SAJEST **OPEN ACCESS**

http://dx.doi.org/10.4314/sajest.v5i1.39821 /sajest.2020.001

Original Article

Influence of planting basins on selected soil quality parameters and sorghum yield along an agro-ecological gradient in South Eastern Zimbabwe.

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Received: October 2018 / Accepted: 20 January 2020
_ Bindura University Press, Bindura 2020

Abstract

Planting basins are an important soil and water conservation technology. This study evaluated the effects of basins on soil organic carbon (SOC) stocks, aggregate stability (Ima), bulk density, soil moisture retention and sorghum yield in agro-ecological regions III, IV and V of Chipinge district. The experiment consisted of three treatments; namely planting basins (basins) with goat manure and inorganic fertilizer application, hand hoeing with similar fertility amendments (FP+) and hand hoeing without fertility amendments (FP). It was hypothesized that planting basins with fertility amendments would improve the selected soil quality parameters and sorghum yield. Only planting basins significantly ($p<0.05$) improved soil quality parameters in the 0-15 cm depth and bulk density, Ima, SOC stocks ranged from 1356 to 1451 kg/m^3; 314 to 450 and 14.18 to 25.55 Mg ha^{-1} respectively.

Planting basins significantly increased ($p<0.05$) sorghum yield relative to hand-hoeing practices (FP+ and FP) with average grain yield of 2.68, 1.72 and 1.32 t ha^{-1} in agro-ecological regions III, IV and V, respectively. When compared to FP+ and FP, basins increased grain yield by >130% in all the 3 agro-ecological regions. The hypothesis was accepted and it was concluded that basins improve soil properties and sorghum grain yield in agro-ecological regions III, IV and V. Considering the soil and crop productivity benefits highlighted in this study, there is a strong justification for the widespread promotion and adoption of planting basins in semi-arid agro-ecological regions of Zimbabwe.

Key words

Planting basins, soil and water conservation, soil quality, sorghum, agro-ecological regions

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1. Introduction

Conventional farming systems based on extensive tillage results in a decrease in soil organic matter and are not appropriate for tropical environments (Thierfelder and Wall, 2010; Verhulst et al., 2010).Conventional tillage methods promote soil structure destruction through splitting of aggregates, increased organic matter mineralization and hard-pan creation (Harford et al., 2009), thereby negatively influencing soil quality dynamics (Nyamangara et al., 2014). Given the high levels of soil degradation in smallholder farming systems (The Montpellier Panel, 2013), there is need to improve soil quality through eco-friendly site specific technologies such as planting basins (basins).

Planting basins have been promoted as conservation agriculture (CA) in Zimbabwe and other semi-arid regions and it is based on the creation of permanent planting basins (Nyamangara et al., 2014), which enhance water harvesting and precision application of fertility amendments (Andersson and Giller, 2012; Nyamangara et al., 2013a). Planting basins are a modification of the traditional southern Africa pit system and are also a variation of the West Africa's *zai pit* system (Twomlow et al., 2008). Many different practices tend to be lumped under CA as there is confusion as to what is CA and what is not (Giller et al., 2009). However, under critical evaluation, planting basins alone do not fit into CA principles (Andersson and Giller, 2012; Andersson and D'Souza, 2014), especially when not accompanied by residue retention and crop rotation. Planting basins are however a crucial soil and water conservation technology (Giller et al., 2009) as practices in agro-ecological regions of limited crop water availability and low soil fertility should focus on water harvesting, water use efficiency and soil fertility management (Rumley and Ong, 2007). Trying to put planting basins under CA has resulted in many different names, such as, precision CA (Twomlow et al., 2008; Andersson and D'Souza, 2014), basin-based CA (Nyamangara et al., 2014), hand-hoe based CA (Nyamangara et al., 2013) and conservation farming (Twomlow et al., 2008; Andersson and D'Souza, 2014).

Planting basins are an agro-ecosystems management approach for improved and sustained productivity, increased profits and food security whilst preserving and enhancing the resource base and the environment (Corsi et al., 2012). Planting basins aim to restore degraded lands, preserve fertile lands and increase resilience of agricultural production systems, especially from the threat of climate change (Marongwe et al., 2012). There is a critical need to better understand how basins affect soil quality dynamics in agricultural systems of sub-Saharan Africa (SSA) (Stevenson et al., 2014). This is important in sustaining higher productivity since the crop genetic potential cannot be realized unless the soil physical environment is maintained at optimum levels (Bandyopadhyay et al., 2009). Soil physical properties, represented by such indicators as porosity and bulk density, have been reported as major constraints to rain-fed crop production in Zimbabwe (Wilcocks and Cornish, 1988; Nyamangara et al., 2001).

Cultural practices in agro-ecological regions of limited crop water availability should focus more on water harvesting, water use efficiency and soil fertility than on the maintenance of permanent soil cover (Rumley and Ong, 2007). Consequently, the most common soil and water conservation practice being promoted in southern Africa is based on the creation of permanent planting basins (Nyamangara et al., 2014), which enhance water harvesting and precision application of fertility amendments (Andersson and Giller, 2012; Nyamangara et al., 2013). Planting basins are suitable for semi-arid regions and hence the need to document their effects on soil quality in various agro-ecological regions of the semi-arid zones.

Soil quality is not only affected by management practices such as tillage but, also by environmental factors such as temperature and precipitation (Andrews et al., 2004). In fact, soil quality changes due to tillage is site-specific and depends on soil type, cropping systems, climate, fertilizer application and management practices (Rahman et al., 2008). Most smallholder farms in Zimbabwe are dominated by sandy soils which cover over two thirds of the total area of the country (Nyamapfene, 1991) and has limited capacity to support crop production (Nyamangara et al., 2013) due to inherent infertility and low water holding capacity. Most smallholder farms are located in agro-ecological regions III, IV and V and it is crucial to determine planting basins benefits in these regions.

Planting basins have been developed to try and curb land degradation problems, and can effectively decrease soil erosion, slowing down chemical, biological and physical soil degradation (Thierfelder and Wall, 2012), however their effect on soil quality has not been extensively studied in SSA (Haggblade and Tembo, 2003; Hobbs, 2007), especially under smallholder farmer conditions (Giller et al., 2009; Giller et al., 2011). Studies in southern Africa (Gwenzi et al., 2009; Thierfelder and Wall, 2009; Ngwira et al., 2012; Nyamadzawo et al., 2012) have shown soil fertility benefits of basins when compared to conventional tillage as well as increased infiltration rates and reduced runoff (Nyagumbo, 2002). Most of these documented benefits of basins have been reported from researcher managed trials, with few farmer managed trials (Nyamangara et al., 2014). Moreover, basin-induced soil quality improvements have not been conclusive (Giller et al., 2009). Therefore, more research is needed under various agro-ecological regions to document actual benefits realized from the planting basins technology that is practiced under smallholder farmer conditions.

An international non-governmental organization (NGO), *Action Contre la Faim* (ACF) introduced planting basins in 2010 under the Livelihood for Improved Nutrition (LIFIN) project in Chipinge district of Zimbabwe. This study evaluated the effects of basins promoted under the LIFIN project after three consecutive growing seasons, on soil organic carbon stocks, bulk density, aggregate stability, soil moisture retention and sorghum grain yield in agro-ecological regions III, IV and IV in Chipinge district. The study also assessed the capacity of basins to restore productivity of degraded soils in semi-arid environments. It was hypothesized that basins improve SOC stocks, bulk density, aggregate stability, soil moisture retention and sorghum grain yield along the agro-ecological gradient.

2. Materials and methods

2.1 Study site

The study was conducted in ward 4 of Chipinge district (20^{o} S, 32^{o} E) in south-east Zimbabwe (Figure 1). The ward spans across agro-ecological regions III, IV and V (Figure 1), which are characterized by low, erratic and uni-modal rainfall starting in November and ending in March with high probability of mid-season dry spells, mid-season droughts or full season drought (Vincent et al., 1960). The average annual rainfall is 650 to 800 mm, 450 to 650 mm and less than 450 mm for agro-ecological regions III, IV and V, respectively.

2.2 Selection of the experimental sites

Before the establishment of the experiments, several farmers' fields were surveyed to carefully select fields for experimentation. Fields selected for the study had sandy soils (sand + silt > 80%, and <18% clay), which are representative of a larger area of smallholder farming systems in Chipinge district and in Zimbabwe (Mtambanengwe and Mapfumo, 2005); a gentle slopes (<5%) and similar cropping and management history.

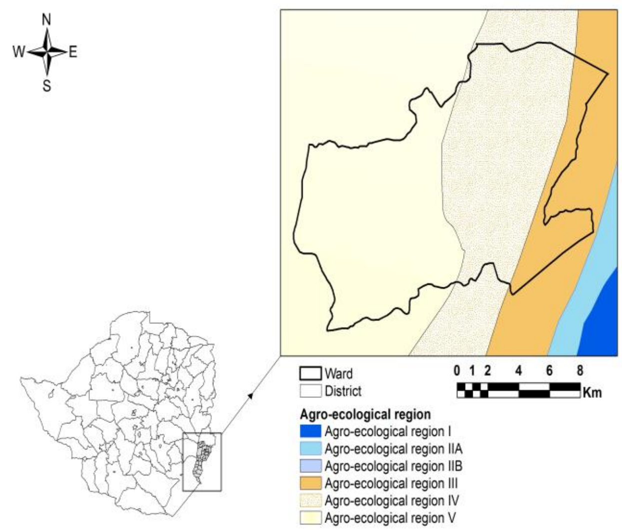

Figure 1: Location of Ward 4 in Chipinge District, Zimbabwe showing the Agro-ecological regions

These factors are the main causes of soil fertility gradients in Zimbabwean farming systems (Carter and Murwira, 1995). Fields where sorghum was produced without any fertility amendments for the previous 5 years were targeted. Fields had to also be at least 0.75 ha to accommodate all the three treatments. A total of eighteen farmers, six farmers in each of the three agro-ecological regions were selected.

2.3 Experimental design and treatments

A randomized complete block design in which a farmer's plot was regarded as a block receiving all the three treatments was used. In a layout with an area of 40 m × 50 m for each of the three treatments, namely planting basins (basins), hand hoeing fertilized at the same rate with basins (FP+) and hand hoeing without fertility amendments (FP) were tested in agro-ecological region III, IV and V. The same fertility amendments rates were maintained for planting basins and FP+ to have a valid comparison (Thierfelder and Wall, 2012). Replication was by farmer and six farmers were selected in each agro-ecological region. Hand hoeing is the common farming practice in semi-arid regions of Chipinge district, where there is shortage of draught power. The farmer digs the soil with the hoe to a shallow depth of about 5 cm thereby removing weeds and mixing the soil. This type of hand hoeing mimics hand hoe weeding and soil is disturbed throughout the field unlike under basins where soil is disturbed only on planting stations during basin preparation and planting. Planting basins were 15 cm long x 15 cm wide x 15 cm deep, spaced at 0.75 m inter-row x 0.75 m in row spacing. The still visible planting basins were merely maintained in subsequent seasons (Nyamangara et al., 2013).

No mulch was applied to the experiment because of unavailability of mulching materials. Sorghum (*Sorghum bicolor cv. Macia*) was used as the test crop, since it is the main crop in these semi-arid regions. Sorghum fertilization was 5.6 N: 4.8 P: 4.6 K kg ha^{-1} in the form of a basal dressing (Compound D) at planting and a top dressing of 27.6 kg N ha^{-1} using ammonium nitrate four weeks after emergence. Goat manure was applied at 7 110 Kg ha^{-1} (400 g per basin whilst it was broadcasted as is the normal practice under FP+). Weeding in all plots was done manually using hand hoes.

2.4 Characterization of soil and goat manure in the three agro-ecological regions

Soil samples were taken from the 0 to 15 cm depth from the selected farmers' fields in the three agro-ecological regions prior to land preparation of the 2010/11 agricultural season. Samples of soil from each farmer were air-dried and ground to pass through a 2 mm sieve prior to analysis for organic carbon using the modified Walkley-Black method, pH using calcium chloride ($CaCl_2$) method, total N and P using the Kjeldhal digestion method (Okalebo et al., 2002). Cation exchange capacity was determined using the ammonium chloride method since pH of soil samples was < 6 (Anderson and Ingram, 1993). Soil texture was determined by the hydrometer method (Okalebo et al., 2002). Goat manure was dug out in September and heaped in the field prior to field manure application. Samples of goat manure from each of the 18 selected farmers were collected from the field heaps during manure application at the beginning of each season. The samples from each farmer were then separately air-dried and ground to pass through a 2 mm sieve prior to analysis for organic carbon, pH, total N and P.

2.5. Soil sampling and analysis for selected soil quality parameters

After three cropping seasons, soon after harvesting in May 2013, composite soil samples consisting of 6 sub-samples per treatment (Nyamangara et al., 2013; Cheesman et al., 2016) were taken using a soil auger at two depth layers (0 to15 cm and 15 to 30 cm). Soil samples were collected close to the planting stations since planting basins technology emphasizes the maintenance of permanent planting positions, making it necessary therefore to determine the soil properties within basins where the crops are nourished from. The soil samples were air-dried and then sieved through a 2 mm sieve before SOC stocks and macro-aggregate stability determination. Bulk density and soil moisture retention were determined from undisturbed core samples from depth ranges of 3 to 10 cm and 16 to 23 cm using 7 cm diameter and 7 cm long stainless steel cylinders (cores).

2.7 Bulk density, soil moisture retention and pore volume

Bulk density was measured using the core method (Okalebo et al., 2002). Soil moisture retention was determined at 5, 10, 33, 100, 200 and 500 kPa suctions (Klute et al., 1986). The tension plate (sand box made of fine sand) method was used for 5 and 10 kPa suctions and the pressure plate method for ≥ 33 kPa suctions but did not get to the permanent wilting point (1 500 kPa) due to faulty equipment. The response of soil structure to different soil management practices is generally expressed at low suctions when assessed by water retention (Sharma and Uehara, 1968; Nyamangara et al., 2014). Therefore, pore volume was calculated as the volume of water draining between 5 and 33 kPa.

2.7. Soil organic carbon stocks

The Modified Walkley-Black method (Okalebo et al., 2002) with external heating at 150 ^{o} C for 30 minutes was used to determine SOC. The volume of soil in the top 15 cm was multiplied by the bulk density of the soil to get the total mass of soil in a hectare

Table 1: Selected soil characteristics in the three agro-ecological regions for the 0-15 cm depth (mean and standard deviation in parentheses; n = 6).

Agro-ecological region	Clay (%)	Silt (%)	Sand (%)	pH ($CaCl_2$)	Total N (%)	Total P (%)	SOC (%)	CEC ($cmol_c$ kg^{-1})
III	16 (0.08)	14 (0.04)	70 (0.08)	5.18 (0.05)	0.063 (0.001)	0.048 (0.001)	0.45 (0.008)	13.35 (0.05)
IV	11 (0.05)	12 (0.08)	77 (0.08)	5.48 (0.05)	0.039 (0.001)	0.035 (0.001)	0.34 (0.008)	9.43 (0.05)
V	9 (0.05)	7 (0.13)	84 (0.05)	5.55 (0.05)	0.025 (0.001)	0.027 (0.001)	0.31 (0.08)	8.85 (0.05)

Table 2: Selected characteristics of goat manure used in the study (mean and standard deviation in parentheses; n=18)

Agro-ecological region	Total (N %)	Total P (%)	OC (%)	pH (H_2O)	C/N ratio (%)
III	1.60 (0.02)	0.86 (0.05)	19.28 (0.03)	7.6 (0.1)	11.54
IV	1.57 (0.03)	0.83 (0.04)	19.26 (0.04)	7.7 (0.1)	12.27
V	1.54 (0.05)	0.80 (0.05)	19.24 (0.03)	7.8 (0.1)	12.49

(Nyamangara et al., 2014). The total mass of soil in the 0-15 cm and 15-30 cm depth was then multiplied by SOC content to calculate SOC stocks.

2.8 Aggregate stability

Macro-aggregate stability was determined using a test by Barthes and Rose (1996). Four grams of air dried soil, passed through a 2 mm sieve were immersed in de-ionized water for 30 minutes. The soil was then wet-sieved for 6 minutes, through a 0.2 mm sieve in a water tank using a motor-driven holder with a stroke length of 1.3 cm and immersion frequency of 35 cycles per minute. The remaining soil (> 0.2 mm) on sieves was oven-dried (105 ^{o} C) for 24 hours and weighed. The aggregate fraction > 0.2 mm (F > 0.2 mm) was then dispersed by sieving in 0.05 M NaOH solution for 30 minutes using the same water tank. The coarse sand fraction (CS) was then obtained after oven-drying at 105 ^{o} C for 24 hours. Macro-aggregate stability, defined as the stable macro-aggregate index (Ima), was then calculated using equation 1 (Barthès et al., 1999):

$$\text{Ima} = \frac{1000\,(F > 0.2 - CS)}{gDM - CS} \qquad (1)$$

Where; DM is the dry matter content of the sample, CS is the coarse sand; g is the mass of sample and F > 0.2 is the fraction of soil on 0.2 mm sieve after sieving.

2.9 Sorghum yield determination

Sorghum grain yield was determined in the 2010/11, 2011/12 and 2012/13 seasons from all the eighteen selected farmers in the three agro-ecological regions. A 3 m x 3 m net plot was harvested in each treatment for sorghum grain yield measurements at the end of every season. The sorghum heads were sun dried in perforated polythene bags over 10 days, threshed and mass of harvested grain yield determined using a digital scale. The grain moisture content was then determined and averaged for three sub-samples per treatment plot using a John Deere SW moisture tester. The fresh grain weight was standardized by adjusting to 12.5% moisture content, as locally recommended by the Grain Marketing Board in Zimbabwe, by calculating the equivalent mass at standard moisture using equation 2:

$$m_{std} = \frac{mf\,(100 - M\%)}{100 - 12.5\%} \qquad (2)$$

Where; m_{std} - *the grain mass at 12.5 % moisture content*; *mf - the measured mass of grain at M % moisture content on a wet basis at harvesting*.

2.10 Statistical analyses

Analysis of variance (ANOVA) for SOC stocks, bulk density, aggregate stability, soil moisture retention, pore volume and sorghum grain yield was generated using Genstat 14th Edition (VSN International, 2011), for each agro-ecological region. Combined analysis of variance for the three agro-ecological regions for each soil quality parameter and sorghum grain yield was also done to test for interactions between agro-ecological region and tillage treatments. Least significant differences ($p < 0.05$) were used to differentiate between statistically different means.

3. Results

3.1 Characteristics of soil and goat manure in the three agro-ecological regions

The soils were sandy loam, and the average nutrient contents were 0.043% for N, 0.037% for P and 0.367% for SOC (Table 1). Clay content, soil organic carbon, CEC, total N, and total P all decreased from agro-ecological region III to V (Table 1). The goat manure showed no significant difference over the 3 seasons and therefore, mean results were presented (Table 2). The goat manure used was strongly alkaline and relatively rich in measured nutrients with an average C: N ratio of 12 (Table 2).

3.2 Soil organic carbon stocks

Planting basins significantly increased SOC stocks ($p<0.001$) in the 0-15 cm depth in agro-ecological regions III, IV and V (Figure 2). However, there was no significant difference in SOC stocks at 15-30 cm depth (Figure 2) and between the two farmer practice treatments (FP+ and FP) at both depths in all the three agro-ecological regions (Figure 2). Soil organic carbon decreased with depth across all treatments in all the three agro-ecological regions (Figure 2).

The average SOC stocks were 25.55, 17.98 and 14.18 Mg ha^{-1} in agro-ecological regions III, IV and V, respectively in the 0-15 cm depth within planting basins. In FP+, the average SOC stocks were 9.51, 7.51 and 7.43 Mg ha^{-1} in agro-ecological regions III, IV and V, respectively. Similarly, the average SOC stocks were 9.16, 7.51 and 7.11 Mg ha^{-1} in agro-ecological regions III, IV and V, respectively under FP. When compared to the conventional farmer practice (FP), basins increased SOC stocks by 179%, 151% and 97% in agro-ecological regions III, IV and V, respectively. Moreover, agro-ecological region and planting basins interaction effects were significant ($p<0.05$) only in the 0-15 cm depth.

3.3 Macro-aggregate stability

In the 0-15 cm depth, aggregate stability was significantly ($p<0.05$) increased within planting basins (Figure 3) when compared to hand hoeing, however, there was no significant difference between the two farmer practice treatments. There was no significant ($p>0.05$) treatment effect in the 15-30 cm depth across all the three agro-ecological regions (Figure 3). Macro-aggregate stability index (Ima) average in the 0-15 cm depth under planting basins treatment was 450, 385 and 314 in agro-ecological regions III, IV and V, respectively. The average macro-aggregation index (Ima) under FP+ in the 0-15 cm depth was 170, 110 and 92 in agro-ecological regions III, IV and V, respectively. Similarly, it was 155, 107 and 89 in agro-ecological regions III, IV and V, respectively under FP. Agro-ecological region and tillage interaction effects were significant ($p<0.05$) only in the top 15 cm. When compared to FP, planting basins increased macro-aggregate stability of planting basins soils by 164.5%, 249.0% and 242.7% in agro-ecological regions III, IV and V, respectively.

3.4 Bulk Density

Bulk density significantly ($p<0.05$) decreased within planting basins in all the three agro-ecological regions (Figure 4) in the 0-15 cm depth. However, there was no significant difference between the two farmer practice treatments (FP+ and FP) in the top 15 cm (Figure 4). There was no treatment effect in the 15-30 cm depth across all the three agro-ecological regions (Figure 4). Bulk density increased with depth in all agro-ecological regions (Figure 4). Agro-ecological region significantly ($p<0.05$) influenced bulk density at all depths. The average bulk density (kg m^{-3}) in the 0-15 cm depth under basins was 1356, 1383 and 1451 in agro-ecological regions III, IV and V, respectively. In the FP+, the average bulk density (kg m^{-3}) in the 0-15 cm depth was 1436, 1470 and 1541; whilst it was 1438, 1473 and 1543 kg m^{-3} under FP in agro-ecological regions III, IV and V respectively. Agro-ecological region and tillage interaction effects were significant ($p<0.05$) only in the top 15 cm. When compared to FP, basin tillage reduced soil bulk density by 5.7%, 6.0% and 5.9% in agro-ecological regions III, IV and V, respectively.

3.5 Soil moisture retention characteristics

Volumetric soil moisture content was significantly ($p<0.05$) increased by planting basins in the 0-15 cm depth at lower suctions (5 kPa and 10 kPa) (Figure 5) in all the three agro-ecological regions. There was no significant difference ($p > 0.05$) between the two farmer practices at all suctions in all the three agro-ecological regions. There was no treatment effect ($p>0.05$) at 15-30 cm depth and between the two farmer practices (FP+ and FP) at all suctions in agro-ecological regions III, IV and V. The average volumetric soil moisture content in planting basins (0-15 cm depth) was 24.2%, 21.5% and 18.4% in agro-ecological regions III, IV and V, respectively at 5 kPa. At 10 kPa, the average volumetric soil moisture content in planting

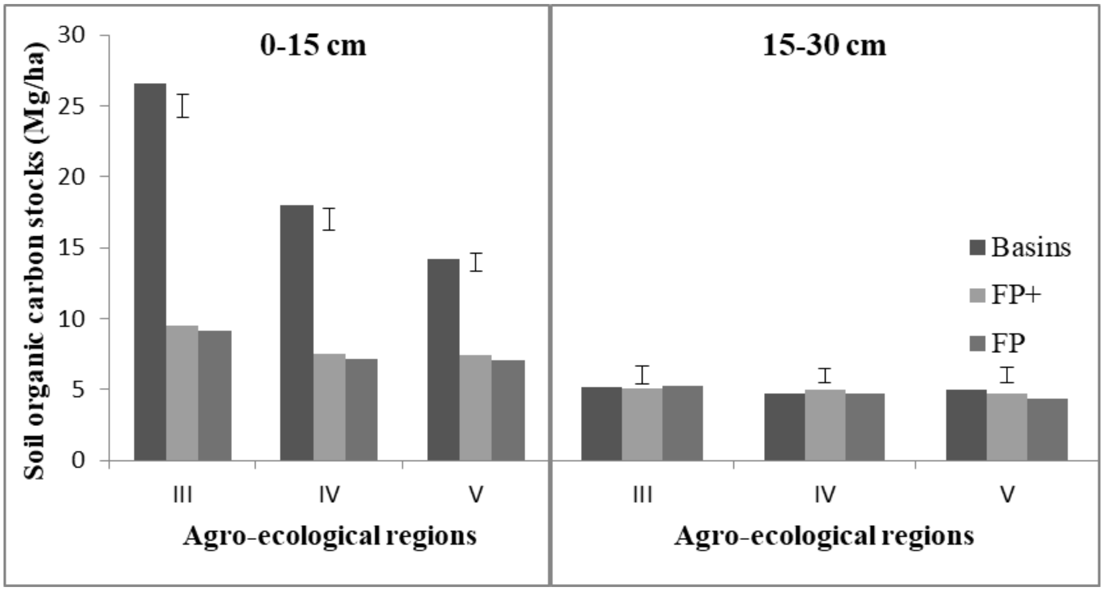

Figure 2: Soil organic carbon stocks (Mg/ha) for two soil depths after three seasons of planting basins (Basins), hand hoeing farmer practice with same fertility amendments as in basins (FP+) and hand hoeing farmer practice without fertility amendments (FP). (Bars represent LSD at P < 0.05).

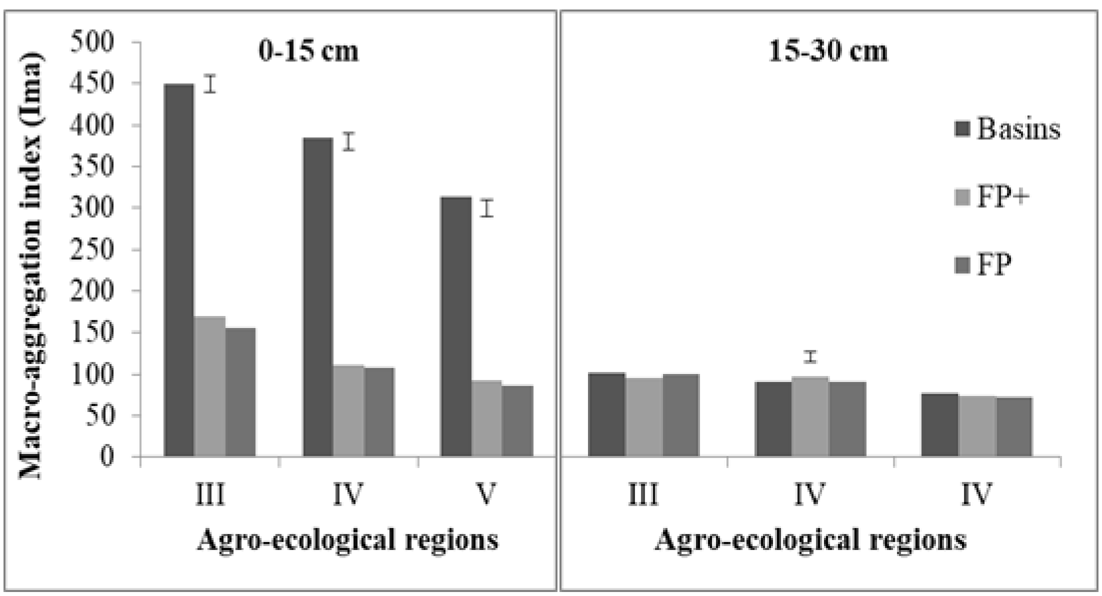

Figure 3: Soil macro-aggregation for two soil depths after three seasons of planting basins (Basins), hand hoeing farmer practice with same fertility amendments as in basins (FP+) and hand hoeing farmer practice without fertility amendments (FP). (Bars represent LSD at P < 0.05).

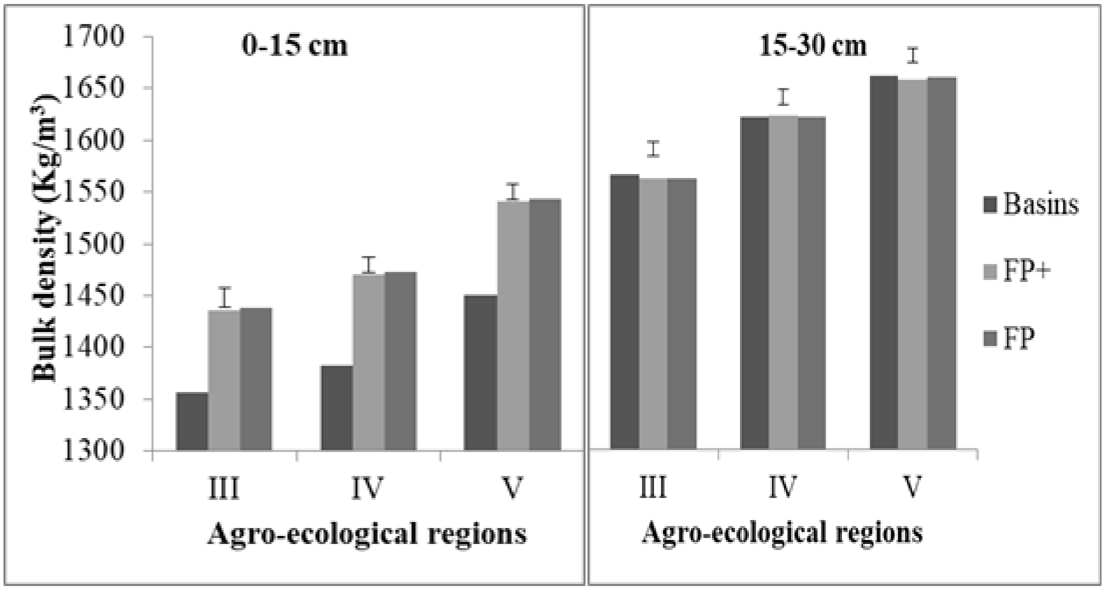

Figure 4: Bulk densities for two soil depths after three seasons of planting basins (Basins), hand hoeing farmer practice with same fertility amendments as in basins (FP+) and hand hoeing farmer practice without fertility amendments (FP). (Bars represent LSD at P < 0.05).

basins was 18.7%, 16.1% and 14.4% in agro-ecological regions III, IV and V, respectively. In the FP+, the average volumetric soil moisture content was 15.7%, 13.5% and 11.9% in agro-ecological regions III, IV and V, respectively at 5 kPa. In the FP, the average volumetric moisture content was 15.6%, 13.4% and 11.7%, whilst at 10 kPa, the average volumetric soil moisture content was 13.4%, 11.3% and 9.5% in FP+ in agro-ecological regions III, IV and V, respectively. In FP, the average volumetric soil moisture content was 13.1%, 11.1% and 9.4% in agro-ecological regions III, IV and V, respectively. Agro-ecological region and treatment interaction effects were significant ($p<0.05$) only in the top 15 cm at 5 kPa. When compared to the farmer practice without fertility amendments (FP), basins increased volumetric soil moisture content by 54.1%, 58.8% and 55.1% in agro-ecological regions III, IV and V, respectively at 5 kPa in the 0 - 15 cm depth. At 10 kPa, planting basins increased volumetric soil moisture content by 40.0%, 44.4% and 41.9% in agro-ecological regions III, IV and V, respectively.

3.6 Pore Volume

Pores draining between suction 5 and 33 kPa (pore volume) were significantly ($p < 0.05$) larger under planting basins than hand hoeing practices (FP+ and FP) in the 0 to 15 cm depth in all agro-ecological regions (Figure 6). Agro-ecological region significantly ($p<0.05$) influenced pore volume in the 0-15 cm depth. In planting basins, the pore volume averaged 12.1%, 11.7% and 10.1% in agro-ecological

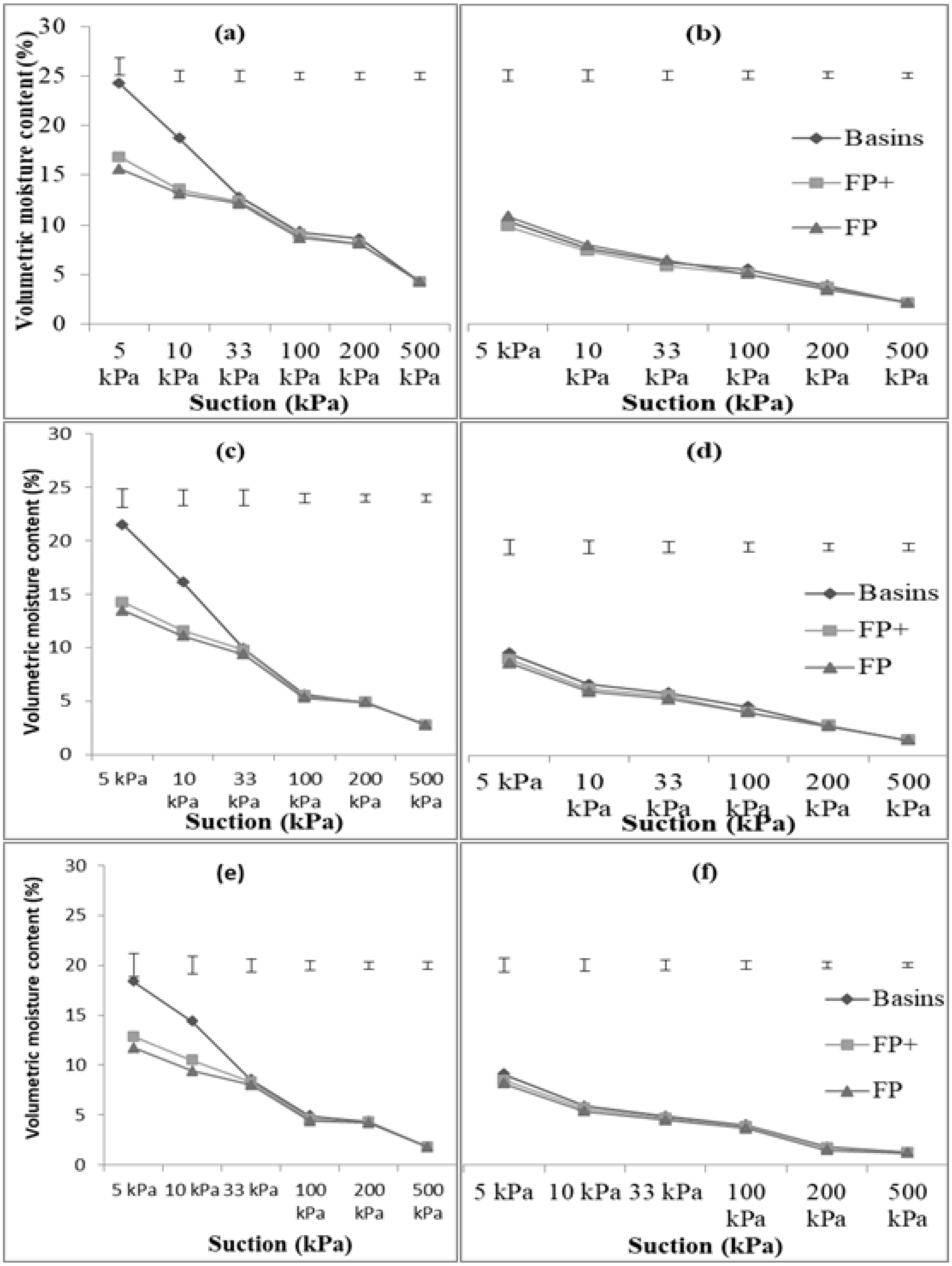

Figure 5: Soil moisture retention curves after three seasons of planting basins (Basins), hand hoeing farmer practice with same fertility amendments (FP+) and hand hoeing farmer practice without fertility amendments (FP). Bars represent LSD at P < 0.05. (a = 0-15 cm and b= 15-30 cm of agro-ecological region III; c = 0-15 cm and d = 15 to 30 cm of agro-ecological region IV; e = 0-15 cm and f =15- 30 cm of agro-ecological region V).

regions III, IV and V respectively, whilst in FP+, the average pore volume was 3.7%, 3.8% and 3.5% in agro-ecological regions III, IV and V respectively. In FP, the average pore volume was 3.5%, 3.6% and 3.3% in agro-ecological regions III, IV and V respectively. In comparison, to farmer practice without fertility amendments (FP), planting basins increased pore volume by 235.6%, 208.5% and 194.7% in agro-ecological regions III, IV and V, respectively. However, there was no significant interaction between agro-ecological region and tillage treatments at all depths.

3.7 Sorghum yield

Planting basins significantly ($p<0.05$) increased sorghum grain yield compared to farmer practices (FP+ and FP) (Figure 7). There was no significant difference ($p<0.05$) between the two farmer practice treatments (FP+ and FP), though grain yield was consistently higher under FP+ than FP. Sorghum grain yield was significantly ($p<0.05$) influenced by agro-ecological region, tillage treatment and season. In planting basins, the average sorghum grain yield was 2.68, 1.72 and 1.32 t ha^{-1} in agro-ecological regions III, IV and V, respectively. In contrast, the average yield was 0.96, 0.67 and 0.45 t ha^{-1} in agro-ecological regions III, IV and V, respectively under FP+ and it was 0.88, 0.61 and 0.40 t ha^{-1} in agro-ecological regions III, IV and V, respectively for FP. When compared to farmer practice without fertility amendments (FP), grain yield increased by 157%, 183% and 192% in agro-ecological regions III, IV and R V, respectively.

4. Discussion

Planting basins with organic and inorganic fertility amendments spot applied significantly increased SOC stocks in the basin soil in the three agro-ecological regions. This may be attributed to the precision application of fertility amendments, root biomass and decomposition of roots within basins which occupy about 4% of the area. Increase in SOC stocks in planting basins was also due to direct organic matter addition through manure as well as enhanced crop growth with higher root biomass (Mikha and Rice, 2004).

Significantly higher SOC stocks under planting basins have been reported from on-station studies in Zambia (Thierfelder and Wall, 2010) and Zimbabwe (Thierfelder and Wall, 2012; Mupangwa et al., 2013). Increased SOC concentrations in planting basins have also been reported from on-farm studies in Malawi (Ngwira et al., 2012; Mloza-Banda et al., 2014) and also in no-till systems (Nyamadzawo et al., 2008). However, planting basins did not significantly increase SOC stocks under on-farm conditions in Zimbabwe (Nyamangara et al., 2014) and this can be attributed to the dilution effect resulting from mixing soils from planting basins with that from outside basins in their sampling design.

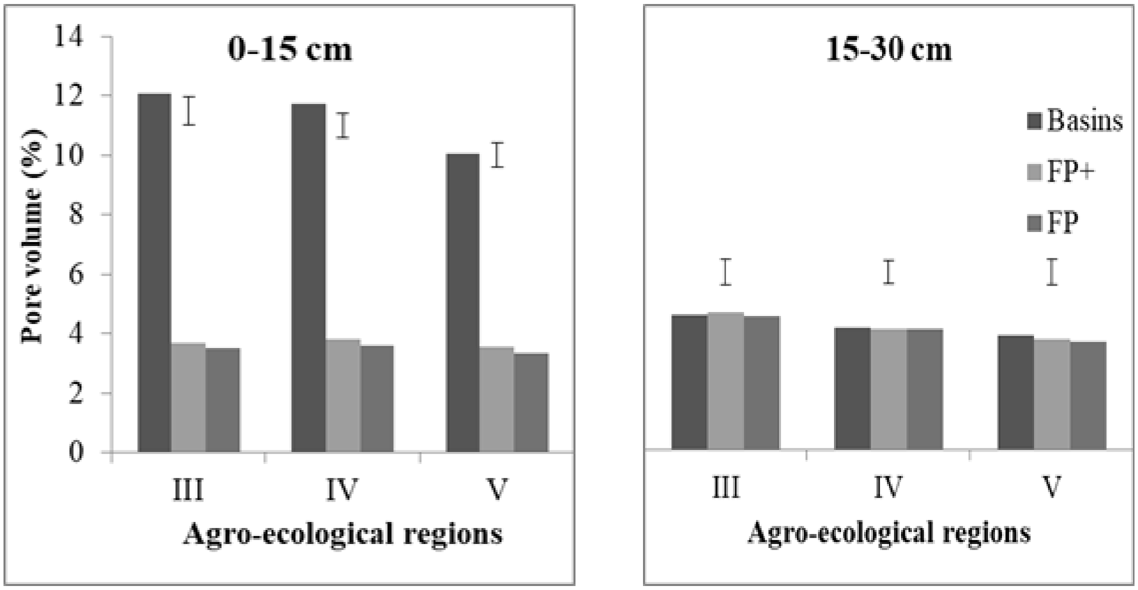

Figure 6: Volume of pores draining between 5 and 33 kPa suction after three seasons of planting basins (Basins), hand hoeing farmer practice with same fertility amendments as in basins (FP+) and hand hoeing farmer practice without fertility amendments (FP). Bars represent LSD at P < 0.05.

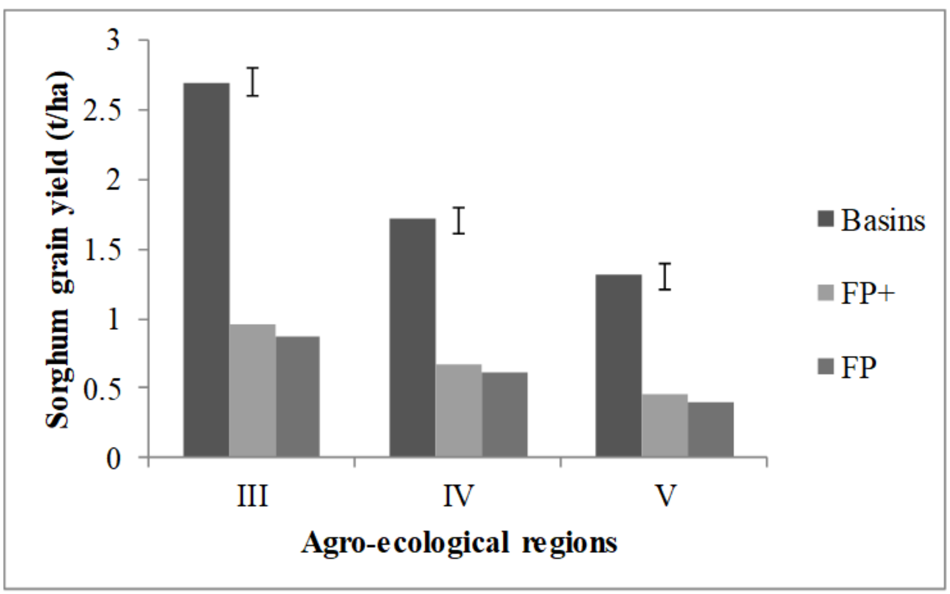

Figure 7: Average sorghum grain yield after three seasons of planting basins (Basins), hand hoeing farmer practice with same fertility amendments as in basins (FP+) and hand hoeing farmer practice without fertility amendments (FP). (Bars represent LSD at P < 0.05).

Improved SOC has also been reported elsewhere (Hati et al., 2006; Mucheru-Muna et al., 2007; Mugwe et al., 2009; Dunjana et al., 2012), after sole or combined application of manure with inorganic fertilizers.

Most Zimbabwean soils have critically low levels of OM. Therefore, the continued use of planting basins will ensure a gradual build-up of SOC stocks. However, to guarantee at least 10 g C kg^{-1} soil, which is considered to be a minimum SOC threshold for crop yield (Nyamangara et al., 2013), smallholder farmers should be encouraged to continuously apply organic materials and maintain permanent planting basins.

Average SOC stocks were highest in agro-ecological region III which has highest clay content (Table 1), showing the significance of clay in protecting OM from decomposition (Nyamangara et al., 2014). Organic materials form associations with clay particles and thus enhancing SOC stabilization within aggregates (Nyamadzawo et al., 2007). In addition, in agro-ecological region III, plant growth and biomass additions from roots is greater. Soil organic carbon stocks decreased with depth in all agro-ecological regions and this was attributed to a decrease in plant biomass and manure inputs as the depth increased. The increased SOC stocks levels suggest the importance of planting basins in improving topsoil quality since surface SOC is a primary indicator of soil functioning (Franzluebbers, 2002). Surface soils in planting basins are less exposed to oxidative losses of SOC as has been reported elsewhere (West and Post, 2002; Sainju et al., 2006), due to minimum soil disturbance. The observed higher SOC stocks in basins enhance soils quality and productivity.

Significant effects of planting basins on macro-aggregate stability were only confined to surface soils in all the three agro-ecological regions. This indicates that localized application of fertility amendments within planting basins resulted in enhanced soil aggregation due to augmented SOM accumulation. Root exudates and fragments plus mycorrhizal hyphae acts as binding agents and thus increases soil resilience to deformation (Kay, 1990; Soane, 1990; Verhulst et al., 2010). In contrast, broadcasting of goat manure resulted in low SOC contents under FP+. Therefore, aggregate stability decreases as it is affected by minimal changes in SOC (Six et al., 2000; Verhulst et al., 2010).

Aggregate stability is closely linked to SOC (Verhulst et al., 2010) even in low clay content soils (Gwenzi et al., 2009). Soil organic carbon greatly influences aggregate stability (Elliot, 1986), by binding soil micro-aggregates together through increased microbial proliferation (Oades, 1984; Six et al., 2000), and this is why the trend in macro-aggregate stability is consistent with observed SOC for those soils. Improved aggregate stability after manure and fertilizer applications were also reported elsewhere (Shirani et al., 2002; Mikha and Rice, 2004; Hati et al., 2006). Low macro-aggregate stability in farmer practice treatments and in the subsoil was attributed to low SOC levels.

The decrease in surface soil bulk density in all agro-ecological regions under basins was attributed to improved soil structure due to increased SOC stocks, aggregate stability, and the sequential increase in pore volume, aeration and root growth. Higher OM level improves soil structure and porosity (Nyamadzawo et al., 2007). Organic matter plays a dominant role in the bulk density of soil because of its much lower density than mineral particles and its aggregation effect on soil structure (De Vos et al., 2005). The dilution effect caused by mixing the less dense organic manures with the denser mineral fraction of the soil reduces bulk density (Khaleel et al., 1981). This decreased bulk density is supported by results in Zimbabwe (Nyamangara et al., 2014), and in Malawi after two years of planting basins practice (Mloza-Banda et al., 2014). The significant decrease in bulk density as observed in this study is a meaningful result for semi-arid smallholder agriculture since high bulk densities are known to cause poor crop emergence and root impedance (Nyamangara et al., 2014). Nyamangara et al. (2014) and Belder et al. (2007) also reported a decrease in bulk density of soils from mulched planting basins in various agro-ecological regions of Zimbabwe. Sharma et al. (2000) also reported similar results after fertilizer and manure additions. Results suggest that conventional hand hoeing increases bulk density and this can be explained by extreme soil disturbances and low SOC. In fact, cultivated soils become unstable and structure collapses rapidly in the presence of water (Osunbitan et al., 2005).

In subsurface horizons, bulk density was similar among treatments (Ga´l et al., 2007; Thomas et al. 2007), because tillage effects on bulk density is mainly confined to the top soil (Verhulst et al., 2010). The pressure exerted by overlying soil layers (Tsimba et al., 1999), plus the decrease in both SOC and aggregate stability explains the increase in bulk density with depth.

Planting basins effects on soil moisture retention were only observed in the 0-15 cm depth at 5 and 10 kPa suctions (Figure 4). This was attributed to improved soil structure and SOC stocks. Soils with higher SOC tend to have greater water holding capacity when compared to soils of the same texture but with lower SOC (Hudson, 1994). These findings agrees with reports by Belder et al. (2007) and Nyamangara et al. (2014) who also observed significantly higher soil moisture retention under basins. Improved soil moisture retention was also reported from other studies (Nyamangara et al., 2001; Dunjana et al., 2012), after manure and fertilizer additions as was the case in basins . Water retention is structurally controlled at lower suctions (≤ 10 kPa) whilst at higher suctions (≥33 kPa) it is texturally controlled

(Hillel, 1982; Hall, 1991). This explains differences in soil moisture retention and is the same reason for its decrease with depth.

The increase in pore volume may have been due to increased SOC stocks and consequent soil structure improvement. These results are supported by Nyamangara et al. (2014) who also reported increased pore volume for planting basins systems in Zimbabwe. Improved pore volume is also reported for no-till systems (Drees et al., 1994; VandenBygaart et al., 1999; Eynard et al., 2004), and these have been attributed to abundance of earthworm and root channels. The improved porosity leads to increased initial infiltration rate (Nyamangara et al., 2014), since it depends on the inter-connectivity, size, shape and quantity of pores (Verhulst et al., 2010). This means that soils under planting basins can better withstand high intensity storms which are common in semi-arid agro-ecologies especially at the beginning of the rainy season (Nyamangara et al., 2014).

The significantly higher sorghum yield under planting basins was attributed to the precision application of fertility amendments. Higher sorghum yield could also be linked to better rain water harvesting through basins. This is supported by findings that basins can increase yields since they capture and conserve moisture (Mupangwa, 2009; Nyagumbo et al., 2009). This increased crop productivity in planting basins systems can remove pressure from marginal and fragile areas as farmers are able to meet their food requirements from smaller land units and thus leave more land under natural vegetation.

The results of this three-year on-farm assessment of planting basins compared to farmer practices with and without supplementary fertility amendments indicates that soil properties such as soil C, aggregate stability, bulk density and soil water retention at low suctions (i.e. easily available water) improved under planting basins only within the 0-15 cm depth. The addition of fertilizers did not improve any of these soil quality parameters under conventional farmer tillage practices, as observed elsewhere in sub-Saharan Africa (Kintchéa et al., 2015), suggesting that planting basins was a pre-condition for significant effects of organic and inorganic fertilization on soil quality, as reported by (Sommer et al., 2014).

5 Conclusions

It can be concluded that short term improvement in soil physical properties due to planting basins where fertility amendments are concentrated is only confined to permanent planting stations. Planting basins with fertility amendments improved SOC stocks, aggregate stability, bulk density, soil moisture retention and pore volume in agro-ecological regions III, IV and V. Therefore, planting basins have the potential to improve soil quality at permanent planting stations in degraded fields of semi-arid regions along an agro-ecological gradient as shown by this short term study in Chipinge district. Planting basins with fertility amendments look promising as a strategy to raise crop productivity under rain-fed conditions and thus improving household food security in semi-arid tropical areas. Considering the soil and crop productivity benefits highlighted in this study, there is a strong justification for the widespread promotion and adoption of planting basins in various agro-ecological regions of Zimbabwe. Thus, basins can play a role in climate change mitigation and adaptation through improved crop and soil productivity.

Conflict of interest

The authors declare that there is no conflict of interests regarding the publication of this article.

Acknowledgement

The authors are grateful to *Action Contre la Faim* (ACF) and the Research Platform - Production and Conservation in Partnership (RP-PCP) for funding the project, CIRAD and the University of Zimbabwe for hosting the project and to AGRITEX extension officers and farmers for their collaboration.

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