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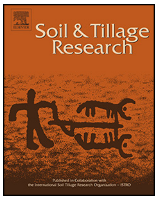

Tillage, mulch and fertiliser impacts on soil nitrogen availability and maize production in semi-arid Zimbabwe

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ABSTRACT

Conservation agriculture has been promoted widely in sub-Saharan African to cushion smallholder farmers against the adverse effects of soil fertility decline, stabilize crop yields and increase resilience to climate change and variability. Our study aimed to determine if aspects of CA, namely tillage and mulching with manure and fertiliser application, improved soil mineral N release, plant N uptake and maize yields in cropping systems on poor soils in semi-arid Matobo, Zimbabwe. The experiment, run for three seasons (2012/13–2014/15), was a split-split plot design with three replicates. Tillage (animal-drawn ploughing and ripping) was the main plot treatment and residue application was the sub plot treatment with two levels (100% residues removed or retained after harvest). Five fertility amendments (mineral fertiliser at 0, 20 and 40 kg N ha-1, 5 t ha-1 manure only and 5 t ha-1 manure + 20 kg N ha-1) were sub-sub plot treatments. Plough tillage stimulated N mineralisation by 4–19 kg N ha-1 and maize N uptake 13–23% more than the ripper tillage. When mulch was added to the plough tillage, mineralisation was slowed resulting in less crop N uptake (by 5–19%) compared with no mulch application. N uptake was highest in the manure treatments. N recovery and agronomic N efficiency by maize were highly variable over the three seasons, reflecting the uncertainty complicating farmers' decision making. Nitrogen recovery in the manure treatments was generally poor in the first season resulting in low grain yields in the range 100–260 kg ha-1 regardless of tillage, though higher in subsequent seasons. In the second season manure application gave the largest grain yields under the ripper tillage, both with and without mulch averaging 1850 and 2228 kg ha-1 respectively. Under the plough tillage, the 40 kg N ha-1 treatment gave the highest grain yields of 1985 kg ha-1. In the third season yields were generally poor under all treatments due to low and poorly-distributed rainfall. The CA principles of minimum soil disturbance and maintenance of a permanent mulch cover resulted in reduced soil mineral N availability for crop uptake and poor maize yields. Nutrient inputs through mineral fertilisers and manure are key to ensuring production in such infertile, sandy soils which predominate in semi-arid regions of southern Africa.

1. Introduction

Smallholder farmers practicing rainfed agriculture in sub-Saharan Africa (SSA) face a myriad of challenges; these include poor soil fertility, low incomes, labour and land constraints, and are further exacerbated by climate variability (Mupangwa et al., 2012; Ngoma et al., 2015; Rurinda et al., 2013). Different approaches to improve soil fertility have been proposed including biological nitrogen fixation, soil surface residue management, fertiliser use, enhanced recycling of animal manure and conservation agriculture (Hobbs, 2007; Mupangwa et al., 2012; Ncube et al., 2009; Nyamangara et al., 2005).

Conservation agriculture (CA) has been promoted throughout sub-humid and semi-arid areas of SSA to cushion smallholder farmers against the adverse effects of soil fertility decline, crop yield decline, and climate change and variability (Hobbs et al., 2008; Ngoma et al., 2015). CA is based on three principles: (i) minimum or no tillage to minimise soil disturbance, (ii) diversification of crop species (often with legumes) grown in rotation and/or association, and (iii) maintaining semi-permanent or permanent soil cover, for example by leaving at least 30% of crop residues (FAO, 2011; Stevenson et al., 2014). This three-pronged approach is reported to

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have the potential to improve farm resource use efficiency and crop yields especially where moisture is limiting (Hobbs et al., 2008).

Although CA is promoted as a soil-fertility enhancing technology, application of crop residues poor in N, such as cereal stover, may result in prolonged immobilisation of mineral N (Giller et al., 1997). In CA systems, reduced N availability has been attributed to slow residue decomposition and N losses from leaching and denitrification (Angás et al., 2006; Verachtert et al., 2009). Nyamangara et al. (2014) proposed that larger N inputs may be required under CA to offset the N immobilisation caused by cereal stover. A combination of high quality manure combined with low quality crop residue may reduce N leakage and increase nutrient use efficiency (Kihara et al., 2011). Qin et al. (2015) found that larger N inputs resulted in a positive effect of straw mulch on maize yields. In sub-humid west Africa, maize grain yield in a no-till system was only increased by mulch when fertiliser was also applied (Lal, 1995). However, smallholder farmers in SSA typically apply only small amounts of N which may not be adequate. (Vanlauwe et al., 2014) argue that appropriate fertiliser use should be considered a fourth principle of CA as fertiliser is required to enhance both crop productivity and produce sufficient crop residues to ensure soil cover.

In the current smallholder farming system, the perturbation by tillage stimulates a flush of mineral N (the “Birch effect”) with the start of the rains (Chikowo et al., 2004; Giller et al., 2011), whereas soil organic matter may have otherwise been protected from degradation. This “Birch effect” is reported to be short-lived and the decomposition rates may fall back to rates similar to that of an undisturbed soil (Andersson and Giller, 2012). Minimum tillage promoted in smallholder areas in SSA under CA is mainly focused on the hand hoe planting basins (Giller et al., 2011; Nyakudya and Stroosnijder, 2015). Farmers with limited access to draught power and using hand hoes prepare their fields in the dry season in order to spread labour requirements for land preparation, allowing for early planting (Nyamadzawo et al., 2012). However, the use of animal drawn conservation tillage methods such as the ripper and direct seeder provides an opportunity to reduce the labour demand associated with land preparation using hand hoes. Mechanisation can increase productivity per unit area by improving timeliness of farm operations including planting. Early planting may coincide with the “Birch effect” which is beneficial to the crop (Chikowo et al., 2004). Minimum soil disturbance in CA systems, however, results in slower mineralisation compared with conventional tillage because of the minimum disturbance (Chivenge et al., 2007) leading to preservation of soil organic matter from decomposition. Due to this slow mineralisation, (Lal, 2007) suggested that resource poor farmers would be better off ploughing their sandy soils to enhance mineralisation of whatever soil organic matter present to enhance nutrient supply in the short term. There are, however, no detailed studies on seasonal mineral N availability in the semi-arid areas under CA practices such as minimum tillage and crop residue retention particularly on soils of poor fertility that are typical in smallholder agriculture in SSA.

We hypothesise that for cropping systems in semi-arid climates and on poor fertility soils, the benefits of CA and added mulch are in immobilising N so that it is not lost from the system and becomes available later for crop growth. The study specifically aimed at determining if and how tillage, mulching, manure and fertiliser application and their interactions improved soil mineral N release, plant N uptake and ultimately maize yields.

2. Materials and methods

2.1. Site description

The study was carried out in Nqindi ward, Matobo district, Matabeleland South, Zimbabwe (20 39.58′S, 28 15.58′ E; 900 masl). Matobo district lies in Agroecological Zone IV, characterised by semi-arid climate typical of south west Zimbabwe. Rainfall is unimodal with a distinct wet (November–March) and dry (April–October) season. The wet season receives 450–650 mm annual rainfall with a long term average annual rainfall of 580 mm. Droughts are frequent as are severe dry spells during the wet season. There is only a 45–65% probability of rainfall between October and April exceeding 500 mm (Vincent et al., 1960). The dominant soils are Eutric Arenosols derived from granite (WRB, 2006). These sandy soils constitute >15% of the total land area in Zimbabwe (Hartemink and Huting, 2008). The smallholder farming system in Matabeleland is characterised by privately managed arable fields and communally-managed grazing lands. The arable fields are also communally grazed during the dry season unless if securely fenced off. Matobo district is largely rural (99.4%) with Nqindi ward having a total population of 3507 persons (ZIMSTAT, 2012).

2.2. Trial layout and treatments

A field experiment was set up in December 2012 on a slightly sloping (<2%) farmer’s field and run for three seasons. The experiment was set up as a split-split plot with plots arranged in a randomised complete block design with three replicates. The tillage system was the main plot treatment with two levels (ox-drawn ploughing and animal drawn ripping) and the mulch management was the sub plot treatment with two levels (100% residue removed and 100% residues retained after harvest). The mulch sub-treatment was not applied in the 2012/13 season as this was the first season. Five fertility amendments (mineral fertiliser at 0, 20 and 40 kg N ha^{-1}, 5 t ha^{-1} manure only and 5 t ha^{-1} manure + 20 kg N ha^{-1}) were randomised as the sub-sub plot treatment. Plots measured 35 m × 12 m with borders measuring 5 m × 15 m. The third CA principle, crop rotation, was not included in the study because of the short duration of the experiment.

2.3. Trial management

A basal application of compound D fertiliser (14 kg N ha^{-1}, 12 kg P ha^{-1} and 12 kg K ha^{-1}) or manure was applied in planting furrows. The 0N fertility treatment received a basal application of single super phosphate (12 kg P ha^{-1}) and muriate of potash (12 kg K ha^{-1}). All plots were planted to a short season maize variety (SC403) at 0.9 m × 0.3 m spacing to achieve a plant population of 37 000 plants ha^{-1}. The remainder of the N requirement (6, 20, 26 kg N ha^{-1} for the 20 kg N ha^{-1}, manure + 20 kg N ha^{-1} and 40 kg N ha^{-1} treatments respectively) was applied as a top dressing, using ammonium nitrate (which contained 34.5% N) at six weeks after planting and when there was enough soil moisture for top dressing. In the second season incessant rains caused waterlogging such that top dressing application was delayed until nine weeks after planting which coincided with the crop flowering stage. The plots were kept weed free by an initial application of glyphosate [N-(phosphono-methyl) glycine] herbicide soon after planting and thereafter by hand hoeing when required. At harvest, in plots where mulch was to be applied, the stover was left on the soil surface. The amount of mulch retained on the surface was dependent on the biomass produced in the previous seasons and ranged from 1 to 2 t ha^{-1} after the 2012/13 season and 2–4 t ha^{-1} after the 2013/14 season which translated to approximately 10–20% and 20–30% surface cover at planting respectively (based on visual assessment of ground cover). In the plough tillage treatment, the mulch was ploughed in at land preparation. The plots were located in a fenced off section of the farm and thus no livestock could feed on crop residues during the dry months.

2.4. Rainfall data

The farmer hosting the trial was provided with a rain gauge and record book to record daily rainfall for the 2012/13 to 2014/15 seasons. The rainfall records were compared and verified with records from the nearby Matopos Research Institute weather station.

2.5. Soil, manure and plant samples

Initial soil samples were collected from each block at incremental depths of 0.10 m up to 1 m. The samples for each depth were bulked, mixed and analysed separately. Soils were air dried and sieved through a 2 mm sieve and analysed for pH, texture, total and mineral N, Olsen P and organic C (Table 1). Aerobically composted manure was collected from one source (Matopos Research Institute's Beef Production Section) to avoid variability. The manure was dug out from the kraals two months prior to application. Manure samples were analysed for total C, N and P using the modified Walkley-Black method with external heating, micro-Kjeldahl and the modified Olsen methods respectively (Anderson and Ingram, 1993). The manure contained 199.0 g C kg^{-1}, 9.8 g N kg^{-1} and 2.6 g P kg^{-1} of manure in 2012/2013; 201.1 g C kg^{-1}, 9.5 g N kg^{-1} and 2.7 g P kg^{-1} of manure in 2013/2014 and 196.0 g C kg^{-1}, 10.0 g N kg^{-1} and 2.6 g P kg^{-1} of manure in 2014/15.

2.5.1. N mineralisation measurements

Detailed field measurements of inorganic N dynamics were made using in-situ incubation of undisturbed soil cores (Anderson and Ingram, 1993; Murwira and Kirchmann, 1993; Raison et al., 1987) throughout the 2013/14 growing season. Six tubes (0.35 m long with an internal diameter of 5 cm) were inserted randomly in each plot, soon after land preparation, to a depth of 0.30 m. Three of the tubes were removed immediately and the soil bulked for each plot. Initial mineral N (NH_4^+ and NO_3^-) was determined from these samples. At the surface, the tubes were covered with a polyethylene sheet to prevent water from entering. The polythene sheets were removed every morning for aeration. These tubes were removed and replaced at four week intervals (days 28, 56, 84 and 112 after planting) until harvesting. N was extracted from the soil samples by shaking the field fresh sample in 0.5 M K_2SO_4 and the NH_4^+-N and NO_3^--N content was determined using methods described in Anderson and Ingram (1993). The net amount of mineralised N was calculated as the difference in mineral N between two points in time ($time_{i+1}$–$time_i$).

2.5.2. Plant samples and crop yield

At harvesting maize grain and stover (above-ground biomass minus grain) yields were determined from net plots measuring 4.5 m × 3 m. Grain and stover samples were subsampled and grain yields were adjusted to 12% moisture content. Plant samples were collected at four-week intervals (28 days) from planting until harvest in the 2013/14 season and at harvest at the end of every season. The plant samples were dried at 70 °C for 48 h and analysed for total N content (Bremner and Mulvaney, 1982) to calculate aboveground N uptake. The apparent N recovery (ANR) was calculated as follows:

$$ANR = \frac{Nuptake_F - Nuptake_C}{FertilizerNapplied} X100\%$$

The grain yields were used to calculate agronomic N efficiency (AE) as follows:

$$AE = \frac{Grainyield_F - Grainyield_C}{FertilizerNapplied} kggrainkg^{-1}N$$

where F and C denote "fertilised crop" and "unfertilised control" respectively (Mengel et al., 2001)

2.6. Statistical analysis

All parameters were tested for normality and found to be normally distributed using the Shapiro–Wilk W test (Shapiro and Wilk, 1965). Soil chemical characteristics were square root transformed to homogenise variances (Gomez and Gomez, 1984). Analysis of variance was conducted on the soil N mineralisation, N uptake, ANR, AE, grain and stover yield. The means of the treatments were separated by least significant difference (LSD) at 5% level of significance. All analyses were conducted using Genstat 14th Edition (VSN, 2011).

3. Results

3.1. Rainfall distribution

Rainfall amount, distribution and intensity were erratic and highly variable across the three seasons (Fig. 1). Severe mid-season dry spells characterised the first (2012/13) and third (2014/15) seasons. The first and third seasons received rainfall totals of 272 and 432 mm that were 54 and 27% lower than the long term average for the site (590 mm) respectively and were also below the lower limit (450 mm per annum) for the agro-ecological region. Both seasons were classified as droughts and the water-limited crop yield potential was negatively affected. In the second season

Table 1
Selected soil characteristics of the study site in Nqindi ward, Matobo district, south-west Zimbabwe.

Depth (cm)	pH ($CaCl_2$)	Total N ($g\,kg^{-1}$)	Organic Carbon ($g\,kg^{-1}$)	C:N ratio	Mineral N ($kg\,ha^{-1}$)	Olsen P ($mg\,kg^{-1}$)	Particle size analysis		
							% Sand	%Silt	%Clay
0–10	4.7	0.51	6.6	13.2	23.3	11.1	84	16	0
10–20	4.7	0.40	4.2	10.5	26.4	5.5	90	10	0
20–30	4.6	0.30	3.5	11.7	33.9	2.6	90	10	0
30–40	4.8	0.30	2.5	8.3	15.7	1.3	88	10	2
40–50	4.8	0.20	1.4	7.0	6.9	ND*	90	10	0
50–60	4.8	0.30	1.1	3.7	11.3	ND	94	6	0
60–70	4.9	0.20	0.7	3.5	15.0	ND	90	10	0
70–80	5.0	0.18	0.5	3.1	21.4	ND	92	8	0
80–90	5.1	0.08	0.3	3.8	11.3	ND	92	8	0
90–100	5.0	0.08	0.3	3.8	16.9	ND	86	14	0

ND – not detected.

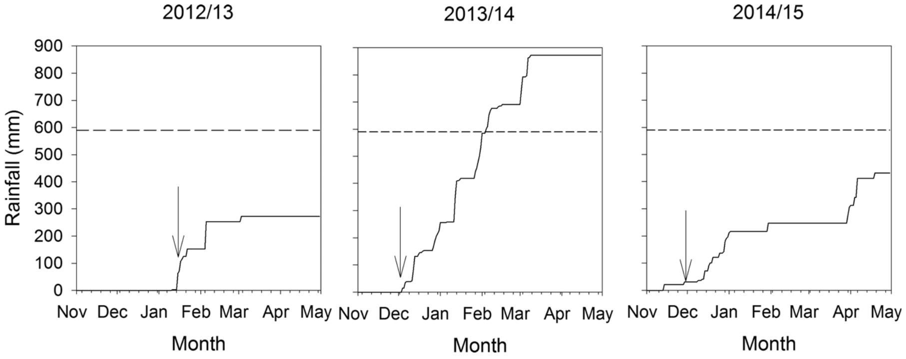

Fig. 1. Cumulative rainfall (a–c) in Nqindi ward, Matobo district, Zimbabwe from the 2012/13–2014/15. The dashed line (a–c) is the long term seasonal average for the region. The solid arrows show the planting date for maize.

(2013/14), the rainfall total of 872 mm exceeded the site average by 48% and several high intensity storms resulted in intermittent waterlogging at the study site.

3.2. Mineral N, N uptake, apparent N recovery and agronomic N efficiency

3.2.1. Seasonal mineral N dynamics and N uptake

There was an initial increase in mineral N in the first 28 days after planting, mineralisation then stabilized until day 84 (vegetative and reproductive stages) and then increased until harvesting (maturity stage) (Fig. 2). N mineralised during the growing season represented 0.71–2.3% of the total N pool in the 0–0.3 m soil depth. Tillage and fertility amendments had a significant effect on N mineralisation ($P < 0.05$) throughout the season. The plough tillage resulted in more N mineralisation than the ripper tillage by 4–19 kg N ha^{-1}. There was also more mineralisation where N was applied either as mineral fertiliser or cattle manure compared with the control (0N) which generally had the lowest cumulative N mineralisation. Except when ploughing and mulching were applied, the highest cumulative N mineralisation was obtained with the 40N treatment. Mulching on its own generally had no significant effect ($P > 0.05$) on N mineralisation but its interactions with tillage and fertility amendments significantly influenced N mineralisation. When mulch was ploughed in, there was a decrease in mineralisation compared with ploughing without mulch by 8–15 kg N ha^{-1} (13–40%) across fertility amendment treatments, indicating N immobilisation. Under the ripper tillage, however, mulching resulted in a 16–100% higher mineralisation compared to no mulching. N mineralisation followed the trend plough (no mulch) > ripper + mulch > plough + mulch > ripper (no mulch) regardless of fertility amendment.

N uptake generally increased until day 84 when total plant N levelled off. Maize that received N fertility amendments had significantly greater N uptake ($P < 0.05$) throughout the season than the 0N control (Fig. 2). Except for the plough + mulch treatment, N uptake was highest in the manure treatments. Tillage had a significant effect ($P < 0.05$) on total N uptake at day 84 and day 112. Maize N uptake under the ripper tillage was 13–23% lower than the plough tillage. Mulching had a significant effect on N uptake by maize ($P < 0.05$). Incorporation of mulch under the plough tillage resulted in significantly lower N uptake ($P < 0.05$) by 5–19% when compared with plough without mulch. N uptake and followed the trend plough (no mulch) >ripper + mulch > ripper (no

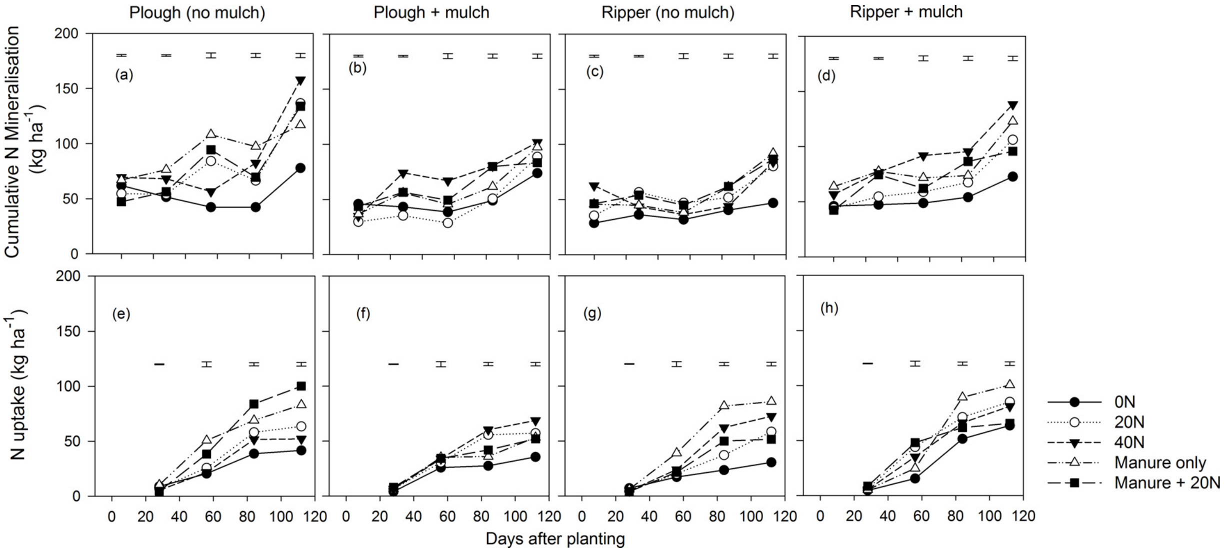

Fig. 2. Cumulative N Mineralisation estimated from the in situ incubation technique (0–30 cm) (a–d) and Net N uptake by maize (above ground parts) (e–h) in the 2013/14 season influenced by soil fertility amendments under plough only (a and e), plough + mulch (b and f), ripper only (c and g) and ripper + mulch (d and h) on a sandy soil in Nqindi ward, Matobo district, south-west Zimbabwe. Bars represent standard errors of the difference of the means for the effect of the interaction of tillage, mulch and fertility amendment on cumulative N mineralisation and N uptake on days 28, 56, 84 and 112.

mulch) >plough + mulch. The effect of the top dressing N fertiliser, applied at 48 days after planting, was not apparent in both the cumulative N mineralisation and the N uptake.

3.2.2. Apparent N recovery (ANR) and agronomic N efficiency (AE)

The ANR and AE were very variable across the three seasons and treatments (Table 2). Only fertility amendments had a significant effect ($P < 0.05$) on both the ANR and AE in the first season and on ANR in the second season. In the second season, fertility amendment significantly affected ANR with recovery highest under the 20N treatment regardless of tillage and mulch application. Tillage and mulching had no significant effect on both ANR and AE in all three seasons. The interactions of mulch and fertility amendments and of all three treatments (tillage, mulch and fertility amendments) had significant effects on ANR in the second and third seasons although these did not follow similar trends between the two seasons. ANR was highest under the ripper (no mulch) +20 N fertility treatment in the second season whilst in the third season, ANR was highest the plough + mulch + manure only. The third season had the poorest and highly variable ANR and AE. All treatments had ANR in the range 7.0–40.4% and averaged 15%. This season had the least AE that ranged (−4.7) −1.3 kg grain kg^{-1} N and averaged (−0.16) kg grain kg^{-1} N. There were, however, no individual treatment effects but interaction effects of mulch and fertility amendments and tillage, mulch and fertility amendments on N recovered by the maize crop in the third season. There were no significant effects of tillage, mulch, fertility amendments and their interactions on AE in the second and third seasons.

3.3. Maize yields in response to tillage, mulch and fertility amendment application

Grain yields in the first season were low and in the range 105–720 kg ha^{-1} under both tillage treatments and across all fertility amendments (Fig. 3). In this season, ploughing gave higher grain (200–720 kg ha^{-1}) and stover yields (1500–2100 kg ha^{-1}) compared with ripping (105–454 kg ha^{-1} grain and 860–1500 kg ha^{-1} stover) although not significant for grain ($P < 0.05$). The harvest indices, although not significant, were generally higher under the plough tillage compared with ripping by 1–10%. There were significant differences in grain yields resulting from the application of different fertility amendments. Both manure treatments resulted in low grain yields under both tillage treatments. The highest grain yields were obtained when mineral N fertiliser was added (both the 20 N and 40 N treatments). The effects of tillage, mulch, fertility amendments and their interactions on stover yields and the harvest indices were no significant.

Although there were no significant differences in grain and stover yields resulting from tillage, ripping, in general, significantly depressed grain yields by 4–60% in the second season when compared with ploughing. The effect of mulch only on grain and stover yields was not significant ($P < 0.05$). Mulching significantly increased grain yields in all fertility treatments under the ripper tillage except for the 0 N and manure only treatments. However, mulching reduced grain yields when combined with ploughing under the 20 N, 40 N and manure + 20 N fertility treatments by between 2 and 60%. In the second season, fertility amendments alone had a significant effect on grain and stover yields. Manure application gave the highest grain yields under the ripper tillage, both with and without mulch (averaging 1850 and 2228 kg ha^{-1} respectively). Under the plough tillage, the 40 N treatment gave the highest grain yields of 1985 kg ha^{-1} on average whilst the manure treatments resulted in the highest stover yields. The harvest indices, were not significant for tillage, mulch, fertility amendments and their interactions

In the third season, the effects of tillage, mulch and fertility amendment treatment on grain and stover yields and harvest indices were not significant. Grain and stover yields were generally poor due to low and poorly distributed rainfall. Grain yields were in the range 200–270 kg ha^{-1}, whilst stover yields 400–900 kg ha^{-1}.

Table 2
Effect of tillage, mulching and fertility amendment on apparent N recovery and agronomic N use efficiency over three seasons (2012/13–2014/15) in Nqindi ward, Matobo district, south-west Zimbabwe.

Tillage	Mulch treatment	Fertility treatment	% Apparent N recovery			Agronomic N efficiency (kg grain kg^{-1} N)		
			2012/13	2013/14	2014/15	2012/13	2013/14	2014/15
Plough	No mulch	20N	67.3	109.2	12.2	19.9	19.2	0.5
		40N	19.4	26.1	15.1	5.7	2.0	0.7
		Manure only	22.0	83.6	14.2	−1.1	27.9	1.1
		Manure + 20N	16.6	83.4	11.5	−1.9	21.6	−0.6
	Mulch	20N	–	107.7	7.8	–	21.3	−4.7
		40N	–	82.8	7.1	–	25.5	2.1
		Manure only	–	35.4	36.4	–	27.7	−1.6
		Manure + 20N	–	23.4	14.7	–	8.6	−0.7
Ripping	No mulch	20 N	42.9	136.1	5.6	8.9	3.6	−1.7
		40 N	8.3	104.8	5.9	8.7	4.8	0.5
		Manure only	13.9	110.1	18.9	2.9	12.4	−0.2
		Manure + 20 N	12.2	59.9	16.2	−0.2	13.2	−0.7
	Mulch	20 N	–	107.2	2.6	–	8.4	0.3
		40 N	–	43.6	26.7	–	44.2	0.7
		Manure only	–	73.7	23.8	–	18.8	1.3
		Manure + 20N	–	2.4	8.0	–	18.1	0.4
Factor			P value SED	P value SED	P value SED	P value SED	P value SED	P value SED
Tillage type			0.463 13.37	0.199 2.34	0.534 8.49	0.90 3.96	0.804 3.61	0.574 0.72
Mulch			–	0.348 18.19	0.776 4.55	–	0.305 11.28	0.881 1.53
Fertility amendment			0.007[*] 10.95	**0.014** 16.21	0.165 5.95	<**0.01** 2.72	0.181 8.53	0.041 0.79
Tillage x Mulch			–	0.945 18.33	0.271 9.63	–	0.962 11.85	0.404 1.69
Tillage x Fertility amendment			0.813 18.93	0.496 19.99	0.095 11.19	0.056 5.25	0.588 11.38	0.569 1.24
Mulch x Fertility			–	<**0.001** 26.92	**0.031** 8.59	–	0.159 15.62	0.441 1.83
Tillage x Mulch x Fertility			–	<**0.001** 33.54	**0.015** 14.11	–	0.378 19.32	0.074 2.21

[*] P values in bold signify significant factors.

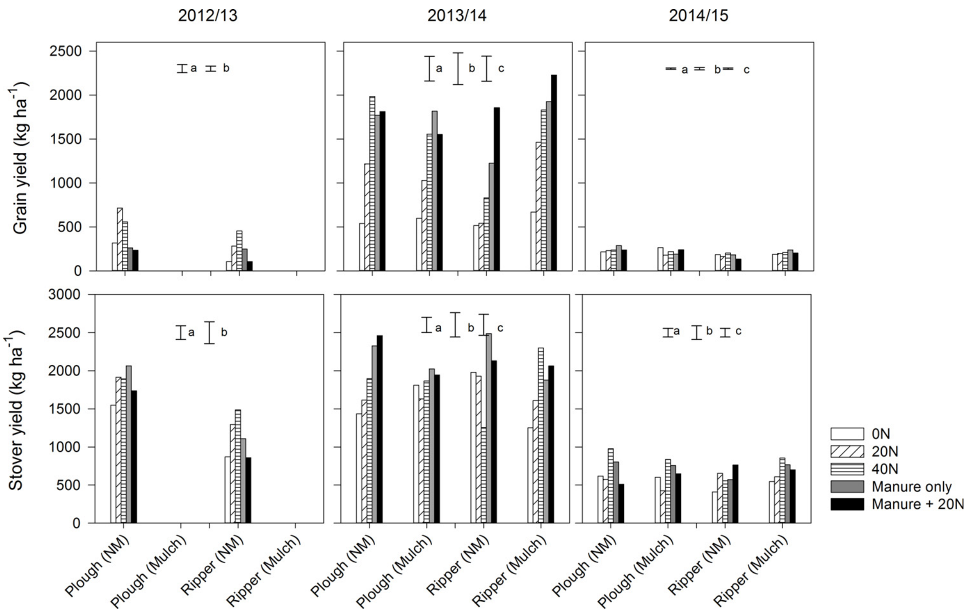

Fig. 3. Maize grain and stover yields in Nqindi ward, Matobo district (2012/13-2014/15 season). Bars represent standard errors of the difference of the means for factors (a) Tillage, (b) Fertility amendment and (c) Mulching.

The grain yields followed the same trends as in the previous seasons.

4. Discussion

4.1. N mineralisation patterns, uptake and recovery

In general, the Conservation Agriculture principles of minimum soil disturbance and maintenance of a permanent soil cover (mulch) resulted in reduced soil mineral N availability for crop uptake and ultimately low yields from a poor fertility soil in semi-arid Zimbabwe. Ploughing enhances the mineralisation of organic matter in the soil by exposing previously unexposed soil surfaces to attack by microbes and by providing the latter with new sources of energy (Peigné et al., 2007). Compared with ploughing, ripper tillage causes less soil disturbance and exposes the soil organic matter less to the climatic elements and soil microbes, with slower mineralisation as a result. Our results concur with studies that reported slower mineralisation of organic matter under reduced tillage compared with conventional tillage because of less topsoil disturbance (Bationo et al., 2007; Chivenge et al., 2007). This low mineralisation associated with the ripper tillage resulted in low N uptake and consequently decreased grain yields (in the second season) when compared with the plough tillage when no mulch was applied under both tillage treatments.

When mulch was ploughed in, mineralisation was slowed compared with no mulch application. Soil inorganic N may have been immobilised during the decomposition of the applied mulch with a large C:N ratio averaging 53:1 whilst the soil's C:N ratio averaged 12:1. The C:N ratio of crop residues is a good indicator of whether mineralisation or immobilisation will dominate during decomposition. N release patterns are regulated by the initial composition of the crop residues and the stoichiometric requirements of the decomposers (Manzoni et al., 2008; Palm et al., 2001). Mineral fertilisers provide a ready source of nutrients and may stimulate decomposition of cereal stover (Sakala et al., 2000).

We observed substantial N mineralisation at the end of the season, which produced a pool of mineral N that may be held in the soil over the dry season due to the absence of leaching and reduced N uptake by plants (Rasouli et al., 2014). Perturbation by tillage further stimulates a flush of N mineralisation with the start of the rains. Crops are not able to store surplus N to improve yields and grain quality in later vegetative stages (Verhulst et al., 2014). This implies that the N mineralised at the end of the season, as well as that which becomes available through the "Birch effect", may well be lost due to the first rains ahead of planting or before the next crop is established and growing actively. In their study, (Chikowo et al., 2003) concluded that there is an inherent problem in managing N originating from mineralisation as it accumulates at the beginning of the season, well ahead of peak demand and root development by crops, and is susceptible to leaching.

There was a decrease in observed mineralisation in the critical vegetative stage. For semi-arid regions, (Piha, 1993) suggested split applications of N fertiliser at rates based on future expected rainfall to maximise fertiliser use and recovery efficiency. In our experiment, we applied fertiliser at planting and at 48 days after planting. The second N application did not result in a significant observed increase in N availability. It may have been because at the start of the incubation experiment, the mineral N was increased by the basal fertiliser application such that a further addition in mineral N later on in the season may not have been apparent. The success of split N application may depend on the number of fertiliser applications and their timing and quantities, on weather conditions and on the amount of available soil mineral N (Piha, 1993; Verhulst et al., 2014). In our experiment, the timing of the second application in the second season was affected by water-logging. We had to wait until all the water had infiltrated before we could apply the top dressing fertiliser. The second application coincided with the maize flowering stage, a critical growth stage, which may have contributed to the higher yields observed in this season in conjunction with the higher rainfall.

The N recovery and agronomic N efficiency by maize were highly variable over the three seasons, which reflects the uncertainty complicating farmers' decision making. Nitrogen recovery by maize in the manure treatments was generally poor in the first season, though greater in subsequent seasons, as reported earlier (Nyamangara et al., 2004). The authors attributed the slow N mineralisation from manure to the C and N stabilisation which occurred during aerobic decomposition of the manure during storage. N recovery from the manure + 20 N treatment was very high in the second season, which is attributed to residual fertility from the previous season, which was very dry. Farmers should use resources available to them as fertility amendments to supply N to the maize cropping system, either as organic manures or as mineral fertilisers. However, manure application is a preserve of cattle owners and mineral fertilisers remain unaffordable to most smallholder farmers in SSA including Zimbabwe (Chianu et al., 2012; Mazvimavi and Twomlow, 2009; Mtambanengwe and Mapfumo, 2005).

Maize grain and stover yields were affected by the quality of the seasons in terms of rainfall amount and seasonal distribution. Two of the three seasons (the first and third) in which the experiment was conducted were classified as droughts, negatively affecting yields. Low rainfall and poor rainfall distribution are a characteristic of and major challenges to crop production in semi-arid areas of southern Africa (Nyamangara et al., 2014). Thierfelder et al. (2013) reported that CA systems showed great potential in mitigating the effects of seasonal dry-spells, as the high infiltration rates in CA would lead to greater soil moisture availability for crops. This was, however, not the case in our experiment (with a mulch cover of 0 and 2–4 t ha^{-1} in the first and third seasons respectively) as the two seasons were characterised by long dry spells midway through the season lasting more than 21 days.

4.2. Methodological limitations of the in situ incubation method

One limitation of the *in situ* method in estimating N mineralisation is that in replacing soil cores into the soil, maize roots may have been severed and retained within the tubes. These roots may have immobilised N during their decay leading to an underestimation of N mineralisation (Raison et al., 1987). Conversely N may have been released during their decomposition leading to an overestimation of N mineralisation (Khanna and Raison, 2013). Furthermore, *in situ* core methods promote the accumulation of $NH_4^+{-}N$ (by preventing uptake). The $NH_4^+{-}N$ may be nitrified leading to accumulation of $NO_3^-{-}N$ which may increase denitrification (Raison et al., 1987). We measured mineralisation in the top 0.3 m which is the plough layer although maize roots explore deeper soil horizons. Hence our N mineralisation results may not account for all of the N available to the crop. Nevertheless, the *in situ* incubation method gave useful insights into the differences among treatments (Fig. 2).

4.3. Input access: drawbacks of smallholder farmers

The principles of CA minimum soil disturbance and maintenance of a mulch resulted in reduced mineralisation (Fig. 2) resulting in low yields whilst a combination of the principles resulted in high mineralisation and yields comparable to conventional plough minus mulch (Fig. 3). Fertiliser application resulted in yield benefits regardless of tillage or mulch application particularly when moisture was not limiting. The potential benefits of the tillage, mulch application and fertility amendment application on crop productivity and soil N dynamics are related to the management intensity individual farmers can achieve. The use of mineral fertilisers is key to production yet their widespread use by smallholder farmers remains low as availability in rural areas remains a key constraint to their use as well as their cost remains prohibitive. With over 40% of households in semi-arid Zimbabwe having access to draught animals (ZimVac, 2012), the use of the ripper may provide a solution to curb the chronic labour demand associated with land preparation in manual forms of in smallholder communities. However, only a few equipment manufacturers have been producing ripper tine attachments for the mouldboard plough and these require pre-financing for production. There are poor market linkages between smallholder farmers market linkages between smallholder farmers and local agro dealers, and agro-dealers and input suppliers. At present, input producers are unwilling to provide fertilisers or equipment such as rippers on credit to local farmers in dry areas as risks of crop failure from the erratic rainfall pattern are high. The high likelihood of crop failure from the poor rainfall in the semi-arid areas is in itself a disincentive for farmers to the purchase and use of fertilisers. Access to inputs still remains a challenge especially to poor farmers who are often concerned with meeting the immediate household food requirements over the improvement and maintenance of soil fertility on these sandy soils important in the long term.

5. Conclusions

We observed that mineralisation, N uptake and crop yields were stimulated under plough tillage compared with the ripper tillage. When mulch was added together with plough tillage, the mineralisation of N, crop N uptake and maize yields were decreased compared with no mulch application under the same tillage. When combined together, following two principles of CA, the ripper tillage and mulch application did not reduce mineralisation and resulted in yields comparable to those obtained under the plough tillage without mulch. Nitrogen containing fertiliser and manure resulted in more available N for the crop and increased grain yields. We conclude that nutrient inputs are key to ensuring production in the infertile, sandy soils predominant in semi-arid regions of southern Africa.

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