

Research Paper

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Toward greater sustainability: how investing in soil health may enhance maize productivity in Southern Africa

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Abstract

Climate change and soil fertility decline are major threats to smallholder farmers' food and nutrition security in southern Africa, and cropping systems that improve soil health are needed to address these challenges. Cropping systems that invest in soil organic matter, such as no-tillage (NT) with crop residue retention, have been proposed as potential solutions. However, a key challenge for assessing the sustainability of NT systems is that soil carbon (C) stocks develop over long timescales, and there is an urgent need to identify trajectory indicators of sustainability and crop productivity. Here we examined the effects of NT as compared with conventional tillage without residue retention on relationships between soil characteristics and maize (*Zea mays* L.) productivity in long-term on-farm and on-station trials in Zimbabwe. Our results show that relationships between soil characteristics and maize productivity, and the effects of management on these relationships, varied with soil type. Total soil nitrogen (N) and C were strong predictors of maize grain yield and above-ground biomass (i.e., stover) in the clayey soils, but not in the sandy soils, under both managements. This highlights context-specific benefits of management that fosters the accumulation of soil C and N stocks. Despite a strong effect of NT management on soil C and N in sandy soils, this accrual was not sufficient to support increased crop productivity in these soils. We suggest that sandy soils should be the priority target of NT with organic resource inputs interventions in southern Africa, as mineral fertilizer inputs alone will not halt the soil fertility decline. This will require a holistic management approach and input of C in various forms (e.g., biomass from cover crops and tree components, crop residues, in combination with mineral fertilizers). Clayey soils on the other hand have greater buffering capacity against detrimental effects of soil tillage and low C input.

Introduction

Southern Africa is heavily affected by declining soil fertility concurrent with negative impacts of climate change, posing severe risks to the sustainability of farming and food security (Tittonell and Giller, 2013). Current yields of maize (*Zea mays* L.), the most important food crop of the region cultivated on 50–80% of the land area, average only 0.5–2.5 t ha⁻¹, whereas the yield potential for maize is 10–15 t ha⁻¹ under optimal rainfed and unlimited nutrient conditions (FAOSTAT, 2020). Changes in climate will manifest in more erratic rains and increased heat stress that will be further detrimental to maize yields (Cairns *et al.*, 2013). Therefore, efforts are required to identify maize crop management systems that will help ensure long-term sustainable production under these conditions.

Sustainable intensification of crop production under climate change can be achieved, for example, through the build-up of soil organic matter (SOM). SOM supports biological abundance and diversity, represents a store of plant nutrients and confers physical (e.g., soil structure, stability and water holding capacity), biological (e.g., earthworm populations and greater diversity of microbial communities and functions) and chemical (e.g., ion exchange capacity) benefits (Schnitzer and Khan, 1975), which define soil health or the continued capacity of soil to function (Lehman *et al.*, 2015). However, as a consequence of heterogeneity in SOM distribution, changes in organic matter stocks can take several years to be measurable (Chivenge *et al.*, 2007) and under no-tillage (NT) conditions can also lead to stratification with soil depth (Luo *et al.*, 2010). Timescales for measurable changes in SOM content may also vary with soil type (as a function of change relative to the size of the existing SOM stock) (Chivenge *et al.*, 2007), so informed selection and management of improved cropping systems requires early and quantifiable indicators of trajectories toward sustainability for

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beneficial impacts on soil health and nutrient provision. Despite the efforts to investigate soil biological properties in southern Africa (e.g., Bationo *et al.*, 2007), the links between trajectory indicators (e.g., properties linked with SOM abundance) and maize productivity under different management practices, and how they vary between soil types, are largely unknown.

Poor soil health in southern Africa is often exacerbated by the prevalent soil types, including granitic sandy or ferralitic soils, which are characterized by low pH, lack of available phosphorous (P) and nitrogen (N), and low levels of soil organic carbon (C) (Nyamapfene, 1991). SOM accrual promotes soil health through increasing structural stability, reducing nutrient losses associated with erosion, improved nutrient and water capture and reduced leaching losses (Lal, 2016). Decline in soil water and nutrient holding capacity is closely related to reduced SOM-C stocks. This is exacerbated under sandy soils where SOM is the primary mechanism for water retention (Hudson, 1994), and under a tropical climate where there is limited biomass return to the soil, for example, due to crop residue removal. Assessments of soil quality in this region, such as in Zimbabwe, have typically focused on soil chemical and physical properties [e.g., soil texture, structure, bulk density, pH, electrical conductivity (EC), cation exchange capacity (CEC), SOM, and C, N and P concentrations] (Tittonell *et al.*, 2007; Zingore *et al.*, 2007). The biological characteristics of these soils, particularly the microbial biomass that is a key regulator of rates and magnitude of SOM build-up and turnover, are often overlooked and rarely reported. This is despite the microbial-driven turnover of SOM being a key determinant of the availability of some major soil nutrients for crop growth.

Since the 1990s, crop management options designed to improve soil fertility and build SOM stocks have been widely promoted. An example is NT with crop residue retention, as utilized in different forms of conservation agriculture (Thierfelder *et al.*, 2018) that are currently being practiced on more than 180 M ha of arable land worldwide, and on over 1.5 M ha in Africa (Kassam *et al.*, 2019). There have been attempts to relate the soil health impacts of NT with residue retention on crop yield (Thierfelder and Wall, 2009; Nyamangara *et al.*, 2014), but the success of this varies with soil type and environmental constraints (Thierfelder and Wall, 2012). Direct measurement of statistically significant changes in SOM stocks is challenging in the short-term (<15 years), due to stock size and spatial heterogeneity (O'Dell *et al.*, 2015). As timescales for measurable change vary with soil type, as well as agro-ecology and on-site management (Chivenge *et al.*, 2007), this may in part explain contradictory findings in southern Africa, with reports of both evidenced increases (Thierfelder and Wall, 2012) and no increases in SOM-C (Cheesman *et al.*, 2016) in response to NT with residue retention, highlighting the need for additional indices to track trajectories of management impacts on soil health.

Here, we examined the relationships between key soil health attributing properties—chemical, physical and biological—and maize productivity under conventional tillage with crop residue removal and NT with crop residue retention at long-term on-station and on-farm sites of contrasting soil types in Zimbabwe. Our aim was to identify the soil characteristics, or combinations of characteristics, most closely related to maize grain yield and above-ground biomass (i.e., stover) that could serve as early indicators of the sustainability of the management practices.

We hypothesized that (i) relationships between key soil properties and maize productivity (grain yield and above-ground

biomass) vary with soil type, for example, a stronger reliance on soil mineral N concentrations in sandy soils, and (ii) management impacts (conventional management with residue removal vs NT with residue retention) on these relationships also vary among locations with contrasting soil types, with the greatest impact of management in the sandy soils due to their low inherent nutrient status and low buffering capacities.

Materials and methods

Site description

Sites were selected from existing long-term on-station and on-farm trials in Zimbabwe to include contrasting soil types (sandy and clayey soils). Soil sampling was conducted in June and October 2017 at the on-station and on-farm sites, respectively, from paired plots under conventional tillage with crop residue removal and NT with crop residue retention. Two on-station trials with contrasting soil types were selected at the Domboshawa Research Centre (Domboshawa) (−17.603 S; 31.604 E; 1545 m.a.s.l.) and the University of Zimbabwe Farm (Harare) (−17.722 S; 31.021 E; 1494 m.a.s.l.). Additionally, on-farm trials were selected at Hereford Farm (Hereford) (−17.423 S; 31.445 E; 1106 m.a.s.l.), Chavakadzi (Shamva) (−17.189 S; 31.493 E; 1164 m.a.s.l.) and Madziwa (−16.991 S; 31.415 E; 1177 m.a.s.l.). All sites were characterized by moderate, unimodal rainfalls of 600–900 mm which usually fell between November and April (Table 1). The on-farm sites had been under different management practices since 2004/2005 (Shamva) and 2005/2006 (Madziwa and Hereford) cropping seasons, whereas the on-station trials (Harare and Domboshawa) were under treatment since the 2009/2010 cropping season.

Farmers in these areas mostly grow maize which is sometimes rotated or intercropped with groundnuts (*Arachis hypogaea* L.) and cowpeas (*Vigna unguiculata* Crantz), but not as part of a systematic rotation (Waddington *et al.*, 2007). Rotations on more fertile soils may also include soybean [*Glycine max* (L.) Merr] (Table 1). Conventional land management at the sampling sites is based on soil tillage with a single row mouldboard plough at shallow depth (0–15 cm), crop residue removal or burning and monocropping or full rotations with legumes.

Experimental design and crop management

The on-station trials had three replicates and two main treatments (5 m × 4.6 m plot size): (a) conventional management with soil tillage and crop residue removal (CT); and (b) no-tillage and crop residue retention (NT). Sub-treatments for these trials, but not used in this study, were eight maize varieties sown in two plant populations. Seven drought-tolerant and one non-drought-tolerant maize varieties were seeded in these trials. The maize was fertilized with 83 kg N ha^{−1}, 28 kg P₂O₅ ha^{−1} and 14 kg K₂O ha^{−1} supplied as basal dressing at seeding, and 69 kg N ha^{−1} as a split-applied topdressing 4 and 7 weeks after crop emergence (WACE).

The on-farm locations had replicates across farms (six farmer replicates in each community) with three main treatments (each 1000 m² in size; total 3000 m² at each farmer's field): (a) conventionally ploughed maize-legume rotation with residue removal (CT); (b) NT-ripline seeding with a maize-legume rotation and crop residue retention (NT with ripping); (c) NT-animal traction direct seeding with a maize-legume rotation and crop residue

Table 1. General characteristics of the experimental trial sites

Site name	Experiment type	Soil type	Soil texture	Average annual rainfall (mm)	Main crop	Rotational crop	Years under trial
Harare	On-station	<i>Chromic Luvisol</i>	Clay	667	Maize	–	7
Domboshawa	On-station	<i>Chromic Lixisol</i>	Sandy loam	823	Maize	–	7
Madziwa	On-farm	<i>Arenosols</i>	Sand	679	Maize	Cowpea	14
Shamva	On-farm	<i>Luvisols and Lixisols</i>	Sandy clay loam	809	Maize	Soybean	15
Hereford	On-farm	<i>Luvisols and Lixisols</i>	Sandy clay loam	762	Maize	Soybean	14

retention (NT with direct seeding). The main plots were split into four subplots and three drought-tolerant and one non-drought-tolerant maize varieties were seeded in these at all on-farm sites. Fields were fertilized with 11 kg N ha⁻¹, 21 kg P₂O₅ ha⁻¹ and 11 kg K₂O ha⁻¹ as basal dressing at seeding, and 69 kg N ha⁻¹ as topdressing split-applied at 4 and 7 WACE, reflecting low N inputs in smallholder plots in Zimbabwe and southern Africa. In the legume phase of the rotation, only basal dressing was applied at the same rate as maize. The choice of legumes planted at these on-farm sites (Table 1) depended on farmer preferences as well as their suitability for the local soils. However, for the purpose of this study, only maize yields were reported in the assessments. At all sites, weed control was achieved with an initial spray of a non-selective herbicide, glyphosate [*N*-(phosphono-methyl) glycine] at a rate of 2.5 l ha⁻¹ (1.025 l ha⁻¹ active ingredient) followed by manual hoe weeding (1–3 times per season according to weed pressure).

Soil sampling procedures

Soils were sampled from on-station and on-farm trial plots during off-season in June and October 2017, respectively. Ten sub-samples (0–10 cm soil depth) from each plot were thoroughly mixed into a composite sample and sieved through a 2 mm mesh on-site. These soil samples were then packed in cooler boxes and transported to Aberdeen, United Kingdom, where they were stored at 4°C until analyses for soil physico-chemical properties and microbial biomass C (MBC).

Characterization of soil physico-chemical properties and MBC

Soil texture, total nitrogen and carbon

Soil texture determination for on-station sites followed a particle-size soil fractionation procedure of Garcia-Pausas *et al.* (2012). In this procedure, the soil was separated into three size fractions of coarse sand (2000–250 µm), fine sand (250–53 µm) and silt plus clay (<53 µm) by wet sieving. Dry mass of each soil particle-size fraction was determined following oven drying to constant weight at 65°C. Physical particle-size soil fractionation was not performed for on-farm trial sites as recent soil texture data for these sites were obtained from previous work (CIMMYT, unpublished). Whole soil samples (i.e., non-fractionated soil) for on-station and on-farm sites were ball milled and analyzed for total C and N concentrations on a Flash EA 1112 Series Elemental Analyzer (Thermo Finnigan, Bremen, Germany). In addition, soil bulk density data for on-station sites were obtained from previous work (CIMMYT, unpublished) and used to

estimate soil C and N stocks. Soil C and N stocks were not determined for on-farm sites in this study as soil bulk density data for these sites were not available.

Electrical conductivity, pH and cation exchange capacity

Soil pH and EC were measured using an electrode in a soil/water suspension (15 g soil and 45 ml H₂O) (Thomas, 1996). As soil pH values were <7, CEC was estimated as the sum of exchangeable cations and exchangeable acidity (Ross and Ketterings, 1995). Exchangeable cations and exchangeable acidity were determined according to the methods described by Thomas *et al.* (1982) and Parker (1929), respectively.

Ammonium, nitrate and MBC

Soil mineral N (NH₄⁺ and NO₃⁻) concentrations were determined using an autoanalyzer (Technicon Traaks 800, Saskatoon, Canada) following extraction of 10 g fresh soil with 50 ml of 1 M KCl solution. To determine soil MBC, chloroform fumigation-extraction was used according to Vance *et al.* (1987), where fresh fumigated and non-fumigated soil samples (equivalent 12.5 g dry soil) were extracted with 50 ml of 0.5 M K₂SO₄ solution. Organic C of the extracts was analyzed on a TOC Analyzer 700 (Corporation College Station, Texas, USA). MBC was calculated as the difference between organic C in the paired fumigated and non-fumigated extracts using a conversion factor *k*_{EC} of 0.45 (Vance *et al.*, 1987).

Crop productivity

Maize was harvested at physiological maturity. Fresh cob and biomass samples were taken from 10% of the on-farm treatment areas and 60% of the on-station treatment areas and weighed in the field. A representative sub-sample was then collected, measured fresh, dried for 4 weeks, shelled and the grain and biomass sub-samples reweighed, and the grain moisture determined. The final grain yield was then averaged for all varieties and plant populations for 2018 and 2019 seasons, resulting in a single average yield value for statistical analysis, expressed as kg ha⁻¹ at 12.5% moisture content.

Statistical analyses

The software package GenStat (Eighteenth Edition, VSN International Ltd) was used to test for data normality and to conduct two-way analysis of variance (ANOVA) to assess, using models, the effects of management practices (called management where necessary), trial location, and their interaction on soil physico-chemical properties, MBC, and on maize grain yield

Table 2. Texture (0–10 cm depth), pH (H₂O), electrical conductivity (EC) and cation exchange capacity (CEC) of soils at Domboshawa and Harare on-station sites and Madziwa, Shamva and Hereford on-farm sites under conventional tillage (CT) with crop residue removal and no-tillage (NT) practices (ripping, direct seeding) with residue retention

Sites	Management practice	Silt + clay fraction (%)	Sand fraction (%)	pH	CEC (meq 100 g soil ⁻¹)	EC (μS cm ⁻¹)
<i>On-station</i>						
Domboshawa	CT	16.3 ± 0.2a	83.7 ± 0.4a	4.79 ± 0.03a	1.01 ± 0.04a	94.3 ± 2.3a
	NT	19.6 ± 0.2b	80.4 ± 0.4b	5.11 ± 0.00b	1.58 ± 0.05b	248.0 ± 13.7b
Harare	CT	61.6 ± 1.5a	38.4 ± 2.5a	5.38 ± 0.02b	12.75 ± 0.09a	152.5 ± 7.5a
	NT	62.6 ± 1.6a	37.4 ± 3.1a	5.28 ± 0.01a	13.61 ± 0.09b	253.5 ± 67.8b
<i>On-farm^a</i>						
Madziwa	CT	8.4 ± 0.7	91.6 ± 0.7	5.76 ± 0.09a	1.7 ± 0.4a	195.0 ± 5.34a
	NT ripping	10.4 ± 1.9 ^b	89.6 ± 1.9 ^b	5.94 ± 0.22a	1.8 ± 0.3a	213.7 ± 8.91a
	NT direct seeding			5.68 ± 0.21a	1.5 ± 0.3a	208.0 ± 9.54a
Shamva	CT	44.2 ± 3.4	55.8 ± 3.4	6.02 ± 0.11a	20.7 ± 1.4a	194.3 ± 8.88a
	NT ripping	48.7 ± 5.9 ^b	51.3 ± 5.9 ^b	6.23 ± 0.30a	23.1 ± 1.2a	228.0 ± 33.0a
	NT direct seeding			6.59 ± 0.28a	23.8 ± 1.2a	298.3 ± 45.9a
Hereford	CT	35.0 ± 4.7	65.0 ± 4.7	5.77 ± 0.11a	22.4 ± 1.5a	156.4 ± 5.75a
	NT ripping	30.5 ± 3.0 ^b	69.5 ± 3.0 ^b	5.93 ± 0.15a	23.0 ± 1.7a	174.8 ± 7.58a
	NT direct seeding			5.93 ± 0.16a	23.5 ± 1.8a	187.4 ± 11.7a

Notes: Values are means ± one standard error of the mean. Lowercase letters indicate significant differences ($P < 0.05$) between treatments within columns for each site.

^aSoil texture of on-farm sites was determined in previous work (CIMMYT, unpublished).

^bAverage value of NT systems (i.e., ripping and direct seeding).

and aboveground biomass as measures of crop performance (Equation 1). In these models, replicates were regarded as random effects.

$$Y_{ijk} = \mu + \text{Site}_j + \text{Management}_k + \text{Site}_j \times \text{Management}_k + \xi_{ijk} \quad (1)$$

where Y_{ijk} is response variable in the j th site and k th management, μ is the overall response variable average, $\text{Site} \times \text{Management}$ is the interaction effect of Site_j and Management_k and ξ_{ijk} is the error associated with the j th site and the k th management and is normally and independently distributed. In addition, one-way ANOVA was used to test for differences in soil properties and maize crop performance between management practices. For these analyses, on-station sites ($n = 3$) were analyzed separately from on-farm sites ($n = 6$) due to the different trial designs. Where significant ($P < 0.05$) treatment effects were found, least significant difference tests were used to separate the individual means.

In addition, principal component analysis (PCA) was used to assess the relationships between maize productivity and soil characteristics under the different management practices and trial locations or soil types. Since the different variables were recorded at different scales, all data were first standardized by scaling using the $\text{PCA}()$ function of the 'FactoMineR' package in R. The eigenvalues (variances retained) for each of the principal components were calculated using the $\text{get_eigenvalue}()$ function of the 'factoextra' package in R. A correlation analysis was conducted using the 'corrplot' package (Wei and Simko, 2017) in R and using the Pearson product moment correlation test, to measure the strength of the relationships.

Results

Soil texture differed between sites (Table 2), so we divided the sites into two broad textural groups based on their silt + clay content: 'sandy' (for Domboshawa and Madziwa; <20% silt + clay content) and 'clayey' (for Harare, Shamva and Hereford; >30% silt + clay content).

Maize crop performance

Maize grain yield and above-ground biomass averaged across management practices were significantly lower ($P < 0.05$, Table S1) at the sandy soil sites than at the clayey sites (Figs. 1 and 2). Average grain yield and above-ground biomass across treatments at Domboshawa were 2.3 and 2.4 t ha⁻¹, and 2.3 and 2.8 t ha⁻¹ at Madziwa, respectively. The highest ($P < 0.001$) average grain yield and above-ground biomass of 5.9 and 6.1 t ha⁻¹, respectively, were obtained at the clay soil Shamva site, whereas yields from the Harare and Hereford sites were intermediate (Figs. 1 and 2).

Management affected grain yield and above-ground biomass at the on-station sites (Domboshawa and Harare), but not at the on-farm sites (Shamva, Hereford and Madziwa) (Figs. 1 and 2, Tables S1 and S2). Both maize grain yield and above-ground biomass were significantly increased ($P < 0.05$, Table S2) under NT with residue retention relative to CT with residue removal at Domboshawa, by 100 and 50% (1.5 t grain ha⁻¹ and 1.0 t above-ground biomass ha⁻¹), respectively. At Harare, above-ground biomass increased ($P < 0.05$, Table S2) by 23% (1 t above-ground biomass ha⁻¹) under NT compared to CT.

Overall and across all sites and management practices, maize grain yield and above-ground biomass were positively correlated

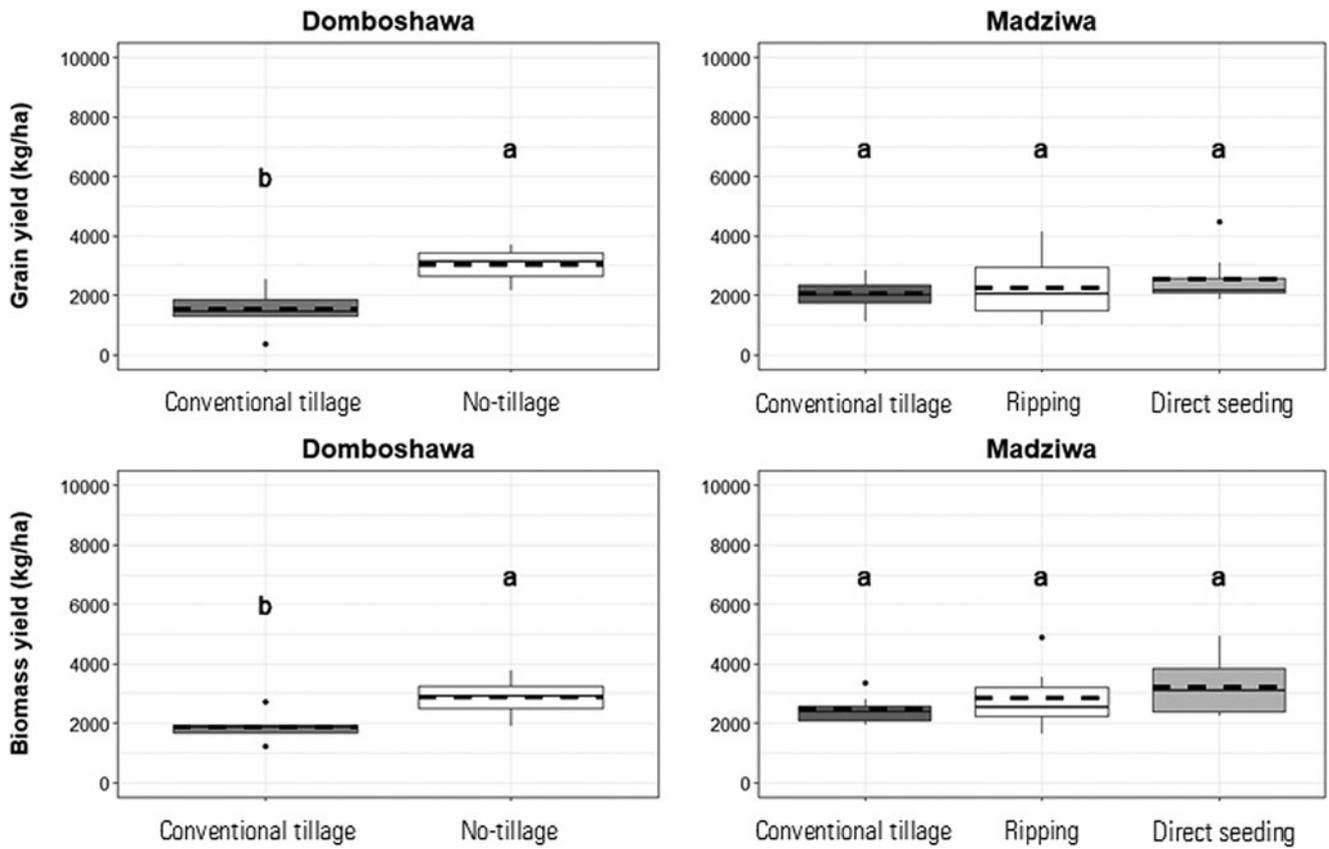


Fig. 1. Boxplots of maize grain yield and above ground biomass in sandy soil sites of Zimbabwe under conventional tillage with crop residue removal and different no-tillage practices (ripping, direct seeding) with residue retention across on-station and on-farm trials. Lowercase letters indicate significant ($P < 0.05$) differences between management practices at each site. Values are means \pm one standard error of the mean (2018 and 2019 seasons).

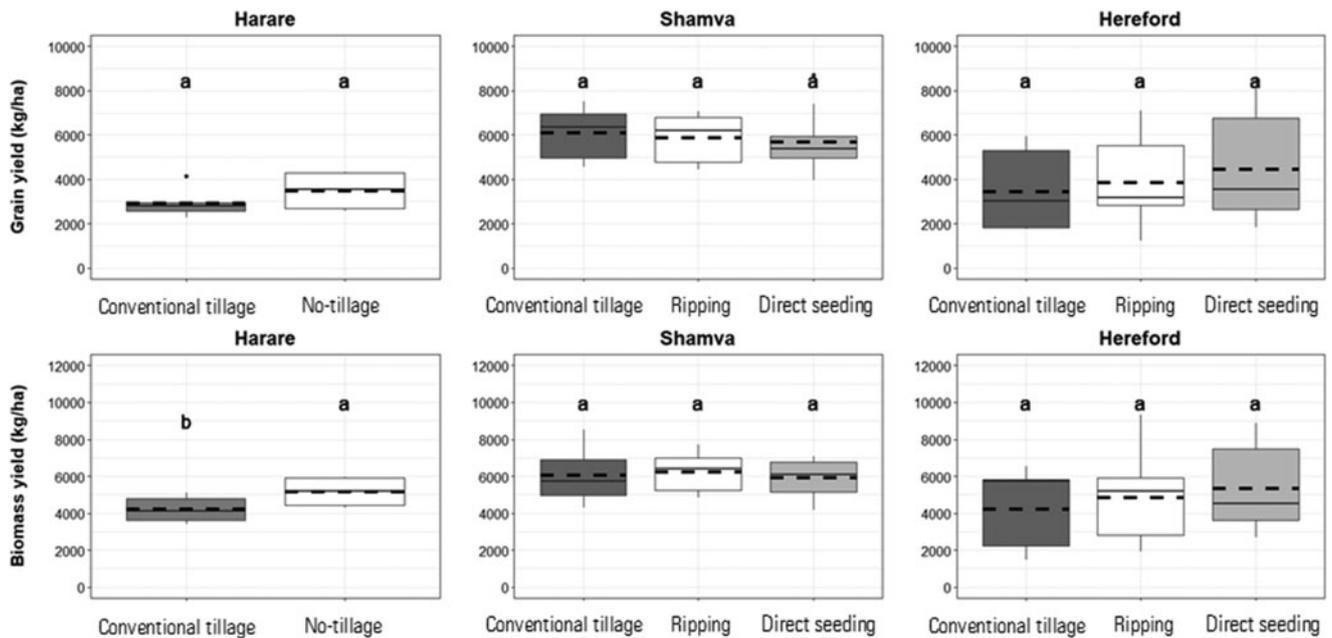


Fig. 2. Boxplots of maize grain yield and above ground biomass in clay soil sites of Zimbabwe under conventional tillage with crop residue removal and different no-tillage practices (ripping, direct seeding) with residue retention across on-station and on-farm trials. Lowercase letters indicate significant ($P < 0.05$) differences between management practices at each site. Values are means \pm one standard error of the mean (2018 and 2019 seasons).

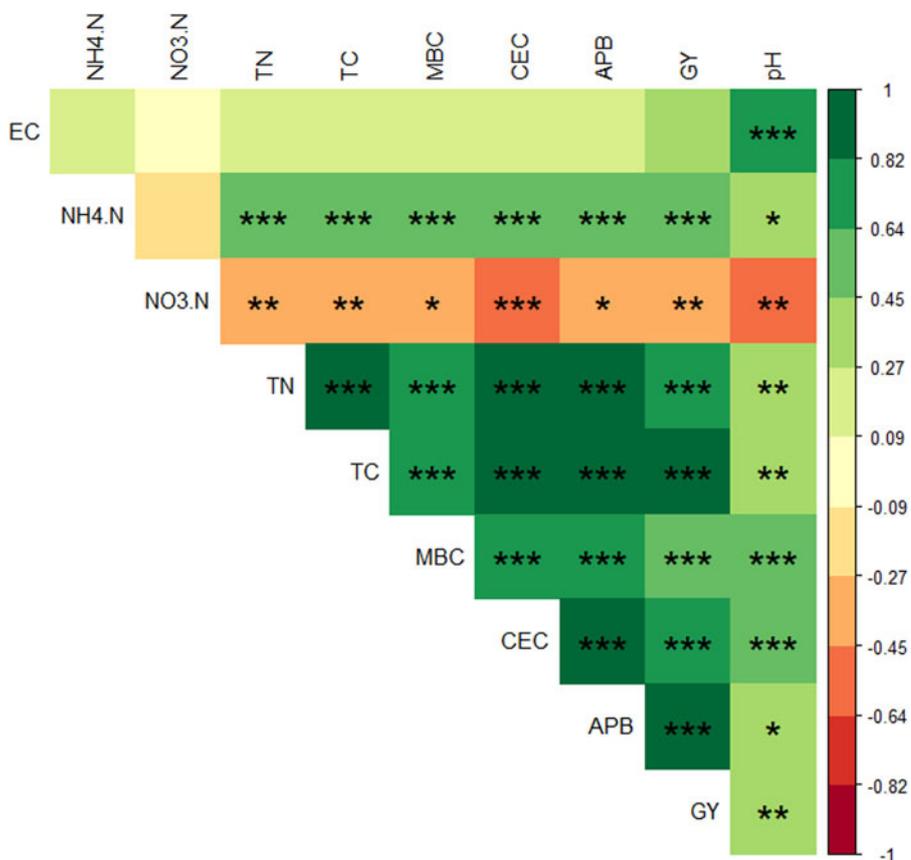


Fig. 3. Combined Pearson correlation analysis of all sites and management practices on combined sandy and clayey soils of Zimbabwe. GY, grain yield; APB, aboveground biomass; MBC, microbial biomass C; TC, total carbon; TN, total nitrogen; CEC, cation exchange capacity; NH₄.N, ammonium nitrogen; NO₃.N, nitrate N; EC, electrical conductivity.

($P < 0.0001$) with total N, total C, MBC, NH₄⁺-N, CEC and negatively correlated ($P < 0.0001$) with NO₃⁻-N whereas EC was not correlated with grain yield and above-ground biomass (Fig. 3).

Soil properties

pH, CEC and EC

Significant effects of management practice on soil pH and CEC were found at the two on-station sites, but not at the on-farm sites (Table 2 and Table S2). Soil pH was higher ($P < 0.05$) under NT (5.11) compared with CT (4.79) at Domboshawa and was lower under NT (5.28) compared with CT (5.38) at Harare, whereas CEC was significantly higher ($P < 0.05$) under NT at both sites (CEC of 1.58 and 1.01 meq 100 g⁻¹ soil under NT and CT, respectively, at Domboshawa, and CEC of 13.61 and 12.75 meq 100 g⁻¹ soil under NT and CT respectively, at Harare). There were no significant differences in pH across the on-farm sites, but CEC was significantly lower ($P < 0.05$) at the sandy Madziwa site compared to the clayey Shamva and Hereford sites (Table 2). EC was significantly ($P < 0.05$) affected by management at both Harare and Domboshawa with a 163% increase of EC under NT as compared with CT in Domboshawa (Table 2).

Total C and N concentrations

On-station, NT significantly ($P < 0.05$) increased total soil C and N concentrations at Domboshawa (both 59%) and Harare (22 and 23%, respectively) as compared with CT. Comparable treatment effects were observed for soil C and N stocks at these sites (Table S3). On-farm, NT with ripline seeding significantly ($P < 0.05$) increased total C and N concentrations compared with

CT at Madziwa (61 and 78%, respectively) and Hereford (21 and 18%, respectively), but differences at Shamva were not significant (Fig. 4a–d). Comparable increases were observed in total C and N concentrations in soil under NT with direct seeding at Madziwa (63 and 80%, respectively) and Hereford (28 and 23%, respectively). Overall, total soil C and N concentrations were significantly higher ($P < 0.05$) at the clayey sites of Harare, Shamva and Hereford, than the sandy sites of Domboshawa and Madziwa (Fig. 4a–d).

Soil mineral N concentrations

At the Domboshawa and Harare on-station sites, soil NH₄⁺-N concentrations were greater ($P < 0.05$) under NT (relative to CT) by 106 and 79%, respectively, whereas NO₃⁻-N concentrations were relatively greater ($P < 0.05$) under NT at Domboshawa and Harare by 18 and 53%, respectively (Fig. 5a–d and Table S1). At the on-farm sites, soil NH₄⁺-N and NO₃⁻-N concentrations significantly ($P < 0.05$) varied between management practices at Madziwa but not at Shamva and Hereford (Fig. 5a–d and Table S2). At Madziwa, soil NH₄⁺-N concentration was 148 and 155% higher ($P < 0.05$) under NT with ripping and direct seeding, respectively, compared with CT. Similarly, at Madziwa, soil NO₃⁻-N concentration was higher ($P < 0.05$) under NT with ripping and direct seeding (+104% and +131%, respectively), compared with CT (Fig. 5a–d).

Overall, soil NH₄⁺-N concentrations were highest ($P < 0.05$) at Shamva and Hereford clayey on-farm sites, but NO₃⁻-N concentrations were lowest ($P < 0.05$) at these sites (Fig. 5a–b). The highest ($P < 0.05$) NO₃⁻-N concentration was at the Harare clayey on-station site (Fig. 5c and d).

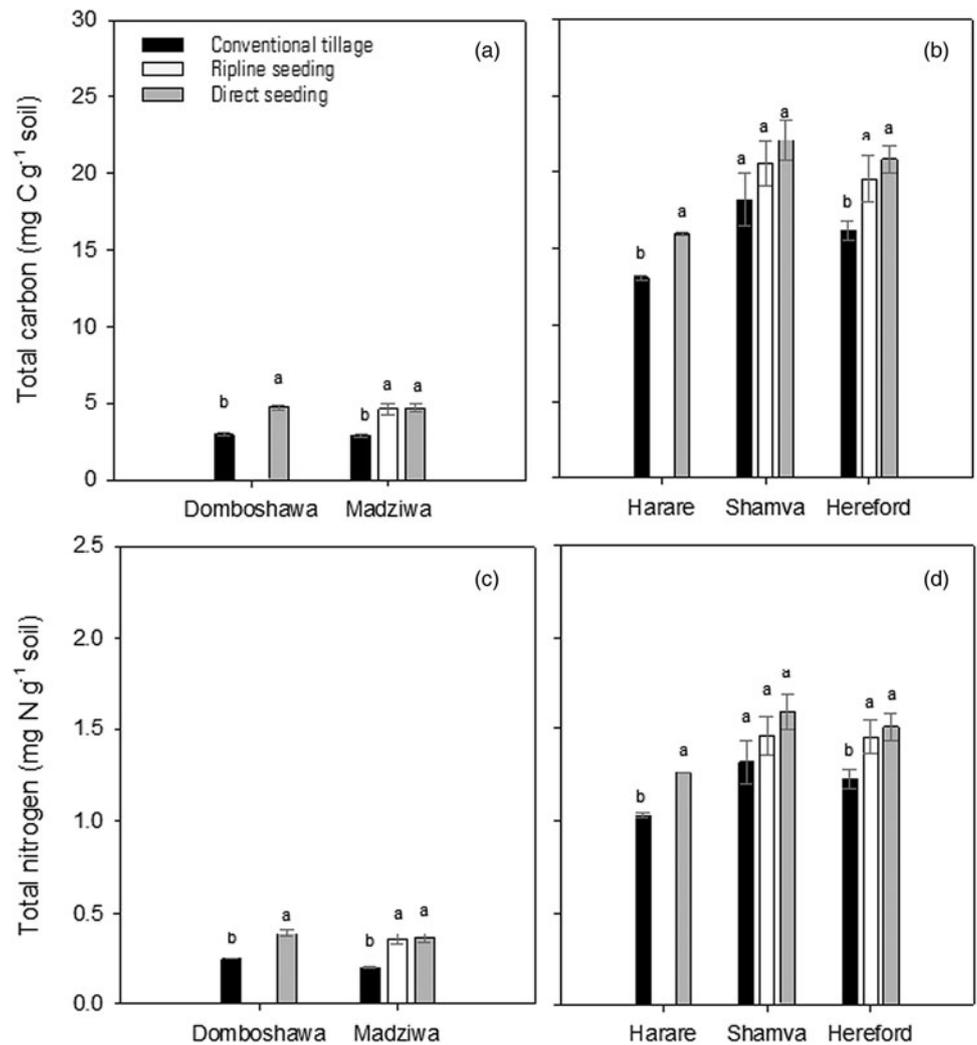


Fig. 4. Total C and N concentrations in soils at two on-station and three on-farm research sites in Zimbabwe under conventional tillage with residue removal and different no-tillage practices (ripping, direct seeding) with residue retention: total C and N at sandy soil sites (a) and (c) and clay soil sites (b) and (d). Lowercase letters indicate significant ($P < 0.05$) differences between management practices at each site. Values are means \pm one standard error of the mean.

Soil MBC

When averaged across management practices, soil MBC concentrations were lowest at the sandy Madziwa site among the on-farm sites, and concentrations were higher at the clayey Harare on-station site than at the sandy Domboshawa on-station site ($P < 0.05$). Management significantly ($P < 0.05$, Table S2) impacted MBC concentrations at the Harare site only, where soil MBC was 61% greater under NT compared to CT (Fig. 5e and f).

Relationships between soil properties, sites, management regime and maize productivity

Specific relationships between all soil properties are presented in Figure 3 and the Supplementary Figures S1–S6, grouped by soil texture and management. PCA showed that the variables considered here explained most of the variation observed at the sites and in the various managements (Fig. 6a). Averaged across all sites and management, total soil C, total soil N and CEC were the strongest predictors of maize grain yield ($R^2 = 0.73$, 0.71 and 0.64 , respectively; $P < 0.0001$) and above-ground biomass ($R^2 = 0.81$, 0.81 and 0.75 , respectively; $P < 0.0001$). However, they exerted a weaker influence on maize grain yield and biomass at the sandy sites of Domboshawa and Madziwa (Fig. 6b). The

influence of management on maize performance varied between the sandy and clayey sites (Fig. 6b and c). At the sandy sites, no individual soil parameters significantly predicted maize grain yield or biomass. There was clear isolation of the CT system with relatively weak associations with any of the soil parameters signifying that CT of the sandy soil had minimal effect on all soil parameters. To the contrary, NT practices associated more with different soil parameters under sandy soils (Fig. 6b). At the clayey sites, there was a wider distribution of system management across the PCA ordination space. Total soil C and total soil N were the strongest predictors of maize grain yield ($R^2 = 0.53$ and 0.44 , respectively; $P < 0.05$) and biomass ($R^2 = 0.40$ and 0.41 , respectively; $P < 0.1$) at the clayey sites (Fig. 6c). Soil texture had a strong effect on relationships as shown by the different responses of the soil and yield parameters when the sites separated into either sandy or clayey sites (Fig. 6b and c).

Discussion

Impact of management on maize productivity

In recent decades, there has been a growing body of research on the links between soil characteristics, tillage and crop performance, although studies under the specific environmental conditions of southern Africa and also integrating soil biological and

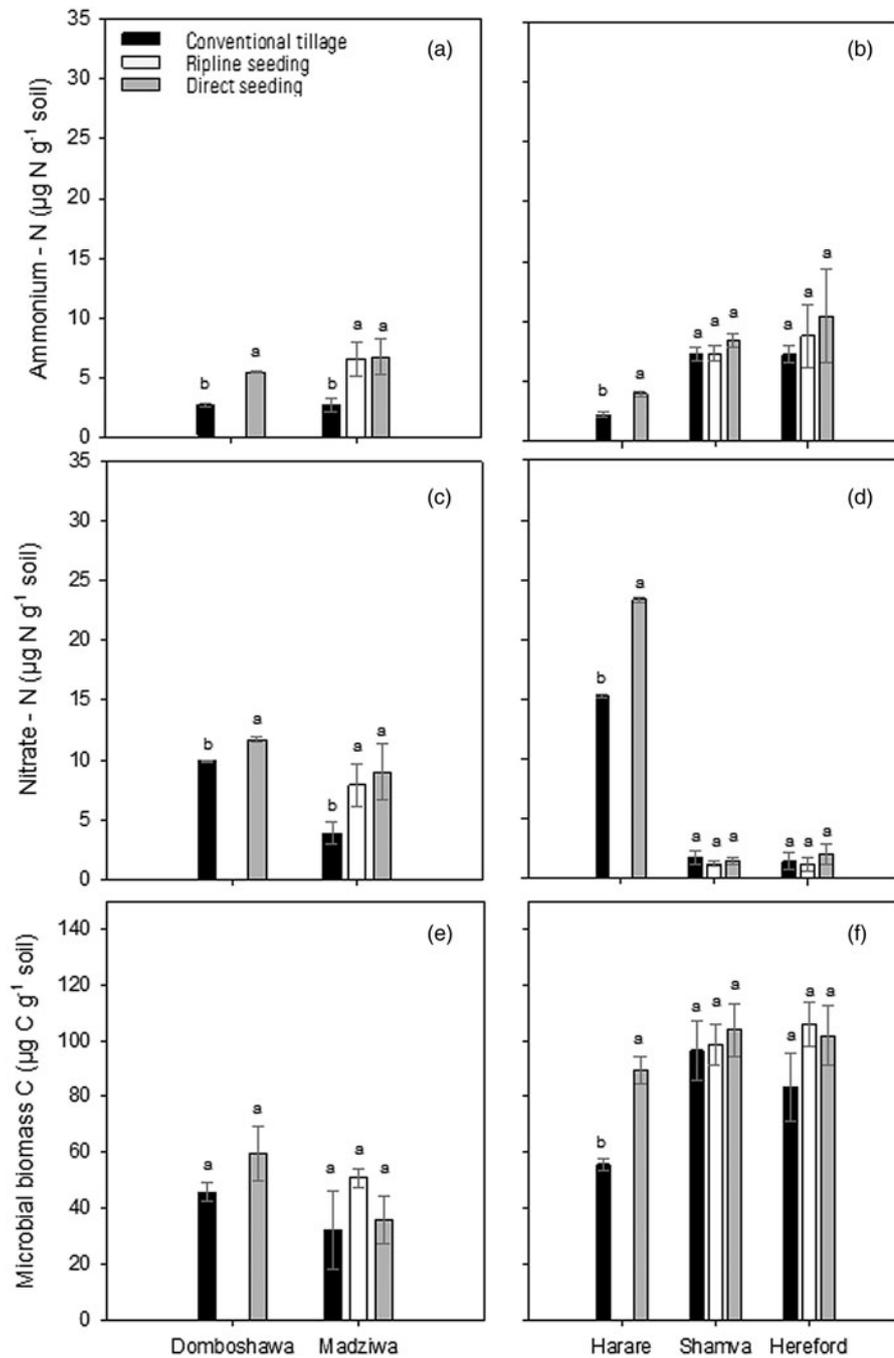


Fig. 5. Mineral N and microbial biomass C concentrations in soils at two on-station and three on-farm sites in Zimbabwe under conventional tillage with residue removal and no-tillage practices (ripping, direct seeding) with residue retention: ammonium, nitrate and microbial biomass C levels are shown in sandy soils sites (a, c and e) and in clay sites (b, d and f). Letters above the columns indicate significant ($P < 0.05$) differences between management practices at each site. Values are means \pm one standard error of the mean.

physical fertility indicators remain limited (De la Cruz-Barrón *et al.*, 2017; Eze *et al.*, 2020). Our study was conducted under both controlled conditions (i.e., in on-station trials), and under smallholder farmer-managed conditions to acknowledge the diversity and heterogeneity of more real farm situations. Across the sites with more fertile, clayey soils (Harare, Shamva and Hereford), management had no significant effect on grain yield, and NT with residue retention increased maize above-ground biomass only at the Harare site. This lack of management impact on grain yield and on-farm maize above-ground biomass reflects the inherent nutritional status and buffering capacity of clay soils in Zimbabwe, which do not respond as dramatically to a decline in soil fertility resulting from CT management without residue retention. Clay soils are also more aggregated, which protects

SOM through micro-aggregates from faster decomposition induced by tillage and reduces nutrient leaching (Chivenge *et al.*, 2007).

However, total concentrations of C and N were strong predictors of maize grain yield and above-ground biomass in the clayey soils (Fig. 6). Management practices influenced these soil characteristics, and increased total C and N concentrations and stocks under NT with residue retention at Harare and Hereford. This suggests that residue retention and increased physical protection of organic matter in clay soils, with reduced soil disturbance and increased water storage, likely had benefits for crop productivity, although this did not result in a statistically significant increase in grain yield. Higher total C and N concentrations and stocks under the NT practices are in accordance with

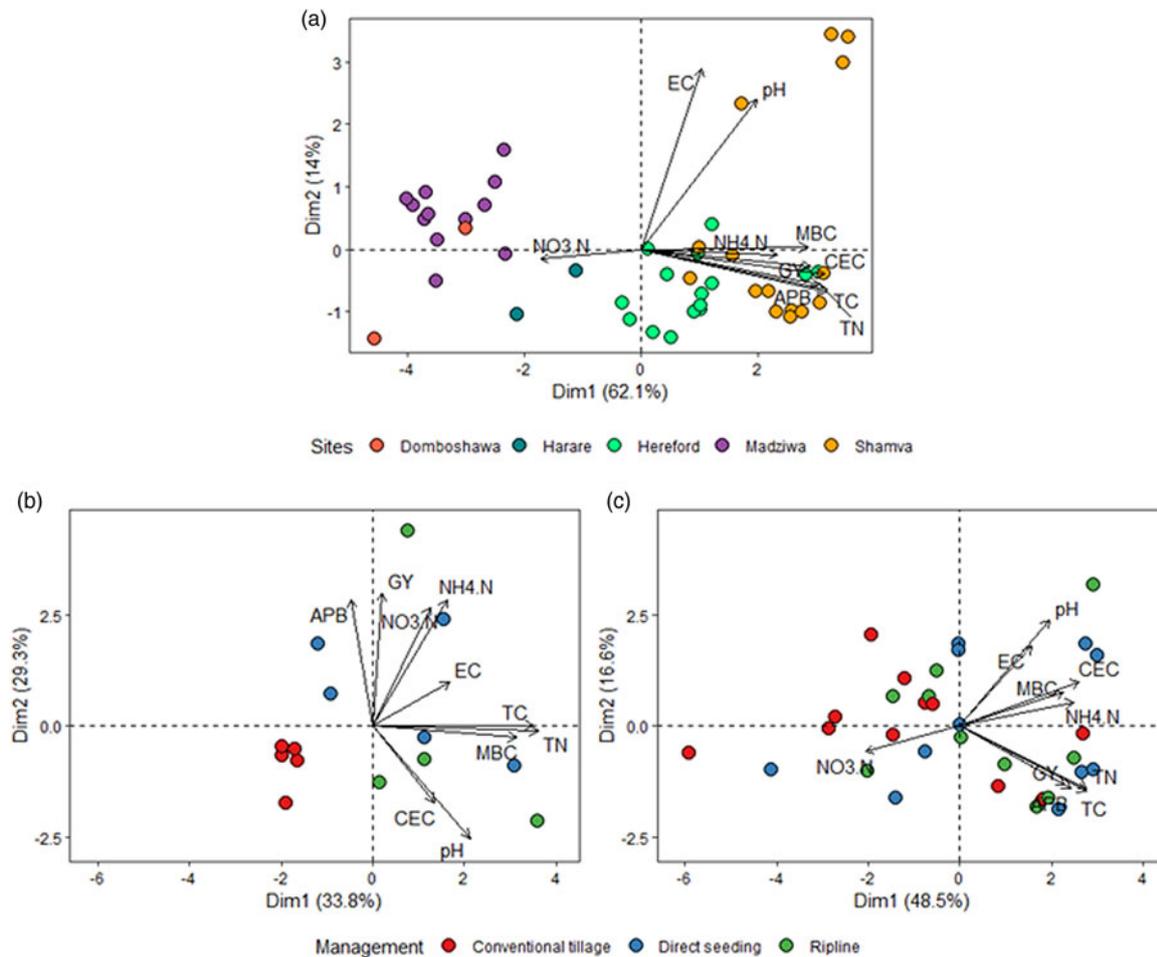


Fig. 6. Principal component analyses (PCA) of soil properties and maize productivity (grain yield and above-ground biomass) in (a) all sites under both conventional tillage with residue removal and no-tillage practices (ripping, direct seeding) with residue retention, (b) sandy soils and (c) clayey soils. GY, grain yield; APB, aboveground biomass; MBC, microbial biomass C; TC, total carbon; TN, total nitrogen; CEC, cation exchange capacity; $\text{NH}_4\text{-N}$, ammonium nitrogen; $\text{NO}_3\text{-N}$, nitrate N; EC, electrical conductivity.

increased SOM stocks under minimum soil disturbance and crop residue retention (Lal, 2009), and may provide possible trajectory indicators for sustainability through SOM build-up. Management practices influenced both total concentrations and stocks of C and N similarly. Soil $\text{NO}_3\text{-N}$ and MBC concentrations were also higher under NT at the Harare on-station site, likely due to higher microbial activity at this more fertile site. Conversely, the stronger correlation between MBC and total N under CT may be indicative of increased coupling between native SOM and microbial abundance in this inherently fertile soil, as opposed to responses of microbial activity to inputs of maize aboveground biomass, with a wide C:N ratio, under NT with residue retention. However, previous research by Gentile *et al.* (2009) from Kenya and Mupangwa *et al.* (2018) from Zimbabwe highlight the challenge of N immobilisation under NT with cereal residue retention as opposed to CT, which affect maize yields and suggests that crop rotations with leguminous crops are essential in overcoming this challenge.

Despite soil CEC only being significantly impacted by management at the on-station trials (Table 2), the positive correlations between CEC and total N, total C, $\text{NH}_4\text{-N}$ concentrations and MBC under both managements (Fig. 3) are indicative of CEC being linked to SOM abundance. These correlations were stronger under CT, possibly reflecting that native SOM (as opposed to

recent residue inputs of high C:N ratio) dominates in the provision of ion exchange sites in soil (Oorts *et al.*, 2007). As these impacts on CEC were in the absence of clear impacts on SOM stocks, this suggests that increased CEC may be an early indicator of accrual of stabilized SOM. As expected for predominantly negatively charged clays, $\text{NO}_3\text{-N}$ concentrations were negatively correlated with CEC under both managements. Residue retention and reduced tillage had no significant effect on $\text{NO}_3\text{-N}$ concentrations at Shamva and Hereford where concentrations were very low, suggesting a strong influence of the constituent 1:1 clays (mainly kaolinite) on the high CEC at these sites, and the potential for leaching of $\text{NO}_3\text{-N}$.

Responses to management varied between on-station and on-farm sites, most likely due to differences in soil mineralogy, cropping history, site heterogeneity and different timescales under NT, but also possibly reflecting biases arising from researcher vs farmer management. Our on-station and on-farm clayey soil sites had been 7 and 14/15 years under NT, respectively, with the effects of NT with residue retention on total C, total N and $\text{NH}_4\text{-N}$ greater at the shorter duration on-station site (Harare). This may have been due to differences in management adherence and/or more consistent retention of crop residues on-station as compared with on-farm sites.

Management impact varies with soil texture

Given the strong influence soil texture has on soil biogeochemistry and microbiology, we grouped the sites according to soil texture—sandy (Domboshawa, Madziwa) vs clayey (Harare, Shamva, Hereford) soils—and compared management impacts between these two textural groups. Higher total C and N and $\text{NH}_4^+\text{-N}$ concentrations under NT with residue retention may represent the indications of benefits of residue management and minimum soil disturbance in both soils. However, the concentrations of total C and N were lower in the sandy soils than in the clayey soils and were only correlated to maize grain yield and biomass at the on-station site (Domboshawa), where $\text{NO}_3^-\text{-N}$ concentration was also increased under NT. Under CT, maize grain yield and biomass at the sandy sites were also lower (1811–2744 and 2191–3057 kg ha⁻¹) than in the clay soils (4369–4907 and 4930–5555 kg ha⁻¹). PCA and regression analyses showed the influences of total C and total N on grain yield and biomass to be significantly weaker in the sandy soils compared with the clay soils. This may reflect the greater buffering capacity, higher CEC and ability to protect C and N more efficiently in clay soils (Chivenge *et al.*, 2007). Even under NT with residue retention, SOM build-up in the sandy soils did not provide the crop nutrient supply benefit or increase in microbial biomass required to enhance maize above-ground biomass or grain yield, possibly because sandy soils are intrinsically less protective of SOM (physical occlusion and organo-mineral interactions) and available soil water.

The responses of our sandy soils to NT appear to have been due to different drivers than responses in the clayey soils. Other studies have reported the benefits of NT systems with residue retention being larger on sandy soils than clay soils (Nyamangara *et al.*, 2014; Steward *et al.*, 2018), including maize yield at sandy loam on-farm sites across Malawi, Mozambique, Zambia and Zimbabwe (Thierfelder *et al.*, 2015). Our results highlight that NT with residue retention will likely have a greater impact on sandy soils due to lower buffering capacity and improvements in soil fertility. In contrast, clayey soils, already endowed with greater buffering capacity due to nutrient storage in the clay minerals and micro-aggregates, will respond less to an increase in soil fertility in the short term. The influence of soil texture on the response to management in general may in part account for previous variability in response to NT practices with residue retention in southern Africa, meaning that practices may need to be fine-tuned to local conditions, and for which early indicators of trajectory toward sustainability will be invaluable.

Sustainable management of degraded soils

It is well recognized that good quality, healthy soils are essential for sustainable agriculture and food production. In Zimbabwe, ~70% of farmers, and particularly smallholder farmers, cultivate sandy soils (Nyamapfene, 1991). Our results show the importance of management approaches for sustainable production, and how relationships between early indicators of sustainability as predictors of maize productivity differ between two broad soil textural groups. Given the limited impact of the NT practices on maize productivity on the sandy soils, especially in the on-farm plots, we highlight the importance of integrating NT and residue retention with other sustainable management practices for these highly degraded soils.

Sole reliance on inorganic fertilizer inputs in these sandy soils is not a sustainable option for most smallholder farmers, due to

low availability and high cost. In addition, the low buffering capacity and lower CEC of these soils mean that nutrient retention is low, which may lead to non-responsiveness of soils to current fertilization strategies. We suggest that a combination of organic inputs (crop residues, manures) and mineral fertilizers will make a difference to maize productivity on these soils. These principles are also central for Integrated Soil Fertility Management (ISFM) (Vanlauwe *et al.*, 2010), and may be further supported in combination with climate-smart agriculture practices such as NT. For sustainable management, an integrated approach, for example, combining NT with the incorporation of high biomass-producing grain legumes, green manures, even tree-based components, will be necessary to foster the return of soils to sustainable production (Thierfelder *et al.*, 2018). Diversification of current maize-based farming systems could ensure increased and diverse C input into the cropping system, for example, not simply a reliance on maize residues. Increased biomass input will raise soil C levels, potentially increasing SOM-associated physico-chemical and biological benefits such that resilience of these soils to sustainably support crop yields is significantly increased. There is a need to develop measures to reduce livestock grazing of crop residues on cropland during the long dry season in this region (e.g., Valbuena *et al.*, 2012).

Current cropping systems yielding on average 0.5–1 t ha⁻¹ of biomass will be insufficient to close the large yield gap between our Madziwa sandy soil and Shamva clayey soil and would necessitate an additional annual return of at least 3.5–5 t ha⁻¹ residue biomass input per year. This would need to be provided from other sources, such as integrating large biomass-producing cover crops and tree components. Previous research showed that for arid-tropical regions, a combination of 1.6 t ha⁻¹ residue input with 2 t ha⁻¹ animal manure with no N application may provide at least an additional 0.3 t ha⁻¹ grain yield of pearl millet (Aggarwal and Power, 1997), which shows the magnitude of investment needed. For smallholder farmers who cannot afford or access large quantities of mineral fertilizer, improving the soil through combined management of different inputs to enhance SOM levels and in turn soil fertility and water storage (Fageria, 2012) may prove to be an essential climate-smart approach enabling continued maize productivity under the threats of climate change. SOM management for sustainability will depend on soil characteristics, and our results show that consideration of textural differences is key to this.

Conclusions

Our findings indicate the trajectories of soil improvements with no-tillage and crop residue retention, that, in accordance with our hypotheses, were related to maize productivity and varied with soil type: (1) texture had a much stronger influence on maize productivity than soil management; (2) to influence maize productivity, there is a need for an increase in total C and N and $\text{NH}_4^+\text{-N}$ which is particularly relevant for the sandy soils; (3) both total C and N were strong predictors of maize productivity in the clayey soils, but not in the sandy soils; (4) NT and residue retention strengthened the relationship between soil parameters and maize productivity in the sandy soils. Future research should focus on more sites, soil sampling points and harvest seasons.

We propose that sandy soils should be the priority target for wider promotion of NT and crop residue retention. Investment in soil C and gradually increasing the productivity of maize-based

farming systems, especially under sandy soils, will further provide greater benefits as multiple soil indicators (physical, chemical and biological) will be positively influenced, including the nutrient and water-holding capacities, which will confer greater sustainability and climate resilience.

Supplementary material. The supplementary material for this article can be found at <https://doi.org/10.1017/S1742170521000442>.

Data. The data used for this study are held in the University of Edinburgh and CIMMYT repositories and can be made available on request.

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Author contributions.

All authors contributed to the writing of this manuscript. CT, EB, EP, LM, TD, and JC conceptualized the project. LM undertook the soil and data analyses, and BM supported the data analysis and development of Figures.

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