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Effects of hand-hoe tilled conservation farming on soil quality and carbon stocks under on-farm conditions in Zambia

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ABSTRACT

Conservation farming (CF) has been promoted in Zambia since the 1980s. Despite long-term practice of CF in Zambia, its effect on soil fertility, including the storage of soil organic matter (SOM), on smallholder farms are inconclusive. Here, we assess the effect of CF as compared to conventional tillage on soil quality parameters on smallholder farms in the Eastern province (EP, 20 sites, two to six years of CF) and Central province (CP, 20 sites, four to twelve years of CF) in Zambia. Soils under CF (minimum tillage hoe basins, crop rotation and residue retention) were compared with adjacent conventional farms (hoe ridges in EP and overall digging or ridge splitting in CP). Only small differences were observed in the soil quality parameters between the CF basins and adjacent conventional plots after maximum 12 years since CF adoption. The concentration of soil organic carbon (%SOC) and carbon (C) stocks did not differ significantly between management practices, with C stocks in CF basins and conventional plots in EP amounting to 4.41 and 4.63 kg m^{-2}, respectively, while this is 3.37 and 3.57 kg m^{-2}, in CP. Likewise, the % SOC did not differ significantly between soils in the basins and in-between the basins. Both observations indicate that either the annual net accumulation of SOC is very small, or that on-farm surveys involve significant year-to-year changes in the position of the basins. However, the latter is not supported by plant available phosphorus (Bray P) data, which are significantly greater in CF basins than in-between them (12.7 vs 8.3 mg kg soil^{-1} in CP and 8.5 vs 5.2 mg kg soil^{-1} in EP), indicating significant Bray P accumulation in CF basins, due to annual fertilizer addition. Amounts of Bray-P in CF basins did not significantly differ from that under conventional management. Overall, our results show small differences in the soil quality parameters between the CF and conventional practices at smallholder farms after maximum 12 years since adoption of CF.

1. Introduction

Conservation agriculture (CA) may offer climate change adaptation (increased soil fertility and water conservation) and mitigation (reduced emissions of greenhouse gases and C-sequestration) benefits (Pisante et al., 2015). However, reported effects of CA on the buildup of SOM in Sub-Saharan Africa differ considerably between studies (Thierfelder and Wall, 2012; Corbeels et al., 2015; Cheesman et al., 2016) and it is not yet clear whether conversion to a CA system can increase C sequestration (Srinivasarao et al., 2015). According to Powlson et al. (2016) CA comprices three principles; zero or reduced tillage, soil cover by residue retention and crop rotation. In addition, integrated weed management is important in CA (Farooq and Siddique, 2015). An important aspect of CA is reducing negative effects of agricultural activities such as soil erosion, soil organic matter (SOM) decline, loss of soil water retention and soil physical degradation (Farooq and Siddique, 2015; Mafongoya et al., 2016). Different terms for CA are commonly used depending on the specifics of the technology or practice (Thierfelder et al., 2015; Mafongoya et al., 2016). In Zambia, the Conservation Farming Unit (CFU) uses the term conservation farming (CF) for conservation

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tillage (i.e. minimum tillage (MT), using planting basins, retention of crop residues and the incorporation of legumes in crop rotation (CFU, 2011; Aune et al., 2012; Martinsen et al., 2014)).

CF may increase yields, which is attributed to improved soil fertility and plant available water in addition to reduced soil erosion and thus increased nutrient availability (Jat et al., 2012; Gatere et al., 2013; Palm et al., 2014). However, the effect of CF on crop yield and soil physical and chemical properties is the subject of debate due to substantial variations in results between different studies (Giller et al., 2009; Umar et al., 2011; Ngwira et al., 2012; Gatere et al., 2013; Thierfelder et al., 2013; Stevenson et al., 2014; Pittelkow et al., 2015; Powlson et al., 2016). Particularly, climatic and edaphic conditions combined with management practice (e.g. seeding system, residue retention, fertilizer addition and crop rotation) are believed to determine to what extent CF has a positive, negative or no effect on yields and soil fertility (Gatere et al., 2013; Nyamangara et al., 2014; Palm et al., 2014; Pittelkow et al., 2015; Mafongoya et al., 2016; Powlson et al., 2016; Thierfelder et al., 2016). Pittelkow et al. (2015) reported overall reductions in yields under no-till as compared to conventional tillage for 610 studies across 63 countries. However, no-till in combination with residue retention and crop rotation significantly increased yields (+7.3%) in dry climates suggesting that CF may be an important climate-change adaptation strategy in semi-arid regions (Pittelkow et al., 2015).

A recent meta-analysis of soil organic carbon (SOC) stock changes under CF (controlled and on-farm experiments) in two tropical regions by Powlson et al. (2016) reported increases of between 0.28 and 0.96 t C ha^{-1} yr^{-1} in Sub-Saharan Africa under CF (2–16 years) as compared to conventional practices. Results from validation trials in Southern Africa comparing conventional agricultural practice and CF by Cheesman et al. (2016) showed ~0.5 t C ha^{-1} greater soil C stocks for the upper 0–10 cm of the soil at CF sites as compared to conventional sites, after 2–7 years. Increased levels of SOC and improved soil quality at CF sites (2 and 5 years) compared to annual ridge tillage was reported by Mloza-Banda et al. (2016) from smallholder farms in Southern Malawi. Two and five years since adoption of CF, %SOC was increased with 0.3% and 0.8%, respectively, but the increase in soil C-stocks was only significant after more than 5 years. Soil quality parameters including N content (from 0.06% to 0.10%), available P (from 12.7 mg kg^{-1} to 35.6 mg kg^{-1}) and CEC (from 13.4 $cmol_c$ kg $soil^{-1}$ to 15.2 $cmol_c$ kg $soil^{-1}$) were all significantly enhanced after two years since adoption (Mloza-Banda et al., 2016). In contrast, monitoring studies from on-farm sites in Zimbabwe (Nyamangara et al., 2013) and Zambia (Thierfelder et al., 2013) suggest small effects of CF on soil C stocks. Paired comparisons of soils at CA fields (up to 9 years) and adjacent conventional fields from 450 farms in 15 districts in Zimbabwe revealed low SOC contents (<1%) without clear difference in%SOC or levels of total P between the two management practices (Nyamangara et al., 2013). Results from two on-farm sites in Zambia showed no significant effects of CA on soil C-stocks after 3–5 years, but results from an on-station trial suggested significantly greater C-stocks (2.5–3.3 t C ha^{-1}) for the upper 10 cm of the soil after 5 years of CA as compared to conventional treatment (Thierfelder et al., 2013).

The potential of soils to sequester carbon is controlled by intrinsic physciochemical soil characteristics and management practice (Six et al., 2002a,b). Soil management increasing organic residue inputs and reducing decomposition may increase the C sequestration, and improved soil management may thus increase the potential to mitigate greenhouse gas emissions (Paustian et al., 2016). In CA systems, several challenges and constraints are at play simultaneously, which may partly explain the large variations in results between different studies. Such challenges and constraints include different seeding systems, crop rotation, weed control and fertilizer application, all affecting biomass production (e.g. Gatere et al., 2013; Nyamangara et al., 2013; Thierfelder et al., 2015, 2016;

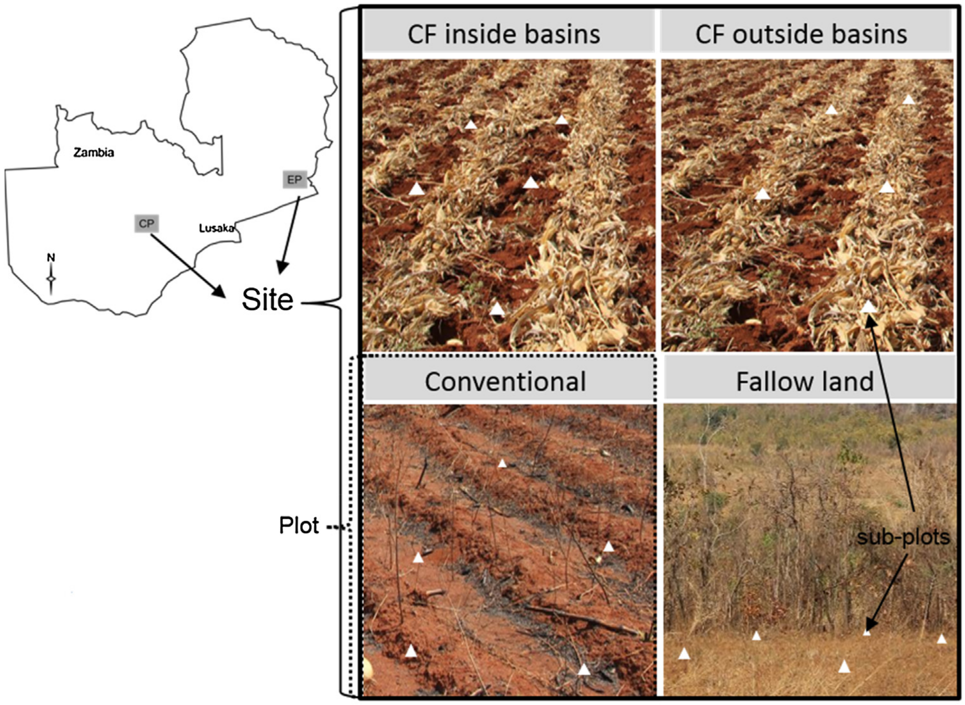

Fig. 1. Setup for soil sampling in the Central (CP) and Eastern Provinces (EP) of Zambia. Soil sampling was conducting at five sub-plots (~0.05 m^2) randomly selected within each of four plots (200–500 m^2) representing the management practices CF inside basins, CF outside basins, conventional farming and fallow land located within twenty sites in the two provinces (i.e. a total of 2 provinces × 20 sites × 4 plots × 5 sub-plots (replicates) = 800 soil samples). The pictures for the CF plots is from a farm where residue retention is done according to CFU- guidelines.

Powlson et al., 2016). On the other hand, management-induced availability of crop residues, e.g. due to burning, removal and grazing may affect the input of organic carbon to soil (Chivenge et al., 2007; Umar et al., 2011; Thierfelder et al., 2013; Cheesman et al., 2016). Although effects of CA on soil fertlity and SOM levels may be significant in controlled experiments at research stations, smaller effects may be expected from monitoring studies on smallholder farms, which are less controlled.

Here, we assess the effect of CF as compared to conventional tillage on soil quality parameters and carbon storage (total C stocks and amount C associated with particulate organic matter) on smallholder farms in the Eastern (EP) and Central (CP) Provinces in Zambia. Smallholder farms were selected from the large pools of CF adopters in Zambia trained by the CFU. Soils of farmers practicing CF were compared with soils from their direct non-CF neighbours (i.e. conventional farmers on similar soils). In the EP, soils of farmers practicing CF by making planting basins using hand hoes and retaining crop residues in the plot were compared to those of adjacent conventional farmers who till their fields using hand hoes and then make ridges on which they plant crop (hoe ridges dry season). In the CP, CF was compared to conventional farming with overall digging or ridge splitting. We hypothesized larger content and availability of phosphorus (P) and nitrogen (N) and greater SOM and cation exchange capacity (CEC) on farms practicing CF as compared to conventional farms.

2. Material and methods

2.1. Study design and sampling

The study was conducted on selected smallholder farms near Chipata, EP and close to Mumbwa, CP, Zambia (Fig. 1). Mean annual temperature and mean annual precipitation are 22 °C and 932 mm in EP and 21.3 °C and 920 mm in CP. The altitude of the sampling areas ranges from 853 to 1189 m a.s.l. in EP and from 1108 to 1246 m a.s.l. in CP. At twenty sites in each of the two provinces soil sampling was conducted at five randomly selected sub-plots (~0.05 m^2) within each of four plots (200–500 m^2), representing the management practices conservation farming (CF) inside basins, CF outside basins, conventional farming and fallow land ($n = 20$ at each site, Fig. 1). The sites were selected based on similar soils, slopes and aspects using the network of farmers established by the CFU. Site selection and sampling of soils was conducted at 18 sites in EP and CP between September and October 2012. Two additional sites in CP and EP were sampled in October 2013 and March 2014, respectively. A site consisted of either one farm practicing both CF (two to six years and four to twelve years in EP and CP, respectively) and conventional farming, or one farm practicing CF and a neighboring one practicing conventional farming on the same type of soil (i.e., they were located close to each other with a max distance of 100 m). Conventional farming practice encompassed annual dry season ridge splitting using hoes in EP (ridges split each season to form new ridges in previous furrows (CFU, 2011)) and overall digging in CP. At each site, land that had been fallow for 3–30 years and partly covered by trees, shrubs, and grasses was included as unfarmed land. Coordinates of the selected sites and farms are given in Tables A.1 and A.2 (Appendix in Supplementary material). Interviews using questionnaires with the farmers (31 farms at 20 sites in both the EP and CP) were carried out to gain information about management practice (residue retention, fertilizer application and weed control), land use history (including number of years since adoption to CF) and crop yield.

2.1.1. CF practice

In this study, farmers practicing CF did dry season preparation of planting basins using hoes. This management practice includes preparation of rows of permanent basins, each with a spacing of 90 cm between rows and 70 cm between basins within rows, giving a total of ~16,000 basins ha^{-1}. Each basin has an area of ~0.05 m^2 and a volume of ~10 L (20 cm depth, 30 cm length, 16.7 cm width) (CFU, 2011). A basal dressing fertilizer of 200 kg ha^{-1}"Compound D" (N, P_2O_5, K_2O, 10:20:10) was applied before planting and a top dressing of 200 kg ha^{-1} Urea (46:0:0) was applied to basins about 4 to 5 weeks after planting. The total amount of NPK on elemental basis corresponded to an application of 112 kg N ha^{-1} yr^{-1}, about 17.5 kg P ha^{-1} yr^{-1} and about 16.5 kg K ha^{-1} yr^{-1}. All CF farmers used legumes (groundnuts, soya beans or green beans) in crop rotation and had grown maize the previous season. Herbicides (glyphosate) or hand weeding was used as weed control.

2.1.2. Conventional practice

Farmers practicing conventional farming either incorporated residues in the soil or burned them. This will have different effects on the input of carbon to the soils, but it was beyond the scope of this study to quantify the effect of burning vs. incorporation. Fertilizer inputs followed the recommended fertilizer applications rates for farmers growing maize under small-scale conditions. This is the same as the rates used by farmers practicing CF. The basal fertilizer Compound D is applied in planting holes or stations, below the seed separated by a small layer of soil, while the top dressing fertilizer (Urea) is spread a few centimeters around the plants. Weed control at the conventional farms consisted of herbicides in combination with hand weeding. As the study was conducted on smallholder farms (i.e. no controlled field trials) the study reflected a real word situation where guidelines may not always have been followed accurately and where differences in management practice e.g. fertilizer application time and rates, planting time, weeding practice and degree of residue retention may have occurred (Gatere et al., 2013).

2.1.3. Sampling

Five to eight soil samples from 0 to 20 cm (depth of the basins) at each of the 800 sub-plots (Fig. 1) were collected using a hand hoe and bulked prior to chemical analysis. Undisturbed clods of soils were collected to determine bulk density (BD). Sampling at the transition zones between the different management practices was avoided. Crop yields were not measured directly, as the sampling was done after the dry season. However, interviews with the farmers indicated the following average and standard deviations (sd) of yields of maize: in EP, 4.7 ± 2.1 t ha^{-1} and 2.4 ± 2.2 t ha^{-1} for CF and conventional practices, respectively, and in CP, 3.0 ± 2.0 t ha^{-1} and 2.6 ± 1.5 t ha^{-1} for CF and conventional practices, respectively (Tables A.1 and A.2). Soil samples from six sites, where farmers had been practicing CF for >6 years, in EP (sites 7, 8, 12, 13, 16 and 17) and from six sites, where farmers had been practicing CF for >12 years, in CP (sites 1, 8, 14, 15, 18, 19) were selected for more detailed soil analysis.

2.2. Soil analysis

2.2.1. All samples

Details of the methods can be found in the Appendix in Supplementary material. Briefly, all soil samples ($n = 800$) were air-dried and sieved (2 mm) prior to analysis. Subsamples of the air-dried and sieved samples were dried at 60 °C to determine dry matter content and then milled prior to determination of total carbon (C) and nitrogen (N). Total C and N were determined by dry combustion (Leco CHN-1000; Leco Corporation, Sollentuna, Sweden) (Nelson and Sommers, 1982) and the Dumas method (Bremmer and Mulvaney, 1982), respectively. Due to the low pH of the soils, total C represents organic C. The BD of the soils was determined using the clod method (Blake, 1965). Carbon and N stocks were calculated by multiplying depth of sampling, BD and elemental concentration (Martinsen et al., 2011). Carbon stocks were also calculated based on an equivalent mass of soil since equal depth sampling may overestimate C stocks due to greater BD under minimum tillage (Ellert and Bettany, 1995; Wendt and Hauser, 2013; Powlson et al., 2016). Soil pH was determined in 0.01 M $CaCl_2$ using a soil to solution ratio of 1:2.5 with a digital pH meter. The particle size analysis was carried out on the fine earth fraction (<2 mm) of the soil using Bouyoucos' (1962) hydrometer method for one sub-plot sample per plot (i.e. management practice) at each of the sites (Tables A.3 and A.4).

2.2.2. Selected samples

Sieved (2 mm) soil samples for the twelve sites selected for detailed analysis were extracted with 1 M ammonium nitrate (NH_4NO_3, unbuffered) to determine exchangeable base cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) and exchangeable Al^{3+} in the extracts. Extractable acidity was determined by back-titration with 0.05 M sodium hydroxide 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).

The plant available P was extracted using the Bray 1 method and determined colorimetrically.

Total and inorganic P was determined according to Møberg et al. (1990). Acid oxalate extractable Fe, Al and P were determined according to van Reeuwijk (1995). The sample was shaken in an acid ammonium oxalate solution (pH 3) dissolving the "active" or short-range order (amorphous) compounds of Fe and Al. Phosphorus sorption capacity (PSC) and phosphorus saturation degree (PSD) was calculated according to Breeuwsma and Silva (1992):

$$\mathrm{PSC}\ (\mathrm{mmol\,kg^{-1}}) = 0.5{*}[\mathrm{Al_{ox}}\ (\mathrm{mmol\,kg^{-1}}) + \mathrm{Fe_{ox}}\ (\mathrm{mmol\,kg^{-1}})] \quad (1)$$

$$\mathrm{PSD}\ (\%) = [\mathrm{P_{ox}}\ (\mathrm{mmol\,kg^{-1}})/\mathrm{PSC}]{*}100 \quad (2)$$

where Al_{ox}, Fe_{ox} and P_{ox} are oxalate extractable Al, Fe and P. Phosphorus adsorption isotherms were determined on bulked samples from the five sub-plots of each of the management practices CF inside basins, conventional farming and adjacent fallow land (n = 18 for both EP and CP). The method of Fox and Kamprath (1970) was used to determine the P-sorption isotherms and the sorption data were described with a Langmuir isotherm

$$q = Q_{max}{*}K_L{*}C_{eq}/1 + K_L{*}C_{eq} \quad (3)$$

where q is the equilibrium content of P adsorbed (mg g^{-1}), Q_{max} is maximum sorption capacity of the soil (mg g^{-1}), K_L is the Langmuir affinity constant (L mg^{-1}) and C_{eq} is the equilibrium concentration of P in solution (mg L^{-1}). Values of Q_{max} and K_L were derived by nonlinear regression.

Particulate organic matter (POM) is uncomplexed SOM containing root fragments and aboveground plant residues (Golchin et al., 1994; Six et al., 2002a). Particle fractionation on the basis of size and density as an indication of C stability was carried out as described by Martinsen et al. (2011) on triplicate soil samples from the six CP (not EP) sites selected for detailed analysis, to retrieve a free, light (density <1.8 g cm^{-3}) POM fraction of 20–2000 μm. Total C and N of the POM fraction were subsequently determined as described above.

Potential N mineralization rates were determined in incubation experiments on air dried and sieved soil samples from the sites 7, 13 and 17 in EP and from the six CP sites selected for detailed analysis. At the start of the experiment (day 0), 10 g of soil from each of the samples was added to PVC tubes in duplicates. To each PVC tube 1.9 mL of distilled water corresponding to ~26 volume% water was added. One sample was immediately frozen (background level), while the remaining sample was incubated (dark) in an incubation cabinet at 20 °C. After 63 days of incubation, the remaining sample was removed and frozen. After thawing, the soils were extracted in 25 mL 2 M KCl (Øien and Selmer-Olsen, 1980) and filtered prior to analysis of NH_4-N and NO_3-N. Rates of net ammonification and net nitrification were determined by subtracting initial extractable soil NH_4-N and NO_3-N (mg g $soil^{-1}$) from final amounts (after 63 days) of extracted NH_4-N and NO_3-N, respectively. The sum of produced NH_4-N and NO_3-N represents net mineralization (Vestgarden and Kjönaas, 2003).

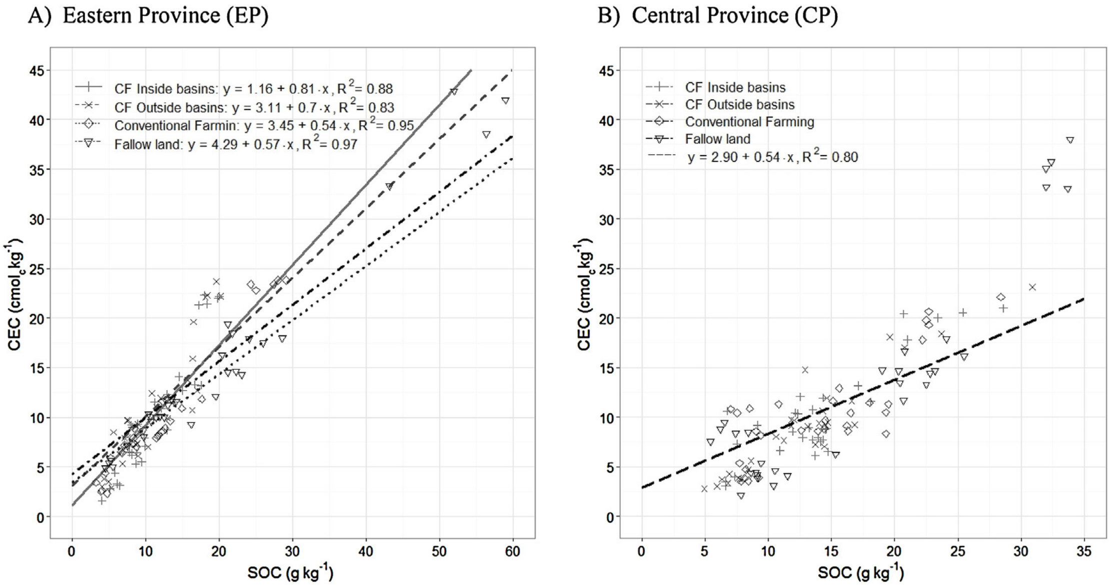

Fig. 2. Relationships between cation exchange capacity (CEC, $cmol_c$ kg $soil^{-1}$) and soil organic carbon (SOC, g kg $soil^{-1}$) for the management practices Conservation Farming (CF) inside basin, CF outside basins, conventional farming and fallow in the EP (A) and CP (B), Zambia. **EP** (n = 120): CF inside basin; CEC = 1.16(±1.46) + 0.81 (±0.08)*SOC, CF outside basins; CEC = 3.11 (±1.40) + 0.70 (±0.07)*SOC, conventional farming; CEC = 3.45 (±1.28) + 0.54 (±0.05)*SOC and fallow land; CEC = 4.29 (±1.24) +0.57 (±0.02)*SOC. **CP** (n = 120): CEC = 2.90 (±1.11) + 0.54 (±0.05)*SOC.

2.3. Statistical analysis

Separate statistical analyses were carried out for data from the two provinces. For all parameters considered we used linear mixed effect models to evaluate differences between the four management practices while accounting for hierarchical experimental design. Thus, management practice was a fixed effect in the linear mixed models. Variation in soil characteristics between the different sampling sites was modelled by introducing random effects associated with each of the sites. Likewise, variation between plots (within sites) was also modelled by means of random effects. Differences between the management practices were assessed by means of pairwise comparisons using model-based approximate *t*-tests with adjustment for multiplicity (Hothorn et al., 2008). Estimates of the fixed effect parameters Q_{max} (maximum sorption capacity of the soil ($mg\,g^{-1}$)) and K_L (the Langmuir affinity constant ($L\,mg^{-1}$)) in the Langmuir isotherms (Eq. (3)) were obtained by nonlinear mixed-effects regression, again including plot- and site-specific random effects (Fig. A5; Table A.7). Subsequently, linear mixed-effects regression models with random intercepts associated with sites and plots were used for exploring associations between selected soil variables (Figs. 2 and 3 , A.1–A.4) and between the estimated site specific Q_{max} obtained from the nonlinear mixed-effect regression models vs. $(Fe+Al)_{ox}$ (Fig. 4) with site-specific random effects only as estimates were obtained per plot. Additionally, R square values were estimated using simple linear regression. Linear regression was used for exploring relationships between CEC and clay fraction and between PSC and clay fraction for the subsets of the data (12 sites selected for detailed analysis) where this information was recorded. Model checking was based on visual inspection of residual and QQ plots. The statistical software package "R", version 2.2.3 (R Core Team, 2015), was used for all statistical analyses. Linear mixed-effects models were fitted using the R extension package lme4 (Bates et al., 2015). The nonlinear mixed-effects models were fitted using the R extension package nlme (Pinheiro et al., 2011). Visualization of the fitted models was achieved using the package ggplot2 (Wickham, 2009).

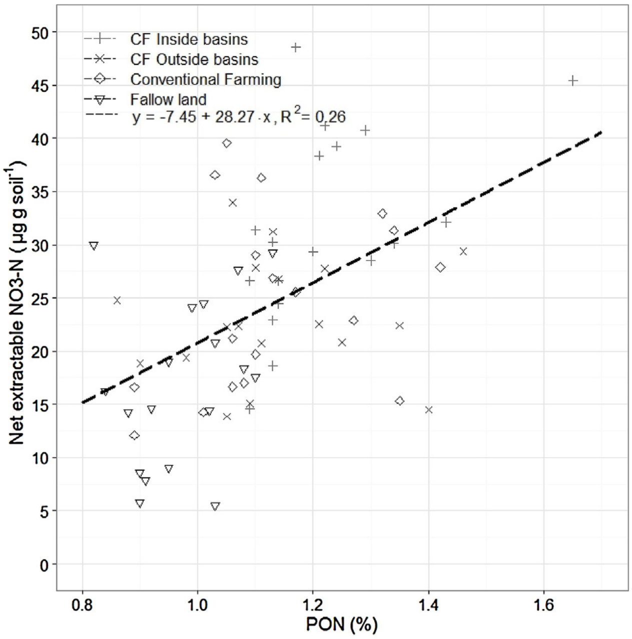

Fig. 3. Relationship between net amounts of extractable NO_3-N ($\mu g\,N\,g\,soil^{-1}$) after 63 days of incubation and concentration of N in particulate organic matter (%PON) from six different sites in CP, Zambia. Negative and positive values of NO_3-N indicate a net immobilization and net mineralization of N, respectively. N = 72. $NO_3\text{-}N = -7.45\ (\pm 7.41) + 28.27\ (\pm 6.47) * PON$.

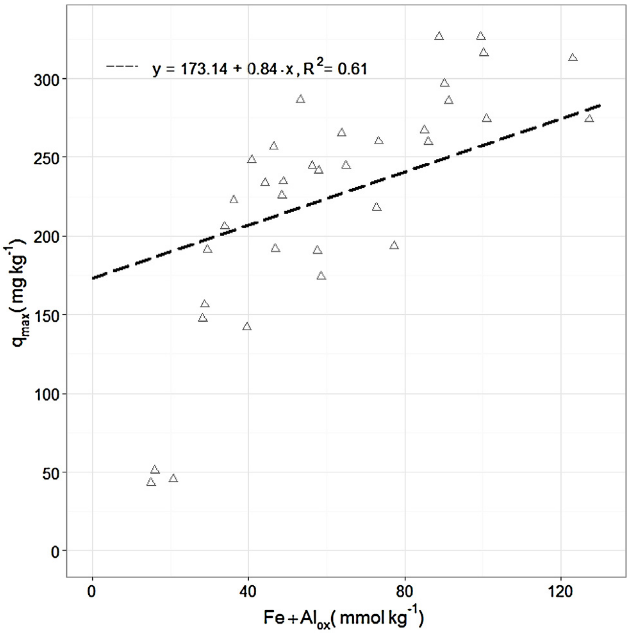

Fig. 4. Relationship between estimated maximum sorption capacity of the soil Q_{max} ($mg\,kg^{-1}$) and content of acid oxalate extractable Al and Fe ($mmol\,kg^{-1}$) averaged across management treatments for the Eastern Province (EP) and Central Province (CP) in Zambia. n = 35 (The fallow land plot, site 16 in EP with $Fe_{Ox} + Al_{Ox} = 262$ $mmol\,kg^{-1}$ was omitted). $Q_{max(EP+CP)} = 173.14(\pm 18.92) + 0.84(\pm 0.17)^{*}(Fe_{Ox} + Al_{Ox})$.

3. Results

3.1. Soil characteristics and relationships based on all sites

The selected sites in EP had greater clay fraction (mean 23.5% ± 8.1% (SD)) as compared to the sites in CP (mean 7.4% ± 2.7% (SD), Tables A.3 and A.4) with no significant differences between the management practices ($p = 0.782$ and $p = 0.849$ in the EP and CP, respectively). Soils at most of the sites were classified as loams (sandy loam, clay loam, silt loam) with the exception of two plots classified as clays at site 1 and 19 and one site classified as loamy sand (site 13, Table A.3) in EP. Mean soil pH_{CaCl2} values were in the range of 5.32–5.97, with small differences between management practices (Table 1). In EP, the BD was significantly lower on the conventional ridges ($1.38\,g\,cm^{-3}$) and on the fallow land plots ($1.37\,g\,cm^{-3}$) as compared to outside CF basins ($1.48\,g\,cm^{-3}$). CF basins ($1.43\,g\,cm^{-3}$) had intermediate BD values. In CP there were no significant differences in BD between the management practices with mean values in the range $1.37–1.42\,g\,cm^{-3}$ (Table 1).

Concentrations of soil organic carbon and nitrogen (%SOC and % SON) were not significantly different between CF and conventional farming practices (Table 1). Normalizing %SOC to the fraction of clay (%SOC:%clay) revealed the same non-significant differences between CF and conventional farming practices (mean ratio 0.17 and 0.07 in CP and EP, respectively). The relatively small differences in BD and %SOC between management practices resulted in non-significant differences in C-stocks (mean levels from 4.41 to $4.63\,kg\,m^{-2}$, and from 3.29 to $3.57\,kg\,m^{-2}$, in EP and CP, respectively) between the CF and non-CF plots in the two provinces (Table 1). In contrast, C-stocks on fallow land in EP were significantly greater (mean $5.83\,kg\,m^{-2}$) than those on cultivated lands, indicating significant C depletion due to both conventional and conservation farming. Estimated C-stocks based

Table 1
Soil properties summarized across 20 sites with different management practices in the Eastern and Central Provinces[a], Zambia.

Region	Plot or landuse	pH				Bulk Density				Total C				Total N				CN ratio				C stock				N stock				C stock eqv. mass[c]			
		(0.01MCaCl$_2$)				(g cm^{-3})				(%)												(kg m^{-2})											
Eastern Province	CF Inside basins	5.42	(±0.07)	ab	*100*	1.43	(±0.02)	ab	*100*	1.57	(±0.21)	b	*100*	0.08	(±0.01)	b	*100*	21.0	(±0.91)	a	*63*	4.41	(±0.55)	b	*100*	0.21	(±0.03)	b	*100*	3.26	(±0.45)	b	*100*
	CF Outside basins	5.42	(±0.07)	ab	*99*	1.48	(±0.02)	a	*100*	1.53	(±0.21)	b	*99*	0.07	(±0.01)	b	*99*	21.5	(±0.93)	a	*52*	4.45	(±0.55)	b	*99*	0.20	(±0.03)	b	*99*	3.18	(±0.45)	b	*99*
	Conventional Farming	5.32	(±0.07)	b	*100*	1.38	(±0.02)	b	*100*	1.71	(±0.21)	b	*100*	0.08	(±0.01)	b	*100*	21.0	(±0.91)	a	*66*	4.63	(±0.55)	b	*100*	0.22	(±0.03)	b	*100*	3.57	(±0.45)	b	*100*
	Fallow land	5.52	(±0.07)	a	*99*	1.37	(±0.02)	b	*100*	2.17	(±0.21)	a	*99*	0.11	(±0.01)	a	*99*	20.9	(±0.89)	a	*75*	5.83	(±0.55)	a	*99*	0.28	(±0.03)	a	*99*	4.52	(±0.45)	a	*99*
Central Province	CF Inside basins	5.97	(±0.10)	a	*94*	1.37	(±0.02)	a	*94*	1.25	(±0.13)	a	*100*	0.06	(±0.01)	a	*100*	16.0	(±1.05)	a	*53*	3.37	(±0.37)	a	*94*	0.17	(±0.03)	a	*94*	2.60	(±0.29)	a	*94*
	CF Outside basins	5.96	(±0.10)	a	*94*	1.41	(±0.02)	a	*94*	1.17	(±0.13)	a	*99*	0.05	(±0.01)	a	*99*	16.1	(±1.11)	a	*43*	3.29	(±0.37)	a	*93*	0.14	(±0.03)	a	*93*	2.44	(±0.29)	a	*93*
	Conventional Farming	5.94	(±0.10)	a	*95*	1.42	(±0.02)	a	*94*	1.27	(±0.13)	a	*99*	0.06	(±0.01)	a	*99*	15.8	(±1.09)	a	*44*	3.57	(±0.37)	a	*93*	0.17	(±0.03)	a	*93*	2.67	(±0.29)	a	*93*
	Fallow land	5.89	(±0.10)	a	*95*	1.41	(±0.02)	a	*94*	1.24	(±0.13)	a	*100*	0.05	(±0.01)	a	*100*	15.7	(±1.11)	a	*40*	3.51	(±0.37)	a	*94*	0.15	(±0.03)	a	*94*	2.61	(±0.29)	a	*94*

		Bray-P[b]				Total inorg. P[b]				Total org. P[b]				Total P[b]				Bray-P stock[b]				Total inorg. P stock[b]				Total org. P stock[b]				Total P stock[b]			
		(mg kg soil^{-1})																(g m^{-2})															
Eastern Province	CF Inside basins	8.45	(±1.46)	a	*90*	337.47	(±69.12)	a	*100*	195.42	(±42.45)	b	*100*	555.55	(±114.05)	a	*100*	2.39	(±0.42)	a	*90*	95.98	(±19.30)	a	*100*	55.58	(±11.84)	b	*100*	158.01	(±31.75)	a	*100*
	CF Outside basins	5.24	(±0.90)	b	*90*	295.20	(±60.47)	a	*99*	211.19	(±45.88)	b	*99*	532.38	(±109.30)	a	*99*	1.54	(±0.27)	a	*90*	87.04	(±17.50)	a	*99*	62.27	(±13.26)	ab	*99*	156.98	(±31.55)	a	*99*
	Conventional Farming	7.06	(±1.09)	ab	*90*	318.26	(±65.19)	a	*100*	197.09	(±55.77)	b	*100*	539.02	(±110.66)	a	*100*	1.93	(±0.34)	a	*90*	87.48	(±17.59)	a	*100*	54.17	(±11.53)	b	*100*	148.15	(±29.77)	a	*100*
	Fallow land	6.33	(±1.22)	ab	*90*	317.28	(±64.99)	a	*99*	256.76	(±42.81)	a	*99*	587.31	(±120.58)	a	*99*	1.72	(±0.30)	a	*90*	86.57	(±17.41)	a	*99*	70.06	(±14.92)	a	*99*	160.25	(±32.21)	a	*99*
Central Province	CF Inside basins	12.74	(±1.95)	a	*94*	159.46	(±23.29)	a	*30*	103.92	(±12.24)	a	*30*	271.64	(±27.70)	a	*30*	3.48	(±0.54)	a	*94*	42.79	(±6.48)	a	*30*	27.88	(±3.12)	a	*30*	72.89	(±7.55)	a	*30*
	CF Outside basins	8.28	(±1.27)	b	*94*	127.59	(±18.64)	a	*30*	103.04	(±12.14)	a	*30*	235.01	(±23.97)	a	*30*	2.34	(±0.36)	b	*94*	35.96	(±5.44)	a	*30*	29.04	(±3.25)	a	*30*	66.23	(±6.86)	a	*30*
	Conventional Farming	8.90	(±1.36)	ab	*94*	124.73	(±18.22)	a	*30*	107.65	(±12.68)	a	*30*	239.09	(±24.38)	a	*30*	2.51	(±0.39)	ab	*94*	36.47	(±5.52)	a	*30*	31.48	(±3.53)	a	*30*	69.91	(±7.24)	a	*30*
	Fallow land	8.04	(±1.23)	b	*95*	114.04	(±16.66)	a	*30*	115.76	(±13.64)	a	*30*	233.84	(±23.85)	a	*30*	2.26	(±0.35)	b	*94*	32.36	(±4.90)	a	*30*	32.84	(±3.68)	a	*30*	66.35	(±6.87)	a	*30*

[a] Soil sampled at the depth of 20 cm. Data are shown as mean (±SE). Mean values within a column followed by the same subscript (for each province separately) are not significantly different from each other at level of significance $p < 0.05$. n for each variable and management practices is indicated in italic. CN ratios were not calculated if total N < 0.05%.

[b] Tests based on ln-transformed data but back transformed means are reported.

[c] The equivalent soil mass was 208 kg soil m^{-2} in the two provinces (BD = 1.04 g cm^{-3}, depth = 20 cm, both conventional practices).

Table 2
Soil properties summarized across six selected sites with different management practices in the Eastern and Central Provinces[a], Zambia.

Region	Plot or landuse	Total C[b]	Total N[b]	C stock[b]	N stock	CEC[b]	Fe (Ox)[b]	Al (Ox)[b]	P (Ox)[b]	PSC[b]	PSD[b]
		(%)		(kg m^{-2})		cmol$_c$ kg^{-1}	(mmol kg^{-1})				(%)
Eastern Province	CF Inside basins	1.05 (±0.26) b	0.06 (±0.02) b	2.96 (±0.69) b	0.17 (±0.06) b	8.58 (±2.31) b	27.00 (±8.15) a	32.45 (±10.34) a	5.43 (±1.83) ab	29.85 (±9.22) a	17.0 (±5.3) ab
	CF Outside basins	1.00 (±0.25) b	0.05 (±0.01) b	2.96 (±0.69) b	0.17 (±0.06) b	9.34 (±2.51) b	28.73 (±8.67) a	33.11 (±10.55) a	4.96 (±1.67) b	31.05 (±9.60) a	15.3 (±4.8) b
	Conventional Farming	1.01 (±0.25) b	0.05 (±0.01) b	2.82 (±0.65) b	0.17 (±0.06) b	8.29 (±2.23) b	25.21 (±7.61) a	30.12 (±9.60) a	5.72 (±1.93) ab	27.74 (±8.57) a	18.1 (±5.7) a
	Fallow land	1.68 (±0.41) a	0.08 (±0.02) a	4.47 (±1.04) a	0.28 (±0.06) a	13.47 (±3.62) a	34.78 (±10.50) a	40.21 (±12.81) a	7.62 (±2.57) a	37.74 (±11.66) a	19.1 (±6.0) a
Central Province	CF Inside basins	1.32 (±0.26) a	0.06 (±0.02) a	3.54 (±0.67) a	0.21 (±0.06) a	9.28 (±2.36) a	18.86 (±3.85) a	26.01 (±4.15) a	2.74 (±0.41) a	22.81 (±3.53) a	12.0 (±1.6) a
	CF Outside basins	1.17 (±0.23) a	0.05 (±0.02) a	3.28 (±0.63) a	0.19 (±0.06) a	7.66 (±1.95) a	18.35 (±3.75) a	26.08 (±4.16) a	1.98 (±0.30) a	22.58 (±3.50) a	8.7 (±1.1) b
	Conventional Farming	1.32 (±0.26) a	0.06 (±0.02) a	3.87 (±0.74) a	0.21 (±0.06) a	9.33 (±2.37) a	20.98 (±4.29) a	26.97 (±4.31) a	2.06 (±0.31) a	24.69 (±3.82) a	8.3 (±1.1) b
	Fallow land	1.47 (±0.29) a	0.07 (±0.02) a	4.18 (±0.80) a	0.25 (±0.06) a	10.11 (±2.57) a	24.13 (±4.93) a	30.93 (±4.94) a	2.09 (±0.31) a	28.14 (±4.36) a	7.4 (±1.0) b

[a] Soil sampled at the depth of 20 cm. Data are shown as mean (± SE). Mean values within a column followed by the same subscript are not significantly different from each other at level of significance $p < 0.05$.

[b] Tests based on ln-transformed data but back transformed means are reported. In the EP (sites nr. 7,8,12,13,16,17) n = 30 for each management practice except for P (Ox) and PSD (21 < n < 25). Site nr. 8 was not included for P (Ox) and PSD because P-levels were below the detection limit for all management practices except for the fallow land plots. One outlier for the variables P (Ox) and PSD was removed at a sub-plot at site 7 conventional farming. In the CP (sites nr. 1,8,14,15,18,19) n = 30 for each management practice. See Table A.5 for more soil parameters. Fe (Ox), Al (Ox) and P (Ox) is oxalate soluble Fe, Al and P, respectively. PSC is phosphorus sorption capacity and PSD is P saturation degree. CEC is cation exchange capacity.

on equivalent mass of soil were smaller than those based on equal depth sampling, but revealed the same non-significant differences between management practices (Table 1). The carbon to nitrogen ratio (CN ratio), which can be used as a proxy for the quality of soil organic matter, did not differ significantly between the management practices (Table 1). In both provinces there was a significant relationship between%SOC and%SON ($p < 0.001$, Figs. A.1 and A.2), which was similar for all management practices.

In both provinces the concentration of plant available P (Bray-P) was significantly greater inside CF basins (12.7 and 8.5 mg kg soil^{-1} in CP and EP, respectively) than outside basins (8.3 and 5.2 mg kg soil^{-1}). The same pattern was observed for plant available P stocks (g m^{-2}, 0–20 cm, Table 1), but this was only significant in CP. Concentrations (mg kg soil^{-1}) and stocks (g m^{-2}, 0–20 cm) of total inorganic P and total P did not differ significantly between management practices (Table 1). Levels of total organic P (35–50% of total P) were significantly greater at the uncultivated (i.e. fallow land) as compared to plots with CF or conventional agriculture in EP (but not in CP), thus having the same trend as observed for C-stocks. There was a significant relationship ($p < 0.001$) between Bray-P and total inorganic P (mg kg soil^{-1}) in both provinces with no significant effect of management practice on intercepts or slopes in EP (Fig. A.3). In CP the intercept for CF inside basins was significantly greater than for CF outside basins and for conventional farming (Fig. A.4), suggesting a greater fraction of plant available P for the same level of inorganic P inside CF basins.

3.2. Soil characteristics and relationships based on selected sites

Concentrations and stocks of SOC and SON at the six selected sites did not differ significantly between CF inside or outside basins and conventional management (Tables 2 and A.5), i.e. in accordance with the full dataset. In both provinces the soil's cation exchange capacity (CEC) was about 10 cmol$_c$ kg soil^{-1} (Table 2). Based on the subset of the data with information on the clay content (viz. 22 sub-plots in the EP and 24 sub-plots in the CP, Tables A.3 and A.4) SOM and clay fraction were jointly significant in explaining the variation in CEC ($R^2 = 0.92$, $p < 0.001$) in the EP, whereas CEC was not significantly correlated with the fraction clay in the CP ($p = 0.17$). In the EP, the CEC was more strongly associated with SOM ($R^2 = 0.89$) than with the fraction clay ($R^2 = 0.03$). The importance of SOC for CEC was further supported by the significant regression between these parameters ($p < 0.001$) based on the data for the six selected sites, as suggested by the small intercepts (from 1.16 to 4.29 cmol$_c$ kg soil^{-1}, Fig. 2).

Small amounts of particulate organic matter (POM) (0.7–0.9%, based on the fraction of the total soil mass) were found for all the treatments (Table A.6). The form of SOM, expressed as ratios of particulate organic carbon to soil organic carbon (POC to SOC ratio), followed the same pattern as the percentage POM and was slightly but not significantly (all $p > 0.17$) greater inside CF basins (0.19) as compared to the other management practices (ratios in the range 0.15–0.17, Table A.6). The concentration of N in POM, i.e., %PON was significantly ($p < 0.05$) greater at the farmed plots (1.13–1.22 %PON) as compared to the fallow land (0.97 %PON). The same significant difference was observed for the CN ratio of POM which was significantly greater at the fallow land plots (28.3, $p < 0.001$) as compared to the other management practices (21.7–23.5, Table A.6).

The N mineralization experiment revealed a significant linear relationship ($p < 0.01$) between net NO_3 production (Table 3) and % PON in the CP soils (Fig. 3): NO_3-N (μg g soil^{-1} after 63 days of incubation) = −7.45 (±7.41) + 28.27 (±6.47) * PON (%). By contrast, no significant ($p = 0.84$) relationship was found with the N concentration of the bulk soil (%SON), illustrating the importance of the quality of POM for N-availability to plants. Furthermore, the

Table 3
Mean (±SE) net amounts of extractable NH_4-N and NO_3-N (µg $soil^{-1}$ and µg SOC^{-1}) of soils (0–20 cm) from three different sites in EP[a] and six different sites in CP[a], Zambia after 63 days of incubation. Negative and positive numbers indicate a net immobilization and net mobilization of N, respectively.

Region	Plot or landuse	Net mobilization or immobilization of NH_4-N						Net mobilization or immobilization of NO_3-N					
		(µg N g $soil^{-1}$)			(µg N g SOC^{-1})			(µg N g $soil^{-1}$)			(µg N g SOC^{-1})		
Eastern Province	CF Inside basins	−4.2	(±1.7)	a	−473.1	(±103.0)	a	8.5	(±4.1)	a	943.9	(±306.3)	a
	CF Outside basins	−4.3	(±1.7)	a	−516.6	(±103.0)	a	8.5	(±4.1)	a	1065.5	(±306.3)	a
	Conventional Farming	−4.0	(±1.7)	a	−469.4	(±103.0)	a	9.3	(±4.1)	a	1107.0	(±306.3)	a
	Fallow land	−6.9	(±1.7)	a	−452.2	(±103.0)	a	19.0	(±4.1)	a	1377.7	(±306.3)	a
Central Province	CF Inside basins	−13.5	(±2.2)	a	−1123.8	(±203.0)	a	31.4	(±2.5)	a	2627.3	(±393.2)	a
	CF Outside basins	−11.9	(±2.2)	a	−1132.4	(±203.0)	a	24.1	(±2.5)	ab	2298.7	(±393.2)	a
	Conventional Farming	−12.3	(±2.2)	a	−1046.9	(±203.0)	a	24.3	(±2.5)	a	1934.5	(±393.2)	ab
	Fallow land	−6.4	(±2.2)	b	−464.2	(±203.0)	b	15.4	(±2.5)	b	1220.1	(±393.2)	b

[a] **Eeastern Province**: Three sites (7,13,17), n = 15 for each management practice. **Central Province**: Six sites (1,8,14,15,18,19), n = 30 for each management practice. Mean values within a column followed by the same subscript are not significantly different from each other at level of significance <0.05.

incubation experiment showed a net immobilization of NH_4-N in all soils (Table 3). In EP there were no significant differences in net immobilization of NH_4-N and net mineralization of NO_3-N between the management practices, but in CP both were significantly smaller at the fallow land as compared to the farmed land. The net mobilization of NO_3-N (8.5–31.4 µg N g $soil^{-1}$) after 63 days of incubation were significantly greater than the net immobilization of NH_4-N (−4.2 to −13.5 µg N g $soil^{-1}$, Table 3), indicating a net mineralization of organic N.

Acid oxalate extractable Al, Fe and P (mmol kg^{-1}) were highly variable with no significant differences between the management practices in CP, whereas in EP significantly greater amounts of P were found at the fallow land plots (7.6 mmol kg^{-1}) as compared to CF outside basins (4.9 mmol kg^{-1}) (Table 2). The P saturation degree (%PSD) was significantly greater at CF inside basins (12%) as compared to the other management practices (7.4–8.7%) in CP. In EP, %PSD differed significantly between CF outside basins (15.3%) on the one hand and conventional (18.1%) and fallow land plots (19.1%) on the other with CF inside basins in-between (17.0%). Phosphorus sorption capacity (PSC in mmol kg^{-1} as defined in Eq. (1)) did not differ significantly between the management practices (Table 2). This is in accordance with the lack of significant differences in the clay fraction between the practices and a significant ($p < 0.001$) positive relationship between PSC and fraction clay in both provinces (EP: $R^2 = 0.66$, n = 21; CP: $R^2 = 0.67$, n = 23). For both provinces, Bray-P (mg kg^{-1}) was significantly related to the total concentration of inorganic P (mg kg^{-1}), which was also observed for all sites (Figs. A.3 and A.4). In addition, Bray-P increased significantly ($p < 0.001$) per unit increase in PSD with no significant management induced effect on the relationship (i.e. slope). Maximum sorption capacities (Q_{max} (mg g^{-1}); 0.22 and 0.23 in the EP and CP, respectively) and Langmuir affinity constants (K_L (L mg^{-1}); 0.84 and 0.77 in the EP and CP, respectively) as estimated based on P-sorption isotherms varied greatly between sites but did not differ significantly between the management practices (Fig. A.5, Table A.7). Q_{max} was significantly correlated with the content of acid oxalate extractable Al and Fe ($p < 0.001$), but there was no significant effect of management practice or province on the relationship (Fig. 4).

4. Discussion

In this study from Zambia comparing soils under CF (two to six years in the Eastern Province (EP) and four to twelve years in the Central Province (CP)), we found only small and non-significant effects of CF on concentrations and stocks of SOC (Table 1). This is in accordance with previous studies from e.g. Zimbabwe, Malawi and Zambia (Ngwira et al., 2013; Nyamangara et al., 2013; Thierfelder et al., 2013; Cheesman et al., 2016). The same pattern was observed for a subset of the farms practicing CF for >6 years in EP and for >12 years in CP (Tables 2 and A.5). Accumulation of SOM is controlled by climatic and edaphic conditions in combination with management practice (Six et al., 2002a; Pisante et al., 2015). These affect inputs of carbon (e.g. seeding system, crop rotation, weed control, fertilizer application and residue retention (Chivenge et al., 2007; Umar et al., 2011; Nyamangara et al., 2013; Thierfelder et al., 2013, 2015, 2016; Powlson et al., 2016)) and decomposition of SOM (e.g. Six et al., 2002a; Chivenge et al., 2007). The content of clay and Fe- and Al- oxides are important for the chemical stabilization of SOM (Six et al., 2002a) and were accounted for when comparing effects of management practices. In our study the fraction of clay and the amount of acid oxalate extractable Fe and Al as well as the maximum P sorption capacities did not differ significantly between the CF and conventional practices in the two provinces indicating that the within site comparisons were conducted on similar soils.

All CF farmers selected for the study were following CFU guidelines (i.e. minimum tillage using permanent planting basins, residue retention and legumes in crop rotation). Fertilizer inputs followed the recommended fertilizer applications rates and should be the same for CF and conventional farmers. Thus, differences in soil quality parameters between the two management practices were assumed to be due to tillage (hoe ridges or overall digging vs. re-opening of basins at the conventional and CF farms, respectively), residue management (incorporation or burning of residues vs. residue retention at the conventional and CF farms, respectively) and crop rotation (CF farms only). The study was conducted under on-farm conditions (i.e. no controlled field trials) where farmers may struggle to maintain sufficient crop residues due to burning, removal and grazing that will reduce C inputs to the soil (Chivenge et al., 2007; Umar et al., 2011; Thierfelder et al., 2013; Cheesman et al., 2016). Also CF guidelines for e.g. fertilizer application rate, planting time and weeding practice may not always have been followed, affecting both yields (Gatere et al., 2013) and input of C to the soil. Furthermore, lack of crop rotation at some of the CF plots may have influenced levels of SOM, although, there is no clear evidence that crop diversification increases amounts of SOM (Pisante et al., 2015) as both positive (Powlson et al., 2016) and negative (Luo et al., 2010) effects have been reported. In summary, the factors discussed above may partly explain the small differences in soil quality between the management practices, as found in our study.

Previously, Thierfelder et al. (2013) found no significant effect of conservation agriculture (CA) on soil C-stock after 3–5 years at two on-farm sites in Zambia. By contrast, a controlled trial on a research station in Zambia revealed significantly larger C-stocks (250–

330 g C m^{-2}) in the upper 10 cm of the soil under CA (1.06–1.14 kg C m^{-2}), as compared to the conventional (0.81 kg C m^{-2}) system. Cheesman et al. (2016) reported ~100 g C m^{-2} greater C-stocks for the upper 0–20 cm of soils after 2–7 years of CF as compared to conventional practice based on 125 on-farm validation trials in Southern Africa, with no significant differences between the management practices when comparing depths at 20–30 cm. The small difference was linked to limited inputs of C from residues (38–360 g C m^{-2} yr^{-1}) at the CF sites (Cheesman et al., 2016). In our study, the difference in C-stocks between CF basins and the conventional plots was ~200 g C m^{-2} but the difference was not significant (Table 1). Average yields of maize in CP were reported to be 300 and 260 g m^{-2} for CF and conventional farming, respectively (Tables A.1 and A.2). To allow for a theoretical calculation of potential C inputs associated with these yields, we assumed that CF farmers left all residues on the soil (i.e. ignoring potential losses of residue, as discussed above) and that conventional farmers removed all residues (i.e. ignoring that some of the farmers might have incorporated the residues in the soil, cf. Section 2.1). Thus, assuming that 1) the amount of stover biomass used for residue retention was the same as the grain yield at the CF plots (while being zero at the conventional plots), 2) the root-to-shoot ratio was 0.053 g g^{-1} (Abiven et al., 2015), and 3) the average C-content of the stover and roots was 45% (Martinsen et al., 2014), the amount of potential C input in residue and roots at the CF plots corresponded to ~142 g C m^{-2} yr^{-1}. This C input can be converted to g C kg $soil^{-1}$ yr^{-1} following Cheesman et al. (2016):

$$C_{input} = C_{residues}/[BD_{avg0-20}*2*100] \quad (4)$$

where C_{input} (g kg $soil^{-1}$ yr^{-1}) is the amount of C added to the soil via residues and roots, $C_{residues}$ is the amount of C from residues and roots (g m^{-2} yr^{-1}), $BD_{avg0-20}$ is bulk density for 0–20 cm soil depth (1.37 kg dm^{-3}, cf. Table 1), the factor 2 is the depth (dm) of the soil layer and 100 is dm^2 m^{-2}. According to this equation, due to residue retention an extra addition of 0.52 g C kg $soil^{-1}$ yr^{-1} (0.052%) occurs at the CF plots as compared to the conventional plots in the theoretical case that all residues would be retained. However, the net effect will be significantly smaller, due to rapid SOM decomposition in the tropics (Six et al., 2002b; Andrén et al., 2007; Mazzilli et al., 2014). Assuming that 10% of the residue C input is converted to SOC (see e.g. Mazzilli et al. (2014)) and ignoring further decomposition of SOM, it is clear that 10 year addition of C with the yields reported in this study (0.52 g C kg $soil^{-1}$ corresponding to 142 g C m^{-2}) cannot be expected to cause a significant increase in %SOC (±SE; 1.3 g C kg $soil^{-1}$) or soil C stocks (±SE; 370 g C m^{-2}), given the variation in the on-farm data with their inherent between farm variability (Table 1).

The amount of POM (based on the fraction of the total soil mass) and the fraction of POC to total SOC (POC to SOC ratio) did not significantly differ between the management practices (Table A.6). Despite the small fraction of POM to the total soil mass (0.7–0.9%) it contributed 15–19% of the total SOC, which is greater than values earlier reported by e.g. Mujuru et al. (2013) and Mazzilli et al. (2014). Assessing effects of land use and management on SOM fractions in Zimbabwe, Mujuru et al. (2013) reported POC:SOC ratios of ~6% (soil depth 0–30 cm) whereas Mazzilli et al. (2014) in soils under no-till (corn crop; soil depth 0–20 cm) in Uruguay found POC:SOC ratios of ~4%. Lokupitiya et al. (2012) found an inter-annual variation in soil C-stocks in US cropland, with large residue inputs in a given year being reflected in larger soil C-stocks in the following year. Since the POM pool is sensitive to management practices, residue retention and crop rotation (Six et al., 2000, 2002a; Luo et al., 2010; Powlson et al., 2016), increased inputs of C through roots and residues would be expected to increase the amount of POM. We found a tendency of increased levels of POM inside CF basins, but the differences were not significant (Table A.6). Furthermore, the CN ratio of the POM fraction was significantly ($p < 0.05$) smaller at all cultivated plots (from 21.7 to 23.5) than in fallow land (28.3, Table A.6) and similar to values reported for the free light fraction SOM in Zimbabwe (Mujuru et al., 2013). Smaller CN ratios of the POM fraction at the cultivated land plots indicates a better quality of the litter and greater turnover at the farmed plots. Greater N content of the POM fraction may in turn increase availability of NO_3^-, which was supported by the significant linear relationship ($p < 0.01$) between net potential nitrification rates (Table 3) and %PON in the soils from CP (Fig. 3).

The CEC (about 10 $cmol_c$ kg $soil^{-1}$ cf. Table 2) was mainly controlled by SOM. Given the relatively high clay content in EP (22.5% ± 8.1% (SD)), this suggests that the clay fraction contains few minerals with high charge density. Previously, mineralogical analyses of the clay fractions of major benchmark soils of Zambia indicated that kaolinite, a low activity clay, is the dominant layer silicate mineral in the clay fraction of most Zambian soils (Magai, 1985). The importance of SOC for CEC was supported by the small intercepts (from 1.16 to 4.29 $cmol_c$ kg $soil^{-1}$) and significant ($p < 0.001$) relationship with SOC (Fig. 2). The slopes of these relationships (from 0.54 to 0.81 $cmol_c$ of CEC per g of SOC, Fig. 2), which estimate the contribution of SOC to CEC, corrected for the contribution of clay minerals, highlight the importance of SOM for nutrient retention in these soils. The increases in CEC per g increase in SOC are greater than those previously reported by Gruba and Mulder (2015) for forested areas in Southern Poland (0.37 $cmol_c$ of CEC per g of SOC), but similar to those reported from cultivated fields in Zambia by Shitumbanuma and Chikuta (2013). Based on 288 soil samples from 59 cultivated fields from nine districts of EP they found a strong relationship between SOC and CEC ($CEC = 1.68 (\pm 0.31) + 0.49 (\pm 0.02)*SOC$, $R^2 = 0.68$, $p < 0.001$), which is similar to the relationship reported in the present study. We found no significant difference in CEC between the tilled management practices, but the CEC at the fallow land plots in EP was significantly greater than at the cultivated lands, due to the greater contents of SOM (Table 2). Previously, comparing CF (five fields under CF for 2 and 5 years, respectively) and annual ridge tillage (ten fields) in Southern Malawi Mloza-Banda et al. (2016) found an significant increase in CEC of 1.86 and 3.52 $cmol_c$ kg $soil^{-1}$ after two and five years since adoption to CF, respectively.

The phosphorus saturation degree (PSD) was significantly greater at CF inside basins (12%) than under conventional tillage and fallow land (7.4–8.7%) in CP. This indicates that P saturation increases in the basins where P fertilizer was added. Despite greater PSD and higher levels of inorganic P, organic P and total P in soils of EP than soils of CP, the correlation between Bray-P and total amount of inorganic P indicated higher amount of plant available P for the same level or inorganic P in soils of CP than EP (Figs. A.3 and A.4). This is consistent with the observed higher PSC of soils of EP compared to those of CP, which also suggests that a greater proportion of P applied to soils in EP is adsorbed by the soil (slightly greater Langmuir affinity constants, cf. Fig. A.5), thereby reducing the proportion of P available for plant uptake, compared to soils in CP with lower PSC. The fact that we did not find any significant differences in the change in Bray-P per unit increase in inorganic P (i.e. the same slopes for the management practices) was not surprising given the small and non-significant differences between the management practices in 1) pH which would affect the available fraction of P due to variation in charged binding sites, 2) the amount of SOM which could increase the availability of P due to more competition for binding sites and 3) the fraction of clay which would most likely be associated with more oxides and thus increase the binding of P.

In addition to reasons discussed above the small differences in soil quality between the management practices observed in this study may be due to re-opening of basins in CF since soil disturbance such as tillage may increase decomposition of SOM by altering aggregate stability and reducing physical protection of SOM (Six et al., 2000, 2002a). Since basins in CF are re-opened every year, the soil organic matter is exposed to oxidation and there is no difference in tillage between the conventional and CF practice *per se* with the exception of the reduced amount (basins only) of soil that is disturbed under CF. In addition, changed location of the basins from year to year which may increase the decomposition of SOM due to direct and indirect effects on aggregation (Six et al., 2002b) may even out the potential difference between CF and conventional management practices. However, this was not supported by concentrations of Bray P, which were significantly greater in CF basins than in-between them (12.7 vs 8.3 mg kg soil^{-1} in CP and 8.5 vs 5.2 mg kg soil^{-1} in EP) indicating significant Bray P accumulation in CF basins due to fertilizer input. Termite activity that may increase with increasing levels of residue retention (Mutsamba et al., 2016), stimulated microbial activity and increased decomposition of recalcitrant C (priming) by fresh residue addition (Diochon et al., 2016) and higher moisture content inside planting basins than outside basins that may have increased C decomposition (Andrén et al., 2004) were not acconted for and may also contribute to the small differences between the mangagement practices observed in this study.

In conclusion, we found that CF (maximum 12 years) was too short to cause significant changes in soil quality compared with conventional practices at smallholder farms despite earlier reported greater yields at CF plots. Possibly, the lack of change of soil quality parameters in soils under CF was due to small annual net accumulation of SOC or due to annual difference in position of the basins in the non-controlled, on-farm studies, so that no real accumulated effect was found.

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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.agee.2017.03.010.

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