion probes (eight cation and eight anion probes for the middle row), were combined into four samples for each treatment combination, thus, representing four replicates (for all regions a total of $n_{cation} = 225$; $n_{anion} = 225$; Table 1). The PRS™-probes were shipped to Western Ag Innovations for analysis

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[NO_3^--N and NH_4^+-N determined colorimetrically using flow injection analysis (FIA) and the remaining nutrient ion contents determined using ICP-MS]. As the ion adsorption is not linear in time, we used the recommended reporting unit "μg (element) 10 cm^{-2} per one month of burial" (*Western AG Innovations Inc.*, 2009). The method detection limits were 2 μg 10 cm^{-2} for NO_3^--N, NH_4^+-N and Ca, 4 μg 10 cm^{-2} for K and 0.2 μg 10 cm^{-2} for P, and 0.4 μg 10 cm^{-2} for Al.

2.5 Soil sampling

Soil (mixed 0–20 cm) used for chemical and physical characterization was sampled from basins without any biochar in triplicate at each of the farms. Each of the triplicates was obtained by pooling samples from five basins (Table 3).

2.6 Chemical analyses

pH was determined electrochemically (Orion, model 720, Orion Research Inc., Cambridge, MA, USA) in suspension with either distilled water or 0.01 M $CaCl_2$ (volume soil : volume solution ratio of 0.4). Exchangeable base cations, exchangeable acidity, and CEC were determined on air-dried and sieved (2 mm) soil and biochar samples as well as washed biochar samples. The methodology for determining CEC is pivotal; washing removes most of the ashes that do not contribute to CEC but are counted as such for unwashed biochars. Thus, CEC based on washed biochar gives an estimate of the actual CEC, whereas CEC based on unwashed biochar is the sum of base cations associated with exchange sites and those in ash. The washing of the biochar included two different approaches. "Washing procedure I" consisted of 20 mL of distilled water being added to 5g char and gently shaken overnight prior to filtration (blue ribbon paper filters, Whatman, 589/3) and further washing with 30 mL water (biochar : water ratio of 5 g : 50 mL). The more stringent "Washing procedure II" consisted of the following: 50 mL of distilled water was added to 0.5 g of biochar and gently shaken prior to centrifugation for 15 min at 200 rpm (Labofuge M Heraeus Sentrifugen). After centrifugation the wet biochars were washed and filtered (0.45 μm) five times with 20 mL distilled water (vacuum filtration). The unwashed samples and the washed procedure I samples were extracted with 1 M NH_4NO_3 and the washed procedure II samples were extracted with 1M NH_4Ac. Base cation concentrations were determined in the extracts. Extractable acidity was determined by titration with 0.05 M NaOH to pH 7. The sum of exchangeable base cations and exchangeable acidity was assumed to equal the cation exchange capacity (CEC) according to *Schollenberger* and *Simon*, 1945. Exchangeable cation concentrations were determined using ICP-OES (Optima 5300 DV, PerkinElmer Inc., Shelton, CT, USA). Total C and N concentrations were determined as described above. Due to the low pH of the soils, total C represents organic C.

2.7 Physical analyses

Soil texture (data not shown) was determined on bulked soil samples according to *Krogstad* et al., 1991 using the "Pipette

Table 3: Mean (± SD) chemical and physical soil characteristics of 11–15 soil samples (mixed 0–20 cm) from 3–5 farms in Mongu, Kaoma, and Mkushi, Zambia.

Location[a]	n	$pH_{(H_2O)}$		$pH_{(CaCl_2)}$		H^+		Na^+		Mg^{2+}		Ca^{2+}		K^+		Al(III)		CEC		Ca:Al ratio		OC		Total N		n	BD (ρb)	
												/ $cmol_c$ kg^{-1}												%			g cm^{-3}	
		mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD		mean	SD
Mongu	12	4.83	0.46	3.95	0.36	0.54	0.24	–	–	0.15	0.12	0.49	0.22	1.89	1.87	0.26	0.14	1.83	1.80	2.63	1.43	0.58	0.21	0.02	0.02	6	1.51	0.05
Kaoma	11	5.93	0.27	5.12	0.37	1.30	1.03	0.03	0.01	0.39	0.23	1.31	0.71	0.10	0.05	0.06	0.06	2.76	1.53	72.75	82.87	0.54	0.23	0.00	0.00	9	1.54	0.06
Mkushi	15	6.31	0.54	5.85	0.57	1.67	–	–	–	0.94	0.43	1.94	0.69	0.54	0.42	0.31	0.42	3.54	1.35	29.66	31.51	0.62	0.18	0.01	0.01	9	1.43	0.06

[a]Five farmers (not farm "MK2") included for the mean values in Mkushi.

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method" and classified according to *FAO*, 2006. Bulk density (BD) was determined on the dry matter mass of soils in 100 cm^3 steel rings. One bulked soil sample from six basins without any fertilizer or biochar addition in each of the three regions (Table 1) was used to determine water holding capacity. Hand packed 100 cm^3 steel rings (in triplicate) containing soil without biochar or soil with unwashed maize biochar [2.5, 5 or 10% (w:w)] were used to determine water holding capacity. The hand-packed samples were saturated with water and the weight determined at different matrix potentials (pF) using ceramic pressure plates (pF 2 and 4.2; *cf. Richards*, 1948). The amount of plant available water was calculated as the difference between volume percentage water at field capacity (pF 2) and volume percentage water at the wilting point (pF 4.2).

2.8 Statistical analyses

The statistical software package "R" (version 2.15.0; *R Development Core Team*, 2012) was used for all statistical analyses. Due to differences in the experimental setup in Mongu on the one hand and Kaoma and Mkushi on the other (Fig. 1) comparisons of means differed between the regions. In Mongu, effects of biochar addition (0 and 6 t ha^{-1}) at different fertilizer rates [0, 70+70, 140+140 and 280+280 kg $(ha \cdot y)^{-1}$] on yield and elemental composition of maize were tested. Two sided t-tests were used to compare treatment means at sites with biochar and sites without biochar (*i.e.*, 0 fertilizer at the side of the field with "no biochar" *vs.* "0 fertilizer at the side of the field with added biochar", "70+70 fertilizer no biochar" *vs.* "70+70 biochar", "140+140 fertilizer no biochar" *vs.* "140+140 biochar", and "280+280 fertilizer no biochar" *vs.* "280+280 biochar", Fig. 1). In Kaoma and Mkushi effects of different amounts (0, 2 and 6 tons ha^{-1}) of biochar at a constant fertilizer rate [140+140 kg $(ha \cdot y)^{-1}$] on yields of maize and groundnuts were tested using two sided t-tests. Two and 6 t ha^{-1} biochar were always compared with no biochar (*i.e.*, "no biochar" *vs.* "2 tons ha^{-1}" and "no biochar" *vs.* "6 t ha^{-1}"). In all three regions relative yield was calculated as percentage yield with added biochar relative to the same fertilizer rate without added biochar. Thus, 100% relative yield indicates the same yield at sites receiving biochar as compared to sites receiving no biochar. Relative yield was tested using a one sided t-test (*i.e.*, greater than μ = 100%). Soil physical and soil chemical changes upon the addition of 0, 2.5, 5, and 10% (w:w) biochar were tested using two sided t-tests by always comparing samples with biochar with samples without biochar (*i.e.*, "0% *vs.* 2.5%", "0% *vs.* 5%", and "0% *vs.* 10%"). The Shapiro–Wilk test was used to test for normality. Variables were ln-transformed if $p < 0.05$. The response in PAW upon biochar addition was tested with linear regression. Treatment effects on plant-available nutrients (adsorbed on PRS™-probes) were tested using one-way ANOVA. In Mongu, there were 7 factor levels because controls without fertilizer and biochar addition were evenly distributed (rows 4, 12, and 20, Fig. 1) at the sides of the fields with applied biochar and at the sides with no biochar {[70+70, 140+140, and 280+280 kg $(ha \cdot y)^{-1}$] x [0 and 6 t biochar ha^{-1}] + [0 kg $(ha \cdot y)^{-1}$ + 0 t biochar ha^{-1}]}. In Kaoma and Mkushi there were three factor levels (0, 2, and 6 t biochar ha^{-1}) for sites with maize and for sites with groundnuts. For Mongu, comparisons between no biochar and biochar at the same fertilizer rate (*i.e.*, "70+70 fertilizer no biochar" *vs.* "70+70 biochar", "140+140 fertilizer no biochar" *vs.* "140+140 biochar", and "280+280 fertilizer no biochar" *vs.* "280+280 biochar") and for Kaoma and Mkushi comparisons between 0 and 2 t biochar ha^{-1} and 0 and 6 t biochar ha^{-1} were done for significant models using general linear hypothesis testing (glht in the library multcomp). Constancy of variance was tested using the Fligner–Killeen test of homogeneity of variances. Residuals were plotted (QQ plots) to assess normality and potential outliers.

3 Results

3.1 Yield

Mongu. There were no significant ($p > 0.16$ for grains; $p > 0.10$ for stover, two sided t-tests) differences at sites receiving biochar as compared to no biochar for absolute yields of maize in Mongu (Fig. 2). However, relative yields (*i.e.*, percentage yield with 6 t ha^{-1} biochar relative to the same fertilizer rate without biochar tested with one sided t-tests) of maize stover and maize grains were significantly ($p < 0.05$) > 100% at 140 + 140 kg (128 ± 6%) and 280+280 kg (232 ± 60%) fertilizer addition, respectively (Fig. 2).

Kaoma. The addition of biochar at the 140+140 kg fertilizer rate increased absolute yields of maize grains at both farms (Fig. 3). However, the increase was not significant ($p = 0.47$ and $p = 0.17$ for the 2 t ha^{-1} and 6 t ha^{-1} biochar addition, respectively). Neither was the increase in relative grain yield significantly different from 100%. Absolute and relative yields of maize stover and groundnuts did not differ significantly between the treatments (Fig. 3).

Mkushi. No significant effects were observed of biochar addition on absolute ($p > 0.66$ for grains; $p > 0.80$ for stover; $p > 0.32$ for groundnuts; $p > 0.35$ for groundnuts and pods) or relative ($p > 0.13$ for grains; $p > 0.31$ for stover; $p > 0.10$ for groundnuts; $p > 0.12$ for groundnuts and pods) yields of maize or groundnuts (Fig. 3).

3.2 Soil nutrient supply rates (PRS™-adsorbed plant available nutrients)

In the Mongu trials with maize, only for K the amount accumulated on PRS™ probes were significantly greater ($p < 0.05$) at 280+280 kg fertilizer with 6 t biochar ha^{-1} as compared to the no biochar treatment (Table 4). Due to a substantial spatial variation, no significant differences in available soil nutrients were observed in Kaoma (neither in maize nor groundnuts; data not shown). In Mkushi, plant available NH_4^+-N was significantly greater ($p < 0.05$) at sites with groundnuts and no biochar (10.2 μg 10 cm^{-2} one month of burial^{-1}) as compared to sites with groundnuts and biochar (3.6 and 3.9 μg 10 cm^{-2} one month of burial^{-1} at 2 and 6 t biochar ha^{-1}, respectively; data not shown). Plant available nutrients under maize were not significantly affected by the treatments in Mkushi.

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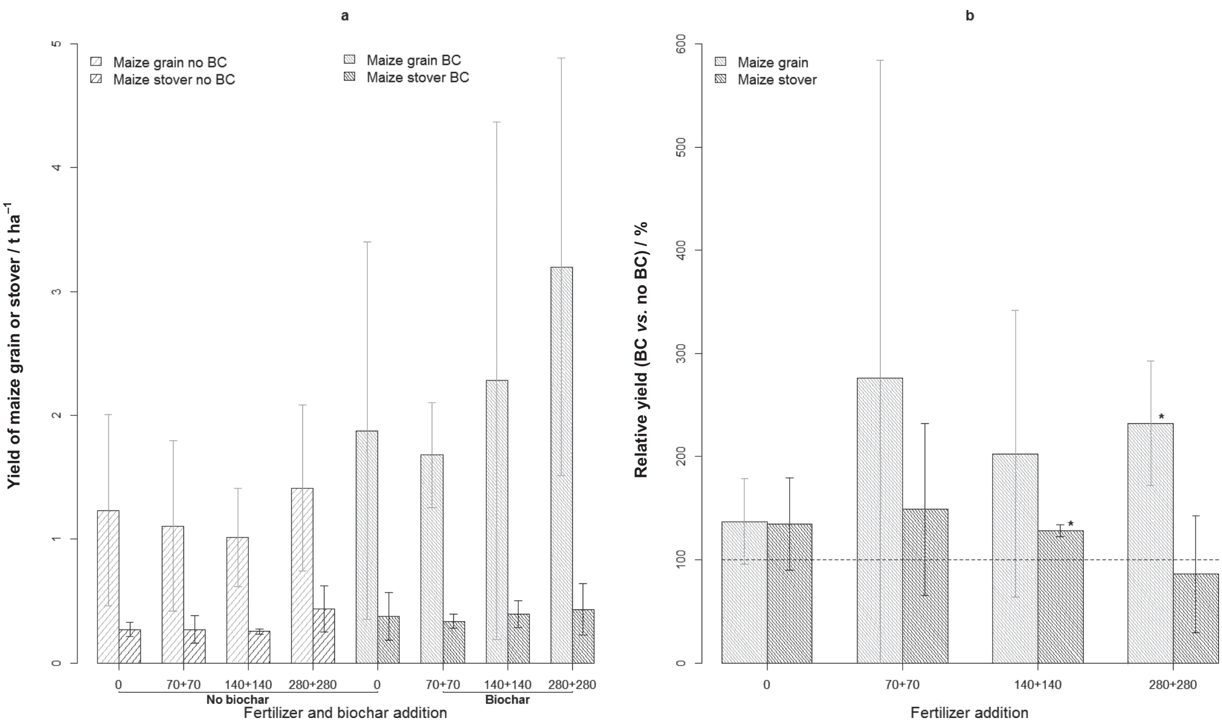

Figure 2: Absolute and relative yields (± SD) of air-dried maize grains and stover (stems and leaves) in sandy soil at Mongu, Zambia, at 0 or 6 t biochar (BC) ha^{-1} and different fertilizer application rates. Relative yield represents percentage yield with biochar relative to the same fertilizer rate without added biochar. Note: 0 fertilizer refers to the control without added biochar. The results are separated to show the difference for the controls on the side of the field where biochar was applied (row 20) and not applied (row 8, *cf.* Fig. 1). * indicates differences at a level of significance $p < 0.05$ between absolute yields at the side with biochar as compared to no biochar (same amount of fertilizer, two sided t-test) or differences from 100% at a level of significance $p < 0.05$ for relative yields (one sided t-test). $n = 3$ for all treatment combinations except for stover yields at 0, 70+70, 140+140 fertilizer addition no biochar and at 0 fertilizer addition 6 t biochar ha^{-1}, where $n = 2$.

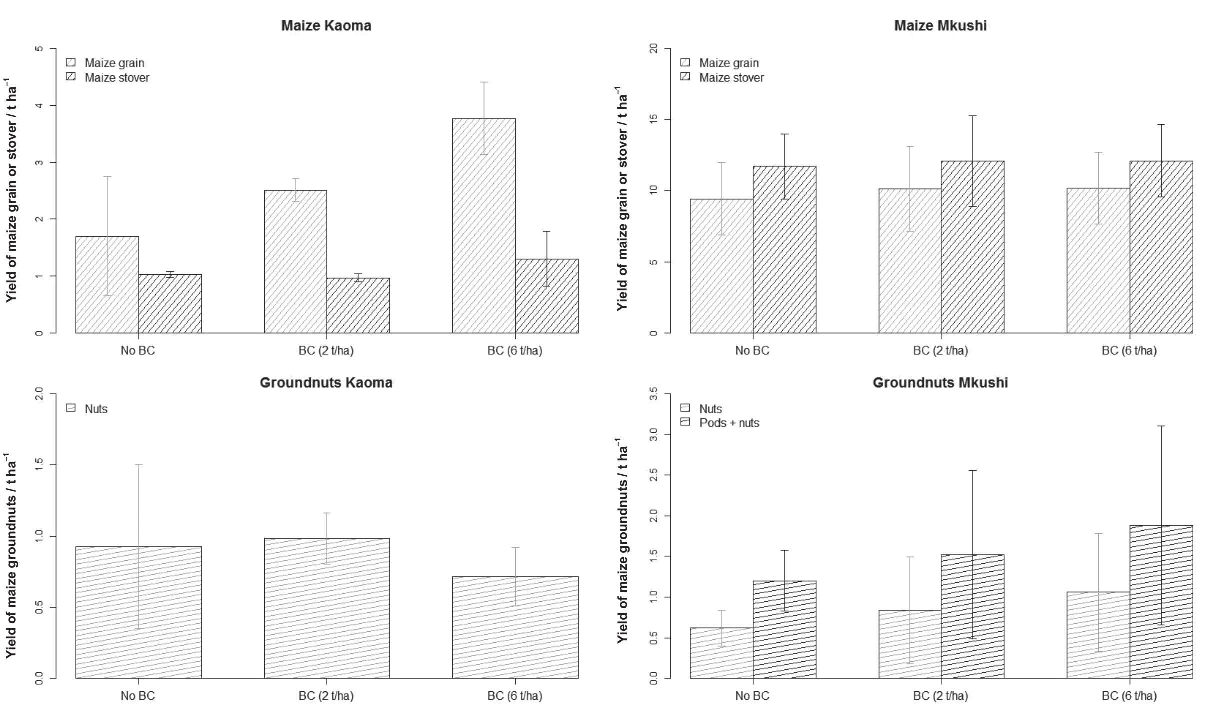

Figure 3: Absolute yields (± SD) of air-dried maize grains and stover (stems and leaves) and groundnuts (pods and nuts) in sandy soil at Kaoma and sandy loam at Mkushi, Zambia. Two and 6 t ha^{-1} biochar were always compared with no biochar (two sided t-test). No differences were statistically significant. Kaoma: $n = 2$ for maize yield, $n = 6$ for yields of groundnuts no biochar, and $n = 3$ for yields of groundnuts with biochar. Mkushi: $n = 5$ for maize yield and $n = 4$ for yields of groundnuts. Note: The scale of the y-axis differs.

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Table 4: Mean (± SD) amounts of PRS™-adsorbed cations and anions and concentrations of elements in maize stover (stems and leaves) in Mongu, Zambia. The PRS-probes were placed in the soil for one month (end of February to the end of March 2012). *, **, ***, or ns indicate difference at a level of significance $p < 0.05$, $p < 0.01$, $p < 0.001$, or $p > 0.05$, respectively. "No biochar" was always compared with "BC 6 t ha^{-1}" for the same fertilizer rate. The tests for PRS™-adsorbed nutrients were based on a one-way ANOVA with subsequent t-tests between "No biochar" and "BC 6 t ha^{-1}" for the same fertilizer rate, and the tests for elemental concentrations are based on individual two-sided t-tests.

PRS™-adsorbed cations and anions																									
Fertilizer[a]	NO_3^--N					NH_4^+-N					PO_4^{3-}-P					K^+					Ca^{2+}				
	μg 10 cm^{-2} one month of $burial^{-1}$																								
	No BC		BC (6 t ha^{-1})			No BC		BC (6 t ha^{-1})			No BC		BC (6 t ha^{-1})			No BC		BC (6 t ha^{-1})			No BC		BC (6 t ha^{-1})		
	mean	sd	mean	sd		mean	sd	mean	sd	n	mean	sd	mean	sd	n	mean	sd	mean	sd	n	mean	sd	mean	sd	n
0 (mean of control row 4, 12, 20)	38.2	38.6	–	–	–	179.9	161.9	–	–	–	32.3	22.2	–	–	–	156.5	119.9	–	–	–	131.0	82.3	–	–	–
70+70	85.8	75.3	61.1	72.3	ns	121.9	114.2	98.6	81.5	ns	34.2	15.0	30.8	14.8	ns	129.5	38.5	380.3	416.0	ns	100.0	60.9	124.0	70.0	ns
140+140	46.2	21.9	50.4	63.7	ns	85.6	96.8	57.2	52.4	ns	36.4	14.4	30.5	16.0	ns	149.7	97.5	233.0	145.9	ns	153.6	81.6	81.7	64.7	ns
280+280	76.6	70.5	30.5	55.4	ns	72.3	65.6	51.7	61.3	ns	25.3	16.9	31.6	14.8	ns	130.8	68.4	313.7	186.5	*	78.2	32.1	119.9	67.0	ns

Concentrations of elements in maize stover																									
Fertilizer[b]	N					CN					PO_4^{3-}-P					K^+					Ca^{2+}				
	%										mg kg^{-1}														
	No BC		BC (6 t ha^{-1})			No BC		BC (6 t ha^{-1})			No BC		BC (6 t ha^{-1})			No BC		BC (6 t ha^{-1})			No BC		BC (6 t ha^{-1})		
	mean	sd	mean	sd		mean	sd	mean	sd		mean	sd	mean	sd		mean	sd	mean	sd		mean	sd	mean	sd	
0 (control row 8 "No BC", row 20 "BC")	0.72	0.17	0.91	0.04	*	66.6	15.8	49.7	1.7	*	2841.7	97.1	2978.2	648.6	ns	6342.2	120.0	3926.8	225.5	***	2159.8	180.7	3948.8	1547.8	*
70+70	1.03	0.25	0.82	0.15	ns	47.1	11.4	57.2	11.2	ns	1534.7	115.4	2095.8	465.8	**	3900.3	1451.9	9926.7	2527.5	***	2476.0	313.7	1760.7	401.5	**
140+140	0.95	0.03	0.66	0.10	***	48.6	1.6	71.2	10.9	***	1791.0	378.6	2287.2	408.6	*	3069.0	345.9	7699.6	405.7	***	2624.0	390.7	1560.7	108.0	***
280+280	1.01	0.17	0.80	0.36	ns	45.0	10.2	66.5	23.5	*	2261.9	414.1	2019.3	1288.6	ns	7107.3	2320.2	7566.2	389.1	ns	1836.8	475.9	2101.0	308.1	ns

[a]Samples from controls without fertilizer and biochar addition were evenly distributed (rows 4, 12 and 20, Fig. 1); n = 9-12 for each treatment combination.
[b]Samples from controls without fertilizer and biochar addition is placed under 'No BC' and 'BC' to show the difference for the controls on the side of the field where biochar was applied (row 20) and not applied (row 8). See Fig. 1; n = 6 for stover "control row 8 'No BC', row 20 'BC'", "70+70" and "140+140" fertilizer with no biochar and 9 for the rest of the treatments.

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3.3 Total nutrient content in maize (Mongu only)

There was a greater variation and larger treatment effects on elemental composition for maize stover (*i.e.*, stems and leaves) as compared to maize grains (data not shown). Biochar significantly increased concentrations of K and P in maize stover. By contrast, a significant reduction of concentrations of Ca and N (at 140+140 kg fertilizer only) was observed in maize stover at sites receiving 6 t biochar ha^{-1} (Table 4). In accordance with the reduced N content, the maize stover had a significant ($p < 0.001$) increase in the C/N ratio at the 140+140 kg fertilizer rate from 48.6 ± 1.6 at the treatments without biochar to 71.2 ± 10.9 at the treatments with 6 t biochar ha^{-1}. With the exception of K, which significantly increased in maize stover at the 140+140 kg fertilizer rate, total nutrient uptake in maize stover and maize grains (t ha^{-1}, *i.e.*, concentration multiplied with yield) was not affected by biochar addition (data not shown).

3.4 Soil and biochar physical and chemical properties

The seven soils in Mongu and Kaoma were classified as sands or loamy sands and the six soils in Mkushi were classified as sandy loams or loam. The soils in Mongu and Kaoma were more acidic (mean pH_{H_2O} = 4.8 and 5.9, respectively) and had a lower CEC (mean CEC = 1.8 and 2.8 $cmol_c\ kg^{-1}$ in Mongu and Kaoma, respectively) than those in Mkushi (mean pH = 6.3; CEC = 3.5 $cmol_c\ kg^{-1}$; Table 3). The biochar produced from maize cobs using an earth-mound kiln (applied in Mongu and Kaoma) had lower pH_{H_2O} (7.6), CEC (32.5 $cmol_c\ kg^{-1}$) and C content (69.7%) than maize cob biochar produced in the brick kiln (applied in Mkushi: pH_{H_2O} = 9.7, CEC = 57.8 $cmol_c\ kg^{-1}$, and C content = 81.1%; Table 2). Washing of the biochars did not have a strong influence on pH, but the CEC was substantially reduced (16.6 and 16.8 $cmol_c\ kg^{-1}$ for the earth mound kiln biochar and brick kiln biochar, respectively, after washing procedure II; Table 2).

The amount of water at field capacity (FC) and the fraction of plant available water (PAW) were greater in the sandy loam from Mkushi (FC = 24.2% and PAW = 18.2%) as compared to the sandy soils from Kaoma (FC = 17.3% and PAW = 14.7%) and Mongu (FC = 5.7% and PAW = 4.5%). The amount of water at FC as well as PAW was significantly increased in response to 2.5, 5 and 10% biochar addition in the soils sampled from all three regions (Table 5, Fig. 4). The per unit increase in PAW upon biochar addition was significantly greater ($p < 0.05$) for the soil sampled in Mongu as compared to the soil sampled in Kaoma (Fig. 4). There was no significant difference between the soils from Kaoma and Mkushi ($p = 0.65$) or Mkushi and Mongu ($p = 0.20$) in the increase of PAW upon biochar addition (Fig. 4). The increase caused by 10% biochar addition was of factor 2.5 for the soil sampled in Mongu (from 4.5% to 11.2%) and 1.2 for the soils sampled in Kaoma (from 14.7% to 18.2%) and Mkushi (from 18.2% to 22.7%).

Cation exchange capacity (CEC) was significantly increased (from 1.4 to 2.7, 3.6 to 6.2, and 2.8 to 5.6 $cmol_c\ kg^{-1}$ in the soils sampled in Mongu, Kaoma, and Mkushi, respectively) upon the addition of 10% biochar (Table 5). Amounts of exchangeable K significantly increased (from 0.02 to 1.6 at 10% biochar, 0.2 to 2 at 10% biochar, and 0.2 to 3.9 $cmol_c\ kg^{-1}$ at 10% biochar in Mongu, Kaoma, and Mkushi, respectively) upon the addition of biochar at all three sites (Table 5), which for Mongu corresponded with *in situ* observations of greater amounts of PRS™ adsorbed K at sites with biochar as compared to no biochar (Table 4). The base saturation increased and available Al^{3+} significantly decreased upon the addition of biochar in Mongu (base saturation from 7.2% to 72.8% with 10% biochar; $p < 0.001$) and Mkushi (base saturation from 43.4% to 90.4% with 10% biochar; $p < 0.01$), but there was no significant effect on the soil from Kaoma due to a high initial base saturation (50.3%) and small amounts of available Al^{3+} even without biochar.

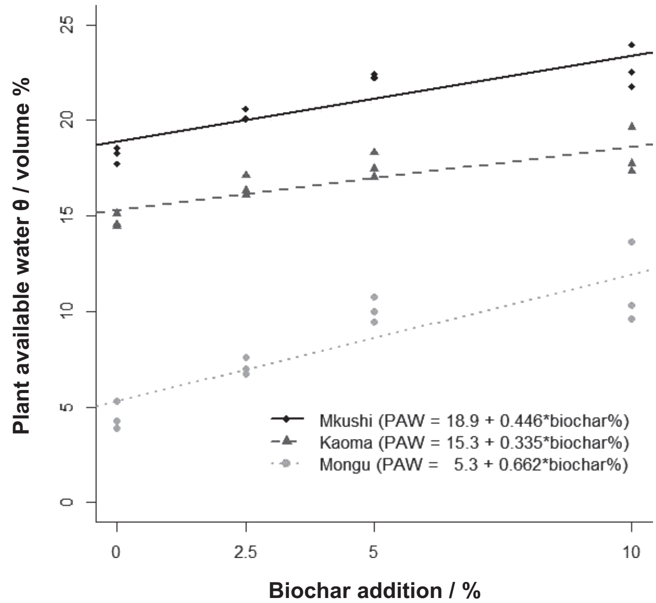

Figure 4: Plant available water of laboratory-packed soils from Mongu, Kaoma, and Mkushi, Zambia, as a response of 0, 2.5, 5, or 10% maize biochar addition produced in an earth mound kiln (for the soils from Mongu and Kaoma) or maize biochar produced in a brick kiln (for the soil from Mkushi).

4 Discussion

Combined with CF the use of a low dosage of biochar may significantly improve soil fertility and crop yields (*Cornelissen* et al., 2013a). Yet, detailed information about effects of biochar addition on crop yields combined with soil chemical and physical properties is rare. In the current extensive farmer-led biochar trials we found a consistent positive response (relative increases of 232 ± 60% in Mongu, 289 ± 216% in Kaoma, and 110 ± 16% in Mkushi) of biochar addition on maize grain yield although we were not able to statistically prove significant increases in absolute yields due to large spatial variations in this real-world situation (as opposed to the usually deployed research farm trials) and limited replication per treatment combination. In Mongu, biochar significantly increased *in situ* plant-available K as well as concentrations of K and P in maize stover. Despite a decrease in amounts of

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Table 5: Chemical and physical soil characteristics of pure soils and soils with 2.5%, 5% or 10% (w:w) added maize cob biochar[a]. The soils derive from single farmers[b] in Mongu, Kaoma, and Mkushi, Zambia. $n = 3$ (replicated in the laboratory) for all except for pH ($n = 1$). *, **, and *** indicate differences at a level of significance $p < 0.05$, $p < 0.01$, and $p < 0.001$. 2.5%, 5% or 10% BC addition was always compared with 0% BC addition. "ns" is non-significant ($p > 0.05$).

Location	Biochar added	$pH_{(H_2O)}$		$pH_{(CaCl_2)}$		H^+			Ca^{2+}			K^+			Al^{3+}			CEC[c]		
						$cmol_c\ kg^{-1}$														
		mean	sd	mean	sd	mean		sd	mean		sd	mean		sd	mean		sd	mean		sd
Mongu	0%	4.41	–	3.48	–	1.25		0.24	0.05		0.01	0.02		0.01	0.39		0.03	1.35		0.25
	2.5%	5.86	–	4.44	–	1.25	ns	0.12	0.10	ns	0.03	0.57	**	0.08	0.30	*	0.03	1.99	*	0.21
	5%	6.16	–	5.09	–	0.76	ns	0.63	0.11	*	0.00	0.90	**	0.07	0.22	**	0.03	1.83	ns	0.55
	10 %	6.62	–	5.59	–	0.79	ns	0.71	0.15	ns	0.06	1.64	*	0.31	0.13	***	0.04	2.69	*	0.44
Kaoma	0%	6.11	–	5.09	–	1.81		0.21	1.31		0.07	0.21		0.02	0.02		0.01	3.63		0.16
	2.5%	6.45	–	5.74	–	1.81	ns	0.21	1.35	ns	0.03	0.75	*	0.11	0.02	ns	0.00	4.23	*	0.29
	5%	6.63	–	6.06	–	2.15	ns	0.43	1.31	ns	0.01	1.20	*	0.23	0.02	ns	0.01	5.02	ns	0.61
	10%	6.82	–	6.2	–	2.43	ns	0.91	1.34	ns	0.18	2.01	*	0.34	0.01	ns	0.01	6.16	**	0.50
Mkushi	0%	5.1	–	4.42	–	1.60		0.52	0.63		0.01	0.21		0.01	0.48		0.01	2.77		0.51
	2.5%	6.59	–	5.99	–	1.11	ns	0.42	0.60	ns	0.04	1.05	*	0.21	0.18	*	0.04	3.08	ns	0.36
	5%	7.08	–	6.49	–	0.42	*	0.39	0.65	ns	0.04	1.75	**	0.10	0.05	***	0.01	3.17	ns	0.40
	10%	7.52	–	7.06	–	0.58	ns	0.51	0.72	ns	0.04	3.92	**	0.36	0.02	**	0.01	5.61	*	0.81

Location	Biochar added	Ca:Al ratio			Base saturation			BD[d] (ρb)			Pore volume			FC (pF 2)			WP (pF 4.2)			PAW[d]		
					%			$g\ cm^{-3}$			%			Vol %			Vol %			Vol %		
		mean		sd	mean		sd	mean		sd	mean		sd	mean		sd	mean		sd	mean		sd
Mongu	0%	0.1		0.0	7.2		1.9	1.61		0.00	39.8		0.8	5.7		0.7	1.2		0.0	4.5		0.7
	2.5%	0.4	*	0.1	37.1	**	3.8	1.55	ns	0.03	41.9	ns	1.3	8.8	**	0.5	1.7	**	0.0	7.1	*	0.4
	5%	0.5	**	0.1	63.1	**	24.0	1.46	*	0.06	43.6	*	1.5	12.2	***	0.6	2.2	**	0.1	10.0	***	0.7
	10 %	1.3	*	0.7	72.8	***	23.7	1.32	ns	0.12	49.3	ns	4.5	15.1	**	1.8	3.9	**	0.4	11.2	*	2.2
Kaoma	0%	57.7		10.2	50.3		3.9	1.61		0.03	38.4		0.7	17.3		0.4	2.6		0.0	14.7		0.4
	2.5%	67.5	ns	1.5	57.4	ns	2.6	1.51	*	0.04	41.8	ns	1.8	19.7	**	0.6	3.2	**	0.1	16.5	*	0.5
	5%	87.5	ns	37.7	57.3	ns	4.2	1.40	*	0.06	45.9	*	2.6	20.8	**	0.7	3.2	*	0.1	17.6	**	0.6
	10%	114.3	ns	49.0	61.1	ns	11.1	1.29	**	0.07	49.1	*	3.7	23.8	**	0.9	5.5	**	0.3	18.2	*	1.2
Mkushi	0%	1.3		0.0	43.4		8.2	1.31		0.03	49.8		0.8	24.2		0.5	6.1		0.1	18.2		0.4
	2.5%	3.6	ns	1.2	64.4	ns	10.6	1.23	ns	0.04	53.3	**	0.9	26.6	**	0.5	6.4	ns	0.2	20.2	**	0.3
	5%	12.3	**	0.9	87.8	**	11.2	1.18	ns	0.08	54.3	ns	2.3	28.6	***	0.5	6.3	ns	0.4	22.3	**	0.1
	10%	48.2	ns	20.7	90.4	**	8.3	1.08	*	0.09	57.7	*	2.3	29.7	**	0.8	7.0	ns	0.5	22.7	*	1.1

[a]Maize cob biochar used in Mongu and Kaoma was produced in an earth mound kiln and maize cob biochar applied in Mkushi was produced in a brick kiln.

[b]Farmer "M4" in Mongu,"K1" in Kaoma and "MK2" in Mkushi.

[c]CEC, exchangeable base cations and extractable acidity (H^+) for unwashed soil and biochar determined according to *Schollenberger* and *Simon*, 1945. Na^+ ($< 0.01\ cmol_c\ kg^{-1}$) and Mg^{2+} ($0.01–0.38\ cmol_c\ kg^{-1}$) were included for the calculation of CEC but are not shown in the table.

[d]Plant available water (difference between pF 2 and pF 4.2); BD = bulk density.

in situ PRS™-adsorbed NH_4^+-N in Mkushi upon biochar addition, there were no clear effects of biochar addition on nutrient supply rates. As predicted, amounts of plant available water and CEC were significantly increased and the pH raised upon the addition of biochar.

4.1 Yield

Grain yields of maize at half of the recommended fertilizer rate (140+140 kg) at 0 biochar and 6 t biochar ha^{-1} increased in the order Mongu (1.0 ± 0.4 t ha^{-1} at 0 biochar and 2.3 ± 2.1 t ha^{-1} at 6 t biochar ha^{-1}) < Kaoma (1.7 ± 1.1 t ha^{-1} at 0 biochar and 3.8 ± 0.6 t ha^{-1} at 6 t biochar ha^{-1}) < Mkushi (9.4 ± 2.5 t ha^{-1} at 0 biochar and 10.2 ± 2.5 t ha^{-1} at 6 t biochar ha^{-1}). The yields are smaller at the two former sites and larger at the latter than average yields (5.2 t ha^{-1}) reported by *Umar* et al., 2011 at CF farms with planting basins in Zambia. The effects of biochar on yields of groundnuts (Figs. 2 and 3) were, however, evaluated as minor and non-significant (relative yields of 123 ± 57% and 88 ± 37% at 2 t biochar ha^{-1} and 6 t biochar ha^{-1} in Kaoma and 120 ± 72% and 155 ± 69% at 2 t biochar ha^{-1}, and 6 t biochar ha^{-1} in Mkushi). A possible reason that biochar is more effective for fertilized maize than for unfertilized leguminous groundnuts is that biochar helps to prevent the added fertilizer from washing out in these low-CEC soils due to biochar's cation retention capacity (*Glaser* et al., 2002; *Lehmann* et al., 2003; *Yamato* et al., 2006; *Hale* et al., 2013).

Earlier research has reported interactions between biochar and fertilizer additions on crop yield (*Manya*, 2012). The addition of biochar to soil in combination with fertilizer has been reported to increase (*Steiner* et al., 2007; *Chan* et al., 2007; *Asai* et al., 2009) or have no effect on yield (*Jeffery* et al., 2011; *Güereña* et al., 2013). In Mongu, the addition of fertilizer in combination with biochar at 6 t ha^{-1} resulted in greater yields of maize grain than with fertilizer addition only, but the relative increase was only significant at the highest fertilizer rate, *i.e.*, biochar addition was most effective at the highest fertilizer rates (Fig. 1). This suggests an interaction between fertilizer and biochar, most likely biochar increasing CEC so that fertilizer can be used more efficiently. Somewhat surprisingly, the grain yields did not significantly increase upon the addition of fertilizer (Fig. 1). We have no data to directly assess this issue, but plausible explanations could be that: (1) nutrients were not the main limitation for plant growth because water was more limiting (hence a positive response upon biochar addition; *cf.* Fig. 4); (2) nutrients from the fertilizer were vertically leached in these extremely sandy soils due to a low nutrient retention capacity which was significantly increased upon biochar addition (from 1.4 $cmol_c$ kg^{-1} without biochar to 2 $cmol_c$ kg^{-1} with 2.5% biochar addition; *cf.* Table 5).

4.2 Soil nutrient supply rates (PRS™-adsorbed plant available nutrients)

We found an increase in amounts of PRS™-adsorbed K with biochar addition in all three regions and the increase was significant at sites with maize in Mongu (Table 4). This increase can be explained by the high available K content of the applied biochar (27 $cmol_c$ kg^{-1}; Table 2). The application of 6 t biochar ha^{-1} resulted in an additional input of 63 kg K ha^{-1} when applied in the basins, as compared to 7, 14, and 28 kg K ha^{-1} added at the three fertilization rates. The observed significant reduction in supply rates of NH_4^+-N at sites with groundnuts and biochar in Mkushi (data not shown) supports that N availability might be reduced upon the addition of biochar (*Lehmann* et al., 2003; *Steiner* et al., 2008). This could also be a result of greater N uptake. However, since the N content of the groundnuts was not analyzed, we could not establish an N balance for this crop. In general, there was, however, a great variation in amounts of PRS™ adsorbed nutrients both within and between regions which could partly be due to intrinsic soil properties (*Van Wambeke*, 1991; *Qian* and *Schoenau*, 2005) and soil moisture regime (*DeLonge* et al., 2013). Previously, positive relationships between N supply rates as determined by PRS™ probes in soils in Canada and N uptake by canola and N uptake in maize was reported by *Qian* and *Schoenau*, 2005 and *Nyiraneza* et al., 2009, respectively. With the exception of K, our results do not show any clear relationships between supply rates of nutrients in the soil and uptake in maize (Mongu only).

4.3 Elemental composition of maize (Mongu)

Concentrations of Ca, K, N, and P in maize stover were significantly affected by biochar addition in Mongu (Table 4). Normally, increased availability of Ca^{2+} leads to an increase in Ca concentration in the leaves (*Marschner*, 2012). In our study, there was no evidence for a significant impact on supply rates of Ca as determined by *in situ* PRS™-exchange resins (Table 4). In addition, due to the low Ca content of the applied biochar (Table 2) and subsequent small effect on amounts of exchangeable Ca after biochar addition in the soil (Table 5), no effect of biochar on concentrations of Ca in maize stover was to be expected. By contrast, concentrations of K in maize stover were significantly increased upon biochar addition (Table 4). Increased concentrations of K in red clover, red fescue and plantain in treatments with biochar as compared to no biochar were recently reported by *Oram* et al., 2014. Concentrations were greater and more variable in the stover (3 to 7.1 g kg^{-1}) as compared to the grains (3.2 to 3.7 g kg^{-1}). This was not surprising as grains and seeds maintain a relatively constant K concentration of ≈ 3 g kg^{-1} (*Marschner*, 2012). The increased K concentration in maize stover upon biochar addition probably results from luxury consumption which occurs when K supply is abundant (*Marschner*, 2012). This is supported by the significant increase in *in situ* soil supply rates of K in the soil from Mongu (Table 4) and significant increase in exchangeable K upon biochar addition (Table 5). Thus, our results clearly show that maize cob biochar has a large positive impact on levels of K both in plants and soils.

A previous study by *Steiner* et al., 2007 revealed no significant influence on nutrient concentration of plant and grains of rice and sorghum grown on a Xanthic Ferralsol in the Brazilian Amazon when comparing the addition of charcoal and fertilizer as compared to mineral fertilizer only. In a temperate maize-based production system on fertilized soils in America, *Güereña* et al., 2013 found no effect of biochar addition on N

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concentrations and total N uptake in maize. We found greater P concentrations and smaller N concentrations (at 140+140 kg fertilizer addition) in maize stover after the addition of 6 t biochar ha^{-1} (Table 4). The increased P concentration could derive from enhanced availability of P in the soil due to increased pH upon biochar addition (Table 5), although not supported by *in situ* soil supply rates of P (Table 4). The decreased concentration of N is most likely associated with a dilution effect (*Skowronska* and *Filipek*, 2010) as the yield was greater upon biochar addition (Fig. 2) and the *in situ* soil supply rates were not significantly increased at sites receiving biochar (Table 4). This also coincides with the significant increase in C/N ratio of maize stover (Table 4) and the greater (but non-significant) N uptake (*i.e.*, concentration times yield, data not shown) after biochar addition.

Total uptake of N, P, and K in maize grains was greater at the recommended 280+280 kg fertilizer rate as compared to no fertilizer (control) both with and without the addition of biochar (data not shown). Increased grain yields and plant N uptake with applied N rate was previously reported by *Ciampitti* and *Vyn*, 2012. *Steiner* et al., 2007 found significantly greater nutrient exports at sites receiving charcoal and fertilizer as compared to mineral fertilizer only due to higher yields at the former. Our findings for the N, P, and K contents of maize grains at the 280+280 kg fertilizer rate with 6 t biochar ha^{-1} are in accordance with those reported by *Steiner* et al., 2007, although we were not able to prove it statistically. An interesting note is that the total amounts of nutrients removed in maize stover (N: 4.4 ± 2.1 kg ha^{-1}, P: 1.0 ± 0.6 kg ha^{-1}, K: 3.4 ± 2.3 kg ha^{-1} at 280+280 kg fertilizer rate with no biochar) and grains (N: 20 ± 10 kg ha^{-1}, P: 4.2 ± 1.9 kg ha^{-1}, K: 4.8 ± 2.4 kg ha^{-1} at 280+280 kg fertilizer rate with no biochar) are substantially smaller than the amounts added with fertilizer (N: 156 kg ha^{-1}, P: 56 kg ha^{-1}, K: 28 kg ha^{-1}) suggesting an excess of N, P, and K that is either lost through leaching or gaseous emission (N only), or stored in the soils. At sites with applied biochar, nitrous oxide could also be adsorbed to the biochar, as biochar can bind nitrous oxide more strongly than mineral and organic soil materials (*Cornelissen* et al., 2013b).

4.4 Soil physical and chemical properties

Positive effects on soil physical, chemical, and biological properties are reported to be the main benefits of biochar addition (*Glaser* et al., 2002; *Jeffery* et al., 2011; *Lehmann* et al., 2011; *Manya*, 2012). Particularly in acidic soils the liming potential of biochar might be positive for crop growth as increased pH and reduced levels of Al is positive for grain yields (*Joris* et al., 2013). The low pH observed for the soil in Mongu (Tables 3 and 5) could result in toxic levels of dissolved Al which increase rapidly at pH < 4.5 (*Mulder* et al., 1989). Our results support the positive effects of biochar addition on soil chemical and physical properties (Table 5). Significant increases of K^+ upon the addition of 2.5–10% biochar for the soils from all three regions are in line with the high K^+ content of the unwashed BCs used in Mongu and Kaoma (27 $cmol_c\ kg^{-1}$) and Mkushi (56 $cmol_c\ kg^{-1}$, Table 2). The significant increase in CEC, pH, and Ca/Al ratio and subsequent reduction in exchangeable Al^{3+} and acid saturation upon the addition of biochar to the soils from Mongu and Mkushi probably all contribute to the explanation of the observed increase in crop yield.

The amount of plant available water (PAW) significantly increased upon the addition of biochar (< 2 mm) for all three soils (Fig. 4, Table 5). The fraction PAW without biochar was 4.5%, 14.7%, and 18.2% for the soils in Mongu, Kaoma, and Mkushi, respectively. At 5% biochar addition PAW increased to 10%, 17.6%, and 22.3%, respectively (Table 5). Especially the doubling of PAW in Mongu upon 5% biochar addition (from 4.5% to 10%) probably contributed to the observed effect of biochar on crop yield. Furthermore, bulk density (BD) in the soils decreased after mixing with biochar (Table 5). In a soil-physical CF study in Zambia, BD was found to be lower on ridges prepared according to conventional practice (1.2 g cm^{-3}) as compared to CF planting basins (1.4 g cm^{-3}) (*Shitumbanuma*, 2010). The addition of biochar in combination with CF may thus prevent soil compaction.

In conclusion, biochar was observed to have positive effects on soil physical and chemical properties in acidic tropical soils, specifically increases in PAW, CEC, available K^+, pH, and decrease in available Al^{3+}. These beneficial effects resulted in increases in the yield of fertilized maize but not in that of unfertilized groundnut. Relative increases were significant for maize in Mongu at the recommended fertilizer rates but not at reduced ones, showing that biochar is probably most effective in combination with fertilization as the CEC and pH increases help to retain nutrients. One of the main merits of the present study is that it was completely farmer-led and thus closer to reality than controlled studies on experimental farms. On the other hand, this lower level of control has led to significant spatial and temporal variability, rendering it difficult to obtain statistically significant effects.

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