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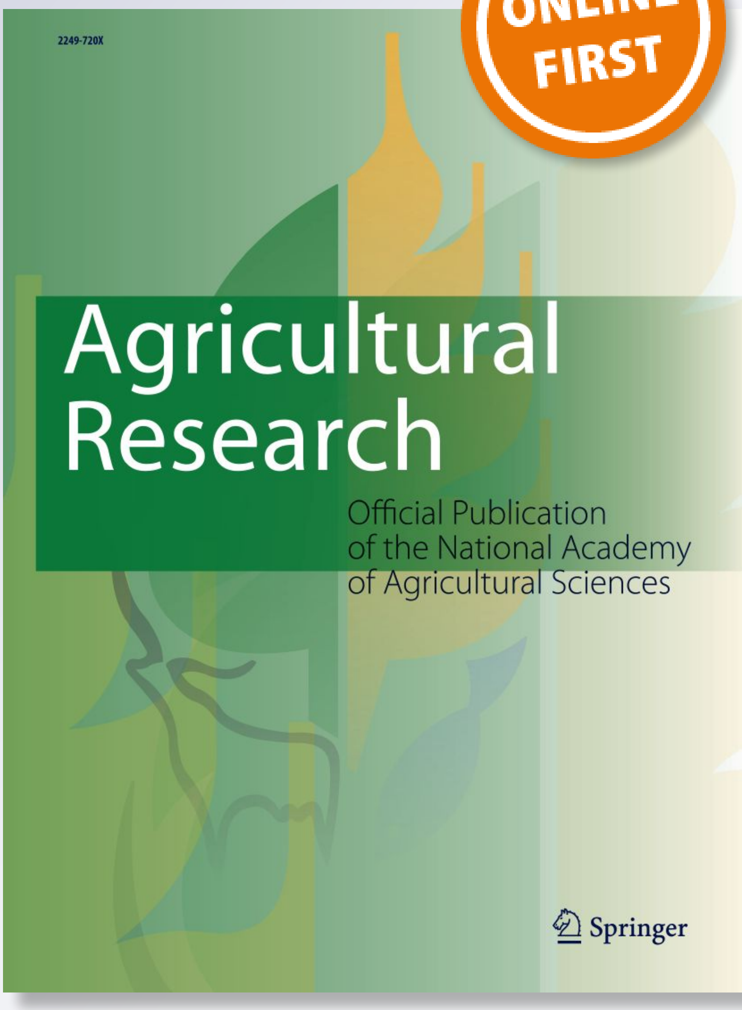

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FULL-LENGTH RESEARCH ARTICLE

Dryland Grain Sorghum (*Sorghum bicolor*) Yield and Yield Component Responses to Tillage and Mulch Practices Under Subtropical African Conditions

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Abstract In the African subtropical zones, the choice of tillage practice is critical to sustainable rainfed crop production. Two season (2015 and 2016) field trials were conducted at Matopos Research Institute (20°24′S; 28°29′E, 1340 m above sea level) in southern Zimbabwe in order to determine dryland grain sorghum yield and 1000 kernel weight responses to tillage and mulch practices under African subtropical conditions. Sorghum grain yield was highest in planting basin tillage plots under 4 T ha^{-1} sorghum stover mulch application (3140.9 kg ha^{-1} for year 2015 and 3415.7 kg ha^{-1} for year 2016). The 1000 kernel weights in both years were least in ripper tillage and greatest in planting basin tillage field trial plots. The mass of 1000 sorghum kernels on planting basin tillage subplots under 2 T ha^{-1} sorghum stover mulching was 8.6 g (25.1%) and 8.4 g (24.2%) in excess of that recorded on mulched ripper subplots for 2015 season. For the season 2016, mass of 1000 sorghum kernels on planting basin tillage subplots under 4 T ha^{-1} sorghum stover mulching was 9.1 g (22.9%) and 8.4 g (21.1%) in excess of that recorded on mulched ripper subplots. The adoption of the planting basin tillage under sorghum stover mulching, a technology designed for smallholder farmers with limited access to animal draft power, can improve considerably the dryland sorghum grain yield and weight of 1000 kernels.

Keywords Conventional · Planting basin · Ripper tillage practice · Grain sorghum yield

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Introduction

In the arid and semiarid climates, water and soil resources are the largest constraining factors for sustainable rainfed crop production. Conservation tillage practices for dryland sorghum have created counterbalance interest worldwide from agricultural research and smallholder farmers [1, 16, 25]. In sub-Saharan Africa, sorghum is the second most important cereal crop after wheat with a total production of 20 million T per annum [5, 7, 36]. In subtropical Africa, sorghum is mainly grown as rainfed grain crop in areas receiving low, erratic and highly variable annual rainfall totals ranging from 400 to 600 mm [14]. Despite its resilience to adverse environmental conditions, research has indicated that the production potential of grain sorghum is considerably limited by soil water deficit in semiarid areas of subtropical Africa [12, 32, 39].

Conservation tillage systems in semiarid zones can effectively harvest rainwater and conserve soil moisture

[4]. Reduced tillage is the more appropriate tillage option for the marginal areas where small grains are mainly grown as it tends to conserve moisture and put the low amount of rainfall received to maximum use [2, 6]. Conservation tillage practices do not only conserve soil and water resources, but simultaneously reduce energy usage and increase or sustain crop production for the resource-poor smallholder farmers [6].

Conservation tillage systems for grain sorghum production in which artificial micro-catchments are created for retention of water during heavy rainfall events can result in significant gains in soil moisture due to reduced runoff losses [14, 15]. The use of planting basin tillage has been recommended to smallholder households with limited or no access to draft animals. Ripping is targeted for smallholder farmers with some draft animal power [16, 17]. The planting basin conservation tillage package was first developed by Oldrieve [28] in Zimbabwe. The central component of the planting basin conservation tillage system is the planting basin. In tillage planting basins, the seeds are sown in small basins which are simple pits that can be dug with hand hoes without having to plow the whole field [38, 39]. In southern Zimbabwe, the planting of the basins takes place in November/December after the basins have captured rainwater and then drained naturally at least once. Immediately, after the first effective rainfall event the smallholder farmers lacking animal draft power plant the sorghum seed rather than wait for draft animals to become available several weeks into the season [38].

Aune et al. [3], Ozpinar and Cay [29], Rockström et al. [33] and Baudron et al. [4] have reported strong relationships between crop residue management, tillage and soil moisture retention. As a combination to the planting basin tillage systems, the smallholder farmers spread crop residues as a surface mulch to reduce soil losses early in the season, conserve moisture later in the season and enrich the soil with nutrients and organic matter as the residues decompose [40]. The use of surface organic mulch or straw can store more precipitation water in soil by reducing storm runoff, increasing infiltration and decreasing evaporation [19, 20].

While grain sorghum has a comparative advantage over other summer crops related to its wider adaptability to limited soil moisture conditions, its dryland production is characterized by considerable variability in yield as crop performance depends highly on soil moisture availability [21]. Soil management practices that increase soil water storage have a positive impact on water use efficiency [38]. The current study is based on the hypothesis that reduced tillage farming strategies coupled with organic mulching would increase considerably the rainfed grain sorghum yield and weight of a 1000 kernel in southern Zimbabwe.

Materials and Methods

Site Description

The field experiments were conducted at Matopos Research Institute (20°24′S; 28°29′E, 1340 m above sea level) which is located at 34 km south of Bulawayo in southern Zimbabwe (Fig. 1). The field experimental site is in agroecological region IV, which receives total rainfall ranging from 250 to 650 mm per annum (average 450 mm). The mean annual temperature is 27°C with insignificant frost occurrence in the months of June and July. Climatic conditions are characterized by a dry winter season that extends from April to September and a wet summer season that normally starts during the month of October up to March [25, 26]. The experimental soil is a Chromic-Leptic Cambisol derived from basaltic greenstone [15].

Experimental Soil Characterization

Fifteen soil samples were collected from the experimental site using a soil auger at depths of 0–20; 20–60 and 60–100 cm for soil characterization. A composite soil sample was obtained after mixing the soil samples in a clean plastic bucket. The composite soil sample was then air air-dried, sieved (< 2 mm) and characterized for mechanical constituents (Table 1). The texture of soil was obtained using the Bouyoucos hydrometer method [9]. Soil organic carbon was determined using the Walkley and Black method described by Nelson and Sommers [27]. The pH of the experimental soil was determined by weighing a 15-g soil sample in a 200-ml honey jar to which 75 ml 0.1 M $CaCl_2$ was added. Thereafter, the mixture was thoroughly shaken mechanically for 30 min and pH was determined using a digital pH meter (Model: Orion 701, Orion Manufacturing, MI, USA). Total N was measured by the Kjeldahl method described by Bremner [10]. The bulk density of experimental soil was determined by the core method [8].

Land Preparation and Plot Establishment

The field trial was conducted during the summer seasons (November–April) of 2015 and 2016 in fixed plots. The land preparation on the 27 plots was undertaken according to the treatments which included conventional, planting basin and ripper tillage systems coupled with sorghum stover mulch applications. The net plot size was 8.0 m × 4.0 m. An oxen-drawn plow (farmer's practice) was used in the conventional tillage to prepare the seedbed. All treatments, including the control plots, were subjected

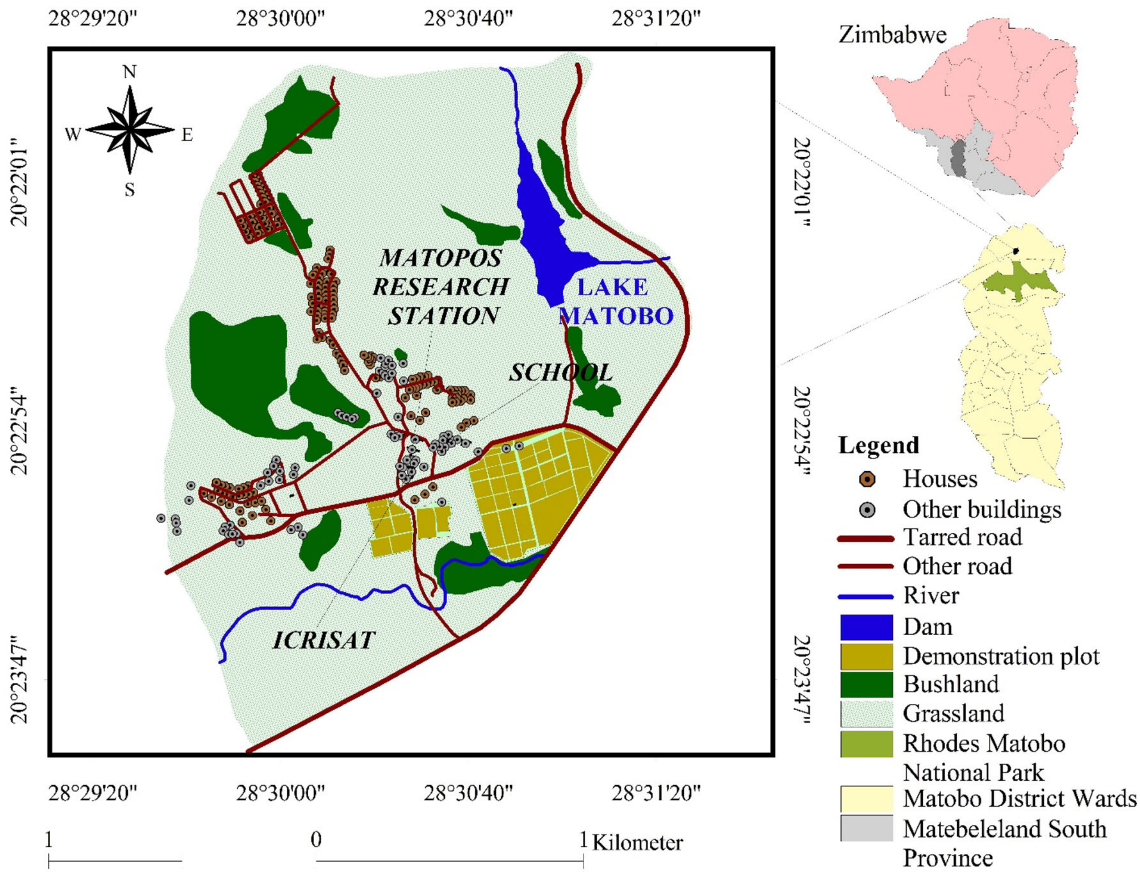

Fig. 1 Experimental site location

Table 1 Chemical and physical properties of the experimental soil

Soil depth (cm)	Soil pH (H_2O)	Org-C (%)	N mg kg^{-1}	Sand (%)	Clay (%)	Silt (%)	Total porosity (cm^3 cm^{-3})	Bulk density (g cm^{-3})	Saturation gravimetric water (g g^{-1})
0–20	7.5	0.90	29.3	35	40	25	0.49	1.36	0.52
20–60	7.7	0.76	21.8	33	50	17	0.44	1.4	0.66
60–100	7.9	0.52	18.1	27	63	10	0.40	1.4	0.70

to a basal fertilizer application of 80 kg ha^{-1} of compound D fertilizer (10% N; 20% P_2O_5, 10% K_2O and 6.5% S) applied by spreading on the surface. At 5 weeks after planting, the sorghum test crop in all treatments was subjected to a top dressing application of ammonium nitrate fertilizer (34.5% N) at 200 kg ha^{-1}.

The planting basins were dug to dimensions of 15 cm deep × 15 cm width × 15 cm length using a hand hoe. Ripper lines were established by digging a 20-cm-deep line in the trial plots using a hoe. For each of the conventional, planting basin and ripper tillage main plots, three subplots were created where 0, 2 and 4 T ha^{-1} of sorghum stover mulch were applied. The mulch was applied at the same time in all plots at seed sowing stage of the trial. Uniform seeds of the semidwarf sorghum cultivar Macia were treated with fungicide captan [cis-N-(trichloromethyl) thio-4-cyclohexane-1,2-dicarboximide] against seed-borne diseases. Sowing was done with a hand drill maintaining inter-row spacing of 90 cm and in-row spacing of 20 cm after thinning on ripper and conventional tillage. The planting basins had spacing of 90 cm × 60 cm with three plants per basin after thinning. The indicated plant spacing for the two tillage systems resolved into 55 500 plants ha^{-1}. The sorghum variety Macia was selected in the trial run among others because it has a number of useful characteristics such as short plant height that is convenient for pest bird scaring, large head size, high yield, low dehulling losses and good eating quality. The seed was sown after the first significant rainfall event (at least 50 mm) during the month of October for each of the two seasons.

Experimental Treatments, Design and Test Crop Management

The field trials had 27 plots distributed into a completely randomized block design in split-plot arrangement in which the three tillage types (conventional, planting basin and ripper line) were the main plot and mulching was the subplot replicated three times. In each tillage type, three rates of mulching were tested (0; 2 and 4 T/ha). Hand hoeing was used to keep the experimental plots weed-free at 3 and 6 weeks after transplanting. Carbaryl (1-naphthyl methylcarbamate) dust was applied at 4 weeks after planting to prevent potential insect damage during the vegetative growth of the sorghum crop.

Grain Sorghum Yield Measurements

Grain sorghum was harvested from ten randomly selected plants of the four central plant rows of each subplot after physiological maturity stage at 20 percent moisture with minimum mechanical damage to the seed. Mature panicles were severed at the base, dried artificially to a grain moisture of 12.5% and hand threshed. The grain sampled from each subplot was weighed to the nearest tenth of a kg. Randomly selected 1000 kernels from the subplots were weighed and recorded.

Statistical Analysis

The treatment effects on measured variables were analyzed using GLM procedure of SAS statistical software, version 9.1 [34]. Differences between treatment means were judged significant at $p \leq 0.05$ as determined by Fisher's protected least significant difference test. Mean separation was performed using the LSD. Statistical significance of the differences between measured variables in the main plots which were subjected to three tillage types and in the subplots subjected to applications of sorghum stover mulch was established by performing t test for unpaired samples.

Results and Discussion

Weather Conditions

The 2015 and 2016 summer cropping seasons in the experimental area were characterized by limited and erratic rainfall with hotter average temperature (Fig. 2). Rainfall and temperature data were collected daily at 10.00 h from a rain gauge at the study site. The meteorological station records daily weather data. Rainfall amounts in the study area were variable for the 2 years (Fig. 2).

Thirty-nine percent (160 mm) of the total rainfall (408 mm) was received in the first half of the 2015 summer cropping season (October to December; Fig. 2). The first three months of the 2016 summer season recorded 251 mm of rainfall representing 51% of the total rainfall recorded for the season (419 mm).

The annual rainfall amounts received in each of the two seasons (408 and 419 mm) were below the long-term average rainfall (570 mm) received at Matopos. The occurrence of annual rainfall totals below the normal average rainfall which was recorded for the two seasons signifies the need for sorghum smallholder farmers in the region to adopt cultural practices that extend the period of water availability to the sorghum crop. The grain filling phenological period, a critical late growth stage for the sorghum crop, coincided with decreasing rainfall totals for both summer rain seasons (Fig. 2). Research has established that soil water stress during the grain filling period is also critical to grain weight and, consequently, the sorghum grain yield [1, 39]. It has been proven that a stress at grain filling phenological stage in the growth and development of sorghum plant could result in either a reduction in photosynthesis due to the closure of stomates [35] or a reduction in photosynthate movement to the developing grain [37]. A related study conducted by Carlos et al. [11] concluded that the grain filling period in the development and growth of grain sorghum is characterized by a rapid translocation of minerals and photosynthates from the roots, stems and leaves to the developing grain.

Grain Yield Response to Tillage and Mulching

Figures 3 and 4 show comparative variabilities in the sorghum grain yield under the conventional and conservation tillage types subjected to three levels of application of sorghum stover mulching. Results indicate that the propagation of sorghum using conventional and conservation tillage types under different rates of sorghum stover mulching had a significant effect ($p < 0.05$) on the grain yield of sorghum grown under dryland subtropical conditions. Sorghum grain yield in basin tillage subplots subjected to 4 T ha^{-1} mulch application recorded the highest grain yield (3140.9 kg ha^{-1} for year 2015 and 3415.7 kg ha^{-1} for year 2016). The main plots subjected to ripper tillage across the three levels of mulching recorded the lowest grain yield of 1246.5; 1737.9; 2117.2 kg ha^{-1} and 1113.4; 1405.7; 1987.8 kg ha^{-1} for the years 2015 and 2016, respectively (Figs. 3, 4).

The second highest recordings of sorghum grain yield occurred on plots that received mulching under conventional tillage systems. When compared with conventional

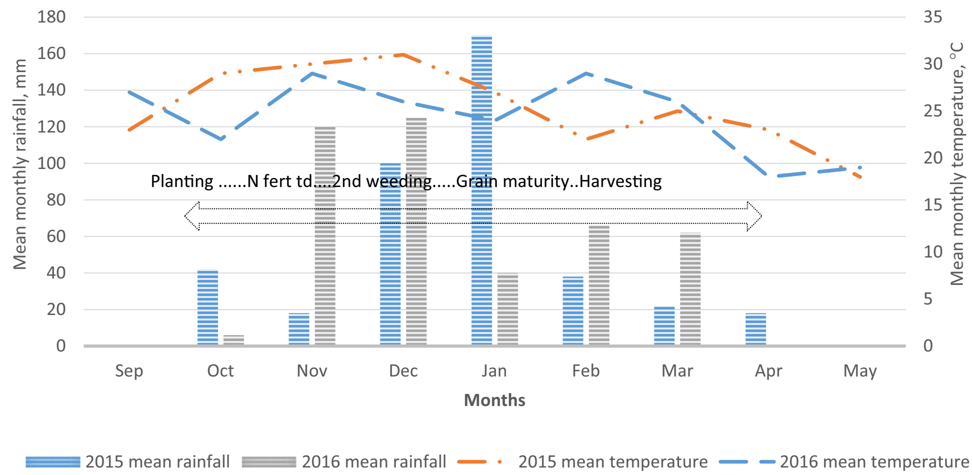

Fig. 2 Weather conditions and test crop management

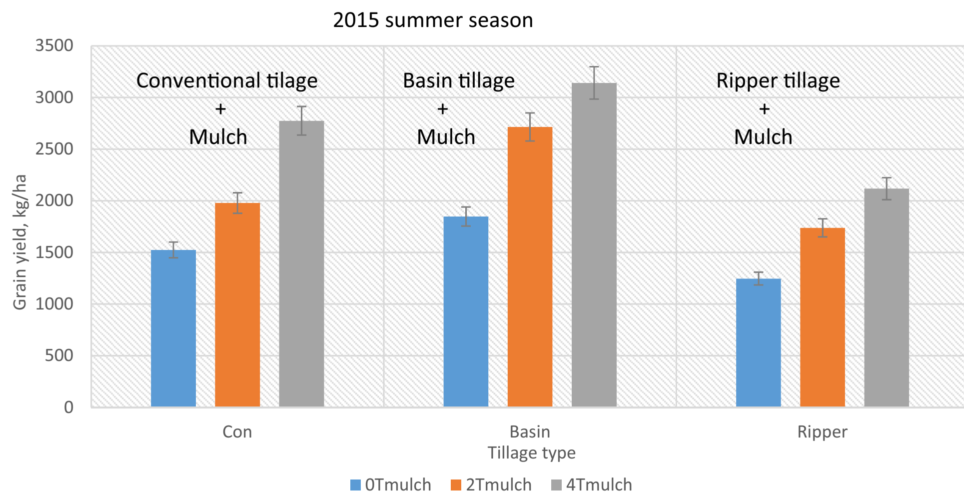

Fig. 3 Grain sorghum yield response to tillage types and mulching for the 2015 summer season. Error bars stand for measure of significant difference significant at $p \leq 0.05$

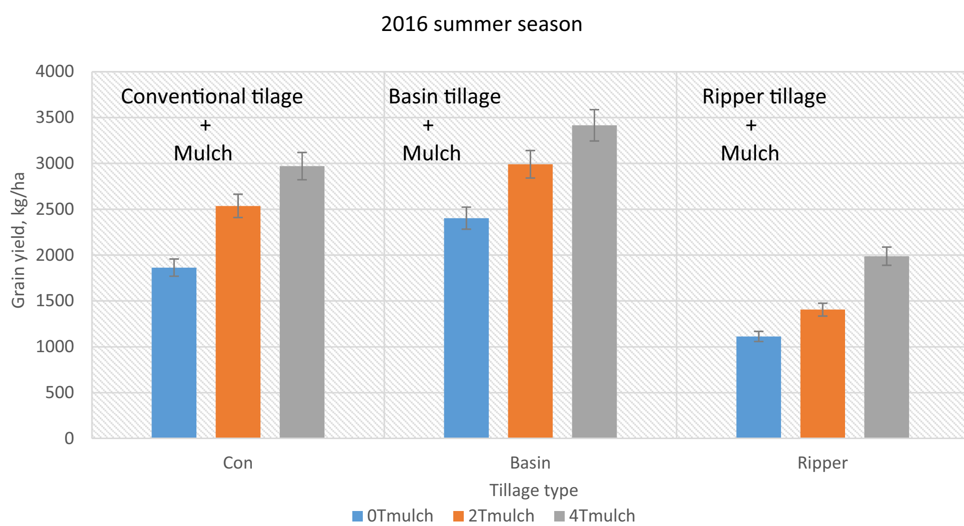

Fig. 4 Grain sorghum yield response to tillage types and mulching for the 2016 summer season. Error bars stand for measure of significant difference significant at $p \leq 0.05$

tillage type, plots under conservation tillage with planting basins under 0; 2 and 4 T ha^{-1} mulching cover were 21.3% (323.9 kg ha^{-1}); 37.2% (736.2 kg ha^{-1}); 13.2% (366.2 kg ha^{-1}) and 29.0% (539.7 kg ha^{-1}); 17.9% (454.7 kg ha^{-1}) and 15.0% (445.6 kg ha^{-1}) of sorghum grain yield in excess of that recorded under conventional tillage for the years 2015 and 2016, respectively.

In sub-Saharan Africa, the intra-season dry spells, which are a common event, have a severe impact on the sorghum grain crop production [26, 33], especially if they coincide with critical stages of crop development as indicated in Fig. 2. The use of water harvesting techniques can improve water supply to the crops in rainfed cropping systems [8]. In related studies on tillage systems and grain yield of sorghum by Gebrekidan [18] and Hiremath et al. [23], it was established that conservation tillage systems can result in significant gains in soil moisture due to reduced runoff losses. The upgraded rainwater harvesting and soil moisture retention in planting basin minimum tillage plots substantially improved the sorghum crop's resilience to the late summer season droughts. Grain sorghum yield in the planting basin tillage plots for both years was correspondingly higher than in the conventional and ripper tillage plots. In addition to the above, the enhanced crop growth under planting basin tillage practice increases the opportunity to return more organic matter as mulch into the cropping system, which in turn increases soil moisture retention.

Study results show that the substitution of planting basins with ripper lines in conservation tillage under 0; 2 and 4 T ha^{-1} organic mulch significantly reduced ($p < 0.05$) grain sorghum yield by 601.0 kg ha^{-1} (32.5%); 976.6 kg ha^{-1} (36.0%) and 1023.7 kg ha^{-1} (32.6%) for the year 2015; 1289.7 (53.7%); 1585.4 kg ha^{-1} (53.0%) and 1427.9 kg ha^{-1} (41.8%) for the year 2016, respectively (Fig. 3).

Generally, ripping in minimum tillage systems is employed to facilitate root growth and to access subsoil moisture [26, 36]. Accessing subsoil moisture implies that deep ripping machines must be employed to break through the deeper soil layer, allowing root access to unconstrained soil water beneath this layer [6, 32, 40]. In the current study, the ripper lines were barely deeper than the recommended 27 cm [39] and, as a consequence, could not reach the deep seated soil moisture which could have increased the grain sorghum yield on plots subjected to ripper minimum tillage systems.

Results show that the grain yield of dryland sorghum appeared to increase considerably ($p < 0.05$) with increasing rates of application of sorghum stover mulch in conventional, planting basin and ripper tillage systems for the years 2015 and 2016 (Fig. 3). When compared with the control (0 T ha^{-1}), the application of 2 T sorghum stover mulch ha^{-1} significantly increased (as shown by the error bars in Figs. 3, 4) the grain yield of sorghum in plots subjected to conventional; planting basin and ripper tillage practices by 30.0% (454.7 kg ha^{-1}); 46.9% (867.0 kg ha^{-1}) and 39.4% (491.4 kg ha^{-1}), respectively, for the 2015 summer season. The application of 2 T of mulching organic material ha^{-1} in conventional; planting basin and ripper tillage plots improved the yield of sorghum by 36.1% (673.1 kg ha^{-1}); 24.5% (588.0 kg ha^{-1}) and 26.3% (292.3 kg ha^{-1}) in excess of that recorded in the control plots for the year 2016 (Fig. 3). When the mulching rates were increased from 2 to 4 T ha^{-1}, grain sorghum yield increased substantially ($p < 0.05$; Figs. 3, 4) by 796.4 kg (40.3%); 426.4 kg (15.7%) and 379.3 (21.8%) ha^{-1} in the conventional; planting basin and ripper tillage practices plots for the year 2015, respectively. Plots subjected to conventional; planting basin and ripper tillage practices under 4 T ha^{-1} mulching rate recorded 433.7; 424.6 and 582.1 kg of grain sorghum yield ha^{-1}, respectively, in excess of those recorded for plots subjected to same tillage practices under 2 T ha^{-1} of mulch application for the year 2016.

Related research by Gebrekidan [2] and Hiremath et al. [18] has demonstrated that organic mulching is beneficial for the sorghum crop growth through its positive effects on soil environment as it modifies the variabilities of soil temperature, reduces surface evaporation of soil water, suppresses weed growth and minimizes soil compaction and erosion. The use of planting basins and organic mulch as cover can result in significant gains in soil moisture due to reduced runoff losses and evapotranspiration [24, 26, 30].

Daniel et al. [13] reported a 25 to 50% increase in rainwater infiltration when surface crop residue is used as mulch under no-till as compared to conventional tillage system. Due to high summer season temperatures in the subtropics of Africa (Fig. 2), soil water evaporation can reach 30 to 50% of the total rainfall leaving only 10 to 30% for crop transpiration [31]. Consequently, the combination of conservation tillage practice with organic mulching effectively increases the dryland grain sorghum yield for smallholder farmers.

Weight of 1000 Sorghum Kernel Response to Tillage and Mulching

The results of analysis of variance for mean squares show that the weight of 1000 grains of sorghum was significantly ($p < 0.05$) influenced by the tillage types and mulch rates (Figs. 5, 6). Generally, kernel weight in plots subjected to conservation tillage practices was higher than that recorded in conventional tillage plots. Sorghum 1000-seed weight in both years was least with ripper tillage and greatest with

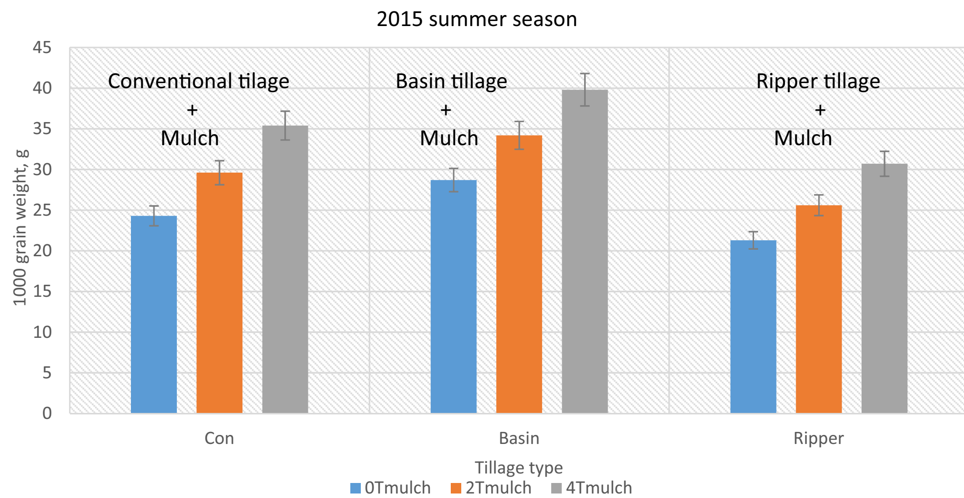

Fig. 5 Effect of tillage types and mulching on 1000 grain weight of sorghum for the 2015 summer season. Error bars stand for measure of significant difference significant at $p \leq 0.05$

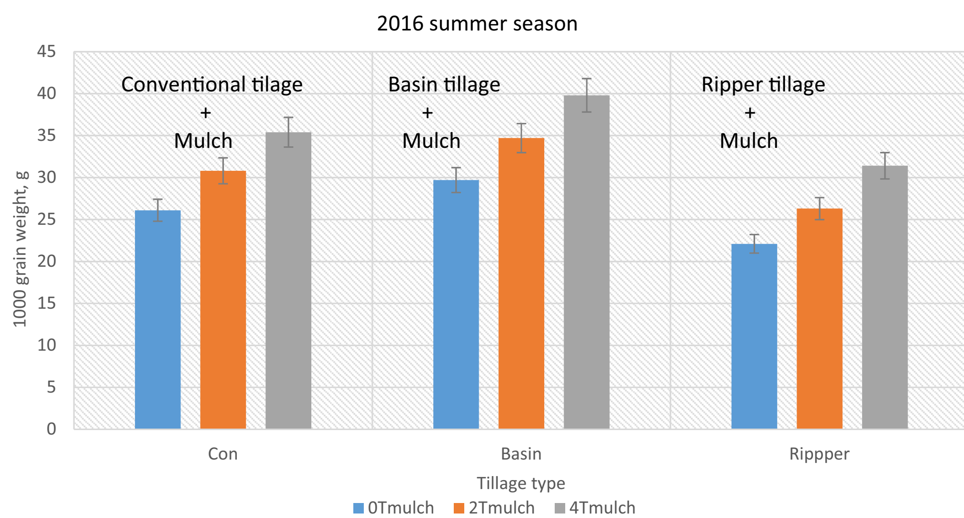

Fig. 6 Effect of tillage types and mulching on 1000 grain weight of sorghum for the 2016 summer season. Error bars stand for measure of significant difference significant at $p \leq 0.05$

planting basin tillage. Within the conservation tillage main plot, the planting basin tillage practice subplots covered with organic mulch recorded significantly higher weight of 1000 kernels ($p < 0.05$) when compared with that recorded on the ripper tillage subplots (Figs. 5, 6) for the two seasons. Results show that the mass of 1000 sorghum kernels on planting basin tillage subplots under 2 and 4 T ha^{-1} sorghum stover mulching was 8.6 g (25.1%) and 9.1 g (22.9%); 8.4 g (24.2%) and 8.4 g (21.1%) in excess of that recorded on mulched ripper subplots for 2015 and 2016 seasons, respectively. The lowest 1000 kernel weights were recorded on subplots subjected to ripper tillage.

In a study on grain sorghum response to row spacing and plant populations in the Texas Coastal Bend region, Fernandez et al. [17] reported that grain development and individual grain weight are a function of the quantity of photosynthates reaching the grain during the grain filling phenological stage. Consequently, the environmental conditions which interfere with the plant's physiological functions will considerably reduce grain weight. The use of basin tillage improved the mass of 1000 grains by 11.1 to 13.5% compared with conventional tillage over two seasons. Specifically, the application of 2 and 4 T ha^{-1} of the mulch on subplots with planting basin moisture conservation system improved the 1000 sorghum kernel weight by 4.6 g (13.5%) and 4.4 g (11.1%); 3.9 g (11.2%) and 4.4 g (12.4%) above those recorded on plots subjected to conventional tillage under mulch for the years 2015 and 2016, respectively.

The three tillage treatments with 0; 2 and 4 T ha^{-1} sorghum stover mulching harvested and stored different quantities of rainwater with the planting basins having considerably higher rainwater harvested and soil water retention for both seasons. The conventional and conservation tillage treatments affected soil surface micro-topography differently. Specifically, the mosaic of 0.9 m and 0.6 m spaced planting basins covered with sorghum stover mulch generated considerably higher surface roughness when compared with the conventional and ripper tillage treatments resulting in elevated rainwater harvesting, infiltration and retention of soil water. A related study carried out by Guzha [22] on effect of tillage on soil micro-relief, surface depression storage and soil water storage reported greater potential for depression water storage with higher surface roughness. In the current field trial, the greater rainwater harvesting, water infiltration and soil water storage in tillage planting basins covered with higher rate of sorghum stover mulch translated into higher 1000 kernel weight.

Conclusions

The results from the field trials have demonstrated that the choice of tillage practice is critical to crop performance in the African subtropical zones. Planting basin tillage under sorghum stover mulching, a technology designed for smallholder farmers with limited access to animal draft power, improved considerably dryland sorghum grain yield and weight of 1000 kernels. The sorghum grain yield from the three tillage practices in the current trial was higher than the average dryland sorghum grain yield of 800 kg ha^{-1} realized by the smallholder farmers in the semiarid areas of Zimbabwe due to the superior capacity of a combination of tillage practices with soil surface moisture conserving sorghum stover mulch applications.

Authors' Contribution JM designed the experiment, analyzed and described the results and compiled the manuscript. JD executed the experiment and collected data. KM analyzed samples in the laboratory and performed statistical analyses.

Compliance with Ethical Standards

Conflict of interest There are no potential conflicts of interest.

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