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Comparative short-term performance of soil water management options for increased productivity of maize-cowpea intercropping in semi-arid Zimbabwe

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ABSTRACT

Rainfall variability poses a great challenge to rainfed cropping in sub-Saharan Africa. We evaluated, over three cropping seasons, conservation agriculture (reduced tillage and mulching) and farmer prioritized conventional tillage- and mulching-based options on seasonal soil water retention, and subsequent productivity of maize (*Zea mays* L.) and cowpea (*Vigna unguiculata* Walp L.) in mono- and inter-crops in Eastern Zimbabwe. The experiments were established on sand and clay soils. The first cropping season (2014/15) received evenly distributed rainfall (hereinafter referred to as 'wetter'), while the two succeeding seasons (2015/16 and 2016/17) had high incidences of intra-seasonal dry spells (hereinafter referred to as 'drier'). Overall, conventional tillage had 10–31% and 27–40% more moisture than conservation agriculture treatments on sand and clay soils, respectively. Soil moisture was most retained in intercrop under mulch-based conventional tillage. Maize grain yield during the 'wetter' season on sand soil was highest and least ($P > 0.05$) in intercrop under conservation agriculture (2.3 Mg ha^{-1}) and mulch-based conventional tillage (1 Mg ha^{-1}), respectively. On clay soil, intercrop under mulch-based conventional tillage (2.4 Mg ha^{-1}) yielded the best. During the 'drier' seasons, intercrop under mulch-based conventional tillage achieved the best maize grain yield on both sand (1.5 Mg ha^{-1}) and clay (1.4 Mg ha^{-1}) soils. Mulching increased maize grain yield by 55–90% during the 'drier' seasons, but reduced water use efficiency (WUE) by approximately 15% during the 'wetter' season. Over the three seasons, cowpea grain yield did not exceed 1 Mg ha^{-1} in both mono- and inter-crops. The study revealed contrasting short-term effects of soil water management options on soil moisture retention and intercropping productivity as dictated by seasonal rainfall variability and soil type. These findings point to the need for tillage and mulching typologies across soil types to minimize negative effects of rainfall variability on crop productivity.

1. Introduction

Food security in rainfed smallholder farming areas of Southern Africa is under threat from increased adverse weather conditions linked to climate change and variability. In particular, erratic rainfall, characterized by increased incidences of intra-seasonal dry spells, is impacting negatively on cropping systems [1,2]. Over the past two decades, conservation agriculture (CA), anchored on reduced tillage (RT), mulching and diversified cropping (mostly through rotations), has been promoted in Southern Africa as a climate smart technology for securing crop yields in the wake of increasing rainfall variability [3–5]. Increased rain water infiltration, soil water conservation, soil carbon sequestration and improved crop yields are some of the benefits associated with CA [3,6–9]. However, findings on soil water capture under CA systems have largely been inconsistent [10–12]. The inconsistences call for further studies to assess the performance of CA under contrasting soils to inform adaptation of the practice. In addition to CA, smallholder farmers in Southern Africa have traditionally used different soil water conservation

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techniques to minimize risk of crop failure in the face of the changing climate. Most of these techniques have centered on *in-field* water harvesting e.g. pot holing, planting basins, dead level contours, ridging, and deep ploughing soon after crop harvesting to conserve soil moisture and incorporate crop residues [13–20]. While the performance of some of these technologies have been evaluated in the past, farmers are continuously experimenting with their derivatives. It is therefore important to evaluate these techniques against established soil water conservation technologies such as CA. Results of such evaluations are not only key to broadening the range of soil water conservation options available to farmers, but help in the (re) designing and adaptation of technologies.

In Southern Africa, the reported high crop and water productivity under CA have mainly been under maize-grain legume rotations [5,8,17,21], with few studies on intercrops. Intercropping is a commonly practiced crop intensification option in smallholder farming systems of Southern Africa [22,23], but substantial crop yield losses or complete failure can occur due to competition for water between component crops [22,24,25]. On the contrary, complementarity in the use of soil water, nutrients and radiation as well as suppression of weeds, diseases and pests presents an over-yielding advantage of intercrops compared to mono cropping [23,25–28]. Intercrops are often practiced to increase food diversity on smallholder farms and ironically are also meant to minimize risk of total crop failure [22,29]. With crop production in Southern Africa mainly done on sandy soils typified by poor water holding capacity, prolonged dry spells make intercropping a high-risk practice. A question therefore arises whether the improved soil water retention under CA can support intercrops, whose aggregate yields are increasingly threatened by intra-seasonal dry spells.

Mulching in CA systems is mostly done using dead plant material, e.g. crop residues [30]. However, ensuring permanent soil cover through retaining crop residues is usually constrained by competing demands e.g. as livestock feed during the dry season. Furthermore, high prevalence of termites in these tropical environments does not allow mulch cover to last throughout cropping seasons [30,31]. In such environments, intercrops, through improved ground cover due to increased leaf area index (LAI), could provide complementary 'live' mulch, particularly during the later stages of crop growth. The contribution of 'live' mulch to soil moisture conservation and subsequent crop productivity has not been adequately evaluated in rainfed cropping systems of southern Africa. For this study, the objective was to evaluate conservation agriculture [reduced tillage (RT) and mulching] and farmer prioritized conventional tillage (CT)- and mulching-based options on seasonal soil water retention, and subsequent productivity of maize (*Zea mays* L.) and cowpea (*Vigna unguiculata* Walp L.) in mono- and inter-crops in Eastern Zimbabwe. The evaluation was over three cropping seasons. As with other CA-related studies previously done under on-farm and on-station conditions in Zimbabwe [8,21,32,33] and elsewhere in Africa [34], the three year period was considered sufficient to assess the short-term effects of CA on soil water dynamics and crop productivity against other farmer prioritized tillage- and mulching-based options.

2. Materials and methods

2.1. Study site description

The study was conducted over three successive seasons (i.e. 2014/15, 2015/16 and 2016/17 season) in Hwedza District of southern-eastern Zimbabwe. Hwedza District largely falls under agro-ecological zone (Natural Region) III receiving an annual rainfall of 600–800 mm in a unimodal rainy season between November and March. Crop production is predominantly rainfed and intra-seasonal dry spells significantly reduce yields of most crops [35]. The dominant soils are Lixisols characterized by poor inherent fertility and poor water holding capacity. However, patches of red clayey soils (Luvisols) which are inherently more fertile exist. The farming systems is largely dominated by mixed crop-livestock enterprises. Maize is an important staple food and cash crop. Cowpea (*Vigna unguiculata* Walp. L.), is among the commonly grown legumes, which contribute significantly to dietary protein [36,37]. In situations where farmers practice intercropping, cowpea is often planted as a secondary crop to maize at low plant densities resulting in low aggregate yields. Conventional ploughing is the dominant tillage practice, with a small percentage of farmers practicing reduced tillage such as ripping and planting basins.

2.2. Selection of treatments for experimentation

We combined household survey data with farmer participatory research enquiries to select treatments that were tested in this study. The household survey was conducted across 300 households to interrogate soil water conservation adaptation options employed by farmers in the face of increasing seasonal rainfall variability, among other climate change and livelihoods issues. After the household survey, a community meeting was conducted to share the survey results followed by focus group discussions (FGDs) to build consensus on the prioritized soil water conservation adaptation options. The FGDs were conducted with 10 men and 10 women with farming experience spanning over 30 years, community leaders (village heads, headmen) and local Agriculture Extension Officers. The participants were first divided into men and women only groups and then combined for consensus building. The farmers' prioritized options are shown in Table 1. The treatments chosen for this study consisted of CA and other farmer prioritized tillage- and mulching-based options [conventional (CT) and two mulching rates (mulch vs. no mulch)] under three cropping systems (maize monocrop, cowpea monocrop and maize-cowpea intercrop).

2.3. Selection of experimental sites and experimental design

The farmers suggested evaluation of the soil moisture conservation options on major soil types found in the area viz. sand and red clay soils.

Table 1
Prioritized soil water conservation agronomic adaptation options from household survey ($N = 300$) and focus group discussions in Hwedza district, eastern Zimbabwe.

Prioritized option	Perceived benefits[a]
1. Deep ploughing	The deep ploughing during land preparation allow for more rainwater infiltration throughout the season, and incorporate crop residues. Deep ploughing is highly beneficial on compacted soils.
2. Mulching	This is a common practice in home gardens under maize and vegetable production during the dry season (May–November). Locally available thatching grass (*Hyparrhenia filipendula* (L.) Stapf.) is used to cover the soil surface. The mulching significantly reduces frequency of watering. According to the farmers, grass could be a better mulching material for maize cropping than crop residues as the latter is mainly used as livestock feed.
3. Crop diversification	This gives some insurance against complete crop failure. In intercrops, a secondary crop may provide 'live' mulching effect to the primary crop thereby reducing soil water loss through evaporation.
4. Manure application	Improves soil fertility status and can act as mulch when applied in large quantities.
5. Supplementary irrigation	This is mostly beneficial to households with home gardens located in wetlands or near perennial rivers where they can use buckets to water their crops during the dry season. However, cannot be used on bigger land areas.
6. Conservation agriculture	This has been promoted by government and Non-Governmental Organizations and the major benefit has been improved rain water capture from rip lines and planting basins and mulching leading to high crop yields in drought years.

[a] Farmer explanations given during community meetings and FGDs

Transect walks and consultations with local leaders and Agricultural Extension Officers were done to identify and select fields that hosted the experiments. Chidora field [18° 39′ S 31° 37′ E, 1409 m above sea level (m.a.s.l.)] located on sand soil and Masawi field (18° 41′ S 31° 45′ E, 1273 m.a.s.l) on a red clayey soil were thus selected as the representative sites. The selected fields were big enough to accommodate all the treatments, accessible, and had similar catenary positions, and management history. The experimental sites also served as co-learning and information and knowledge sharing platforms under the SOFECSA Learning Centre approach [38]. The treatments were arranged in a split plot design, with soil water conservation option [CT plus mulch (mulch-based conventional tillage), CA and CT without mulch (control)] as the main plot factors, and cropping system (intercrop or mono crops) as the sub-plot. The treatment factors were replicated three times in plots measuring 9 × 7 m (63 m^2). For initial characterization, ten soil samples were randomly taken on each field to a depth of 45 cm. The samples were thoroughly mixed in a plastic dish into a composite sample, air-dried, and sieved through a 2 mm-mesh sieve for determination of soil texture (hydrometer method), pH (0.01 M $CaCl_2$), organic carbon (SOC) (modified Walkley-Black method), total N (Micro-Kjeldahl method) and available P (Olsen method) [39]. Undisturbed soil samples were taken using a core to determine bulk density. The soil physical and chemical properties of the fields are shown in Table 2.

2.4. Establishment and management of experiments

For CT, an animal-drawn mouldboard plough was used to till the whole plot to a depth of approximately 30 cm just before planting. Under CA, a ripper tine attached to the beam of an ordinary ox-drawn mouldboard plough was used to open rip lines approximately 30 cm deep. For mulching, sun-dried locally available thatching grass (*Hyparrhenia filipendula* (L.) Stapf.) was applied at 2.5 Mg ha^{-1} on a dry weight basis soon after maize sowing on all mulched plots to achieve approximately 30% soil surface cover. The length of the grass was nearly 180 cm, and was chopped into approximately 30 cm pieces for easy spreading on the soil surface. The tillage and mulching operations were the same across seasons, and the mulching material was from the same sources (field edges). An early maturing hybrid maize variety, SC 513, (approximately 130 days to maturity), and a semi-erect cowpea cultivar, CBC2, (about 115 days to maturity) were used as the test crops. Maize was sown using an inter row spacing of 0.90 m and intra-row spacing of 0.30 m in both monocrop and intercrop, to give a plant population density of approximately 37 000 plants ha^{-1}. Cowpea was sown two weeks after maize to reduce competition for soil water during the early crop growth stages as well as spreading the labour. A row spacing of 0.40 m and an intra-row of 0.20 m were used in both mono and intercrops, resulting in a plant population density of approximately 125 000 plants ha^{-1}. The intercrop had two rows of cowpea in-between a maize row. Maize was planted with the first effective rains during mid-December in the 2014/15 and 2016/17 season, and late December during the 2015/16 season. For maize, cattle manure was applied at 7 t ha^{-1} at planting, with P and N added at 26 kg ha^{-1} and 90 kg N ha^{-1}, respectively. Phosphorus and part of the N fertilizer were applied basally as Compound D fertilizer (7% N, 14% P_2O_5, 7% K_2O), with the remainder of the N added as top-dressing ammonium nitrate (34.5% N) in 2 splits (40% and 60% at 4 and 6 weeks after emergence, respectively). The monocropped cowpea only received basal P and starter N as Compound D at 26 kg ha^{-1} and 13 kg N ha^{-1}, respectively. In the case of intercrops, the basal mineral fertilizer was halved, with 50% applied during maize planting and the remainder at planting of the cowpea crop. Weed control in CT plots was done manually using hand hoes. In CA plots, glyphosate (N- (phosphonomethyl) glycine) herbicide was sprayed at 3.5 l ha^{-1} before planting for initial weed control. Thereafter, the plots were kept weed free through scratching the soil surface using hand hoes.

Rainfall was the only source of water during all the cropping seasons. The rainfall was measured at each site using a standard rain gauge mounted 1 m above the ground on an uncropped open area close to the experimental fields. The 2014/15 season had shorter dry spells (hereinafter referred to as the 'wetter' season), while the 2015/16 and 2016/17 seasons were characterized by prolonged dry spells, particularly during the first 90 days after sowing (DAS) (hereinafter referred to as the 'drier' seasons). The rainfall distribution during the three growing seasons under study is shown in Fig. 1. The longest dry spell exceeding two weeks occurred during the 2016/17 season. This started during the early vegetative development stage and ended almost two weeks into the flowering stage for both crops. Harvesting was done at physiological maturity from 30 m^2 net plots. After harvesting all the crop residues were removed and bulked at the host farmers' homesteads to provide for animal feed during the winter period. Maize and cowpea grain yield was quantified at 12.5% and 9.5% moisture content, respectively. Treatments were maintained in the same plots with all the procedures repeated during the second (2015/16) and third (2016/17) season except that cattle manure was only applied during the first season to last for two to three seasons [40].

Table 2
Physical and chemical characteristics of top soil (0–45 cm) at experimental fields.

Soil parameter	Sand soil	Red clay soil
Physical		
Bulk density (g cm^{-3})	1.61 ± 0.11	1.46 ± 0.18
Sand (%)	75 ± 0.4	18 ± 0.3
Clay (%)	9 ± 0.2	56 ± 0.6
Chemical		
pH (0.01 *M* $CaCl_2$)	4.66 ± 0.1	4.52 ± 0.1
Total N (%)	0.03 ± 0.004	0.10 ± 0.005
Available P (mg kg^{-1})	3.80 ± 0.23	8.46 ± 0.2
K ($cmol_{(c)}$ kg^{-1})	0.18 ± 0.06	0.29 ± 0.04
SOC (%)	0.47 ± 0.2	0.77 ± 0.3

Figures in parentheses indicate standard error of mean (SEM).

2.5. Measurements

2.5.1. Soil water dynamics

Soil water content was measured using the gravimetric method. Soil samples were collected at three random positions per plot from between crop rows using stainless steel cores. The samples were collected at 15 cm depth increments down to 45 cm. According to Vogel [33], the 45 cm depth is normally considered the effective rooting zone for most crops, and is most exposed to evaporative soil moisture losses. Soil water measurements were first taken at planting to represent the initial soil water content, followed by repeated measurements which started 28 and 14 days after maize and cowpea planting, respectively. This period was deliberately selected to allow the cowpea crop to fully establish, as it was planted two weeks after maize. The rest of the measurements were subsequently taken three days after every rainfall event at an interval of 5 days until the next rain event. Immediately after sampling, the soils were packed in air- and water-tight zip-lock plastic bags and transported to the laboratory. The samples were then oven-dried at 105 °C for 48 h to determine the gravimetric water content as outlined by Anderson and Ingram [39]. The gravimetric soil water content was converted to the volumetric values using measured soil bulk density values as follows:

$$\theta = \left({}^{ds}/_{dw} \right) . U \tag{1}$$

where: θ = Volumetric water content (cm^3 cm^{-3}); ds = soil bulk density (g cm^{-3}); dw = water density (g cm^{-3}); U = gravimetric water content (g).

The soil water content in millimetres (mm) was calculated as the product of volumetric water content (cm^3 cm^{-3}) and soil depth (mm).

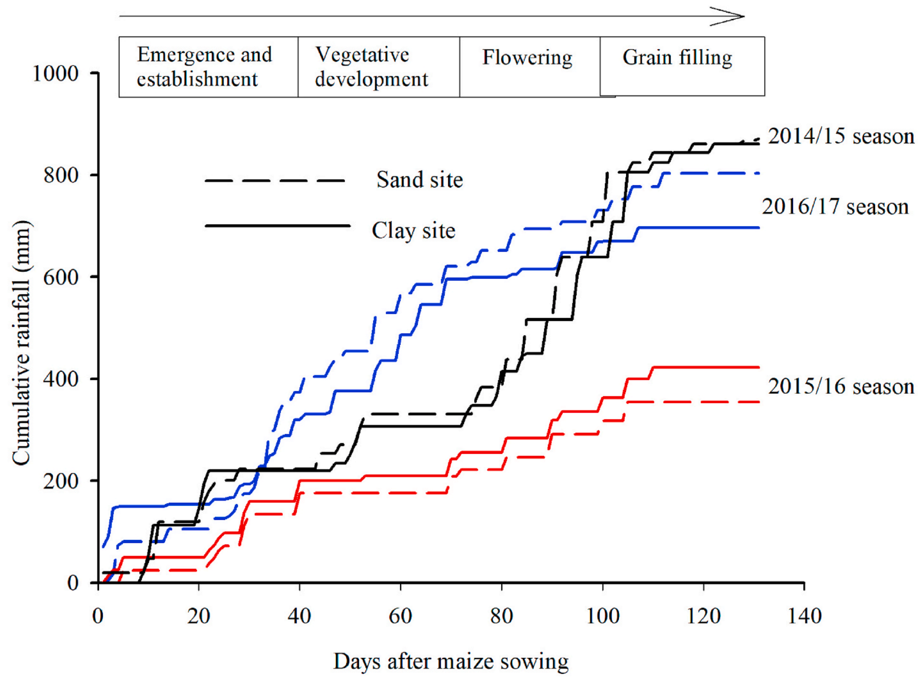

Fig. 1. Cumulative in-crop rainfall distribution at study sites during the 2014/15, 2015/16 and 2017/18 seasons.

Soil water available for plants was calculated as the difference between the measured soil water content and the lower limit value. The lower limit of water availability was estimated on the basis of soil water content during the driest month [41]. In this study area, soil sampling to determine lower limit of water availability was done early October (driest month) during the first season.

2.5.2. Leaf area index (LAI)

Leaf area index (LAI) was measured at early vegetative (21 and 7 days after sowing (DAS)) for maize and cowpea, respectively, early reproductive (42 and 34 DAS), and grain filling (63 and 49 DAS) to determine crop canopy cover development over time. For maize, eight plants from the two rows in each plot were randomly selected and labelled. A non-destructive method was used to estimate the individual leaf area based on leaf length and width. Leaf length was measured from the collar to the tip, and leaf width was measured at the widest point of the leaf. The area of each leaf was then estimated using the equation by Mokhtarpour and others [42] as follows:

$$Leaf\ area = Length\ x\ width\ x\ 0.75 \quad (2)$$

For cowpea, six plants were selected from each plot, and the area of each leaf estimated using the equation by Lima and others [43] as follows:

$$Leaf\ area = ((0.6597(Length\ x\ Width) + 2.1745) \quad (3)$$

Leaf area index was calculated as the sum of the areas of total plants per unit area (m^2 leaf area m^{-2} of soil surface). For intercrops, crop cover development was calculated as the total LAI values of maize and cowpea.

2.5.3. Crop water capture and use efficiency

Evapo-transpiration (ET) was estimated at different crop growth stages (i.e. vegetative, tasselling/flowering, grain filling and harvesting for both crops) to epitomise apparent crop water use using the following water balance equation:

$$ET = IW + TR - (0.25TR + EW) \quad (4)$$

where: ET = Evapo-transpiration (mm); IW = Initial soil water at the beginning of each crop stage (mm); TR = Total in-crop rainfall received during each stage (mm); EW = Soil water at the end of each crop stage (mm).

A constant value of 0.25 was used to represent drainage and runoff losses of the rainfall received based on 10–25% range proposed for semi-arid southern Africa by Rockström and Falkenmark [2]. The profile recharge by capillary rise was considered negligible. The total water capture during the season was then calculated as the summation of estimated ET values during all crop growth stages.

Water productivity was then calculated as grain yield per unit of water used as follows:

$$WUE = Y/_{ET} \quad (5)$$

where: WUE = water use efficiency (kg mm^{-1} ha^{-1}); Y = crop yield (kg ha^{-1}); ET = evapotranspiration (mm).

Comparative change in water resource capture and use efficiency was calculated according to Morris and Garrity [26] to relate intercropping across soil types and seasons. The indices were based on relative rather than absolute values. Change in water resource capture and use efficiency was calculated as shown in Equation (6).

$$\Delta X = \left[\left(\frac{X\ ic}{Pm\ \ X\ \ mm + Pc\ \ X\ \ cm}\right) - 1\right] \times 100 \quad (6)$$

where: X = water capture/water use efficiency; ic = intercrop; *Pm* = proportion of maize in intercrop; *Pc* = proportion of cowpea in intercrop; mm = maize mono crop and cm = cowpea monocrop.

2.6. Statistical analysis

Data on all the measured (soil water dynamics, LAI, grain yield) and calculated parameters (water use efficiency) were first tested for normality using the Shapiro-Wilk test. Afterwards the data was subjected to analysis of variance (ANOVA) using GenStat (2010, 14th Edition) to test for the effects of soil water conservation options on crop productivity in mono- and intercrops, soil water dynamics, and resource use efficiency. In the analysis, which was carried out separately for each cropping season and soil type, tillage and cropping system were considered fixed factors whereas replication were considered random factors. Significantly different treatments were separated using Fisher's Protected LSD (P ≤ 0.05) test. Differences across soil types and seasons were only made on descriptive basis using relative changes according to Morris and Garrity [26].

Intercropping performance was evaluated on the basis of grain yield benefit (GYB) which can either be positive (advantage) or negative (penalty). This was calculated as the percentage difference between grain yield in intercrop and corresponding sole crop for the control treatment (CT without mulch). Conventional ploughing without mulching is the most common farmer practice on smallholder farms in Zimbabwe, and was therefore considered the control. The GYB was computed as follows:

$$GYB\% = \left(\frac{Yi - Ym}{Ym}\right) \times 100 \tag{7}$$

where: *Yi* is the intercropping grain yield, and *Ym* is the mono cropping yield under CT + no mulching plots.

In intercropping, it is most desirable that the yields of component crops is maintained or improved compared to the mono crops. The second best option would be for the grain yield of the primary crop (in this case maize) to be maintained such that the yield of the companion crop (cowpea) becomes a bonus. Negative values, zero change and positive values mean a yield penalty, maintenance and an improvement, respectively.

3. Results

3.1. Soil water content

Trends in soil water dynamics during the 2015/16 and 2016/17 were similar. As such, the reported soil water dynamics is therefore a comparison between 2014/15 ('wetter') and 2015/16 season ('drier') cropping seasons. During the 'wetter' season, plant available soil water content across the season ranged between 14 and 26 mm on the sand (Fig. 2a) and 17–30 mm on clay (Fig. 2c) soils. However, during the 'drier' season, the values did not exceed 14 and 25 mm on the sandy (Fig. 2b) and clayey (Fig. 2 d) soils, respectively. During the 'wetter' season, the intercrop + mulched CT treatment consistently had the

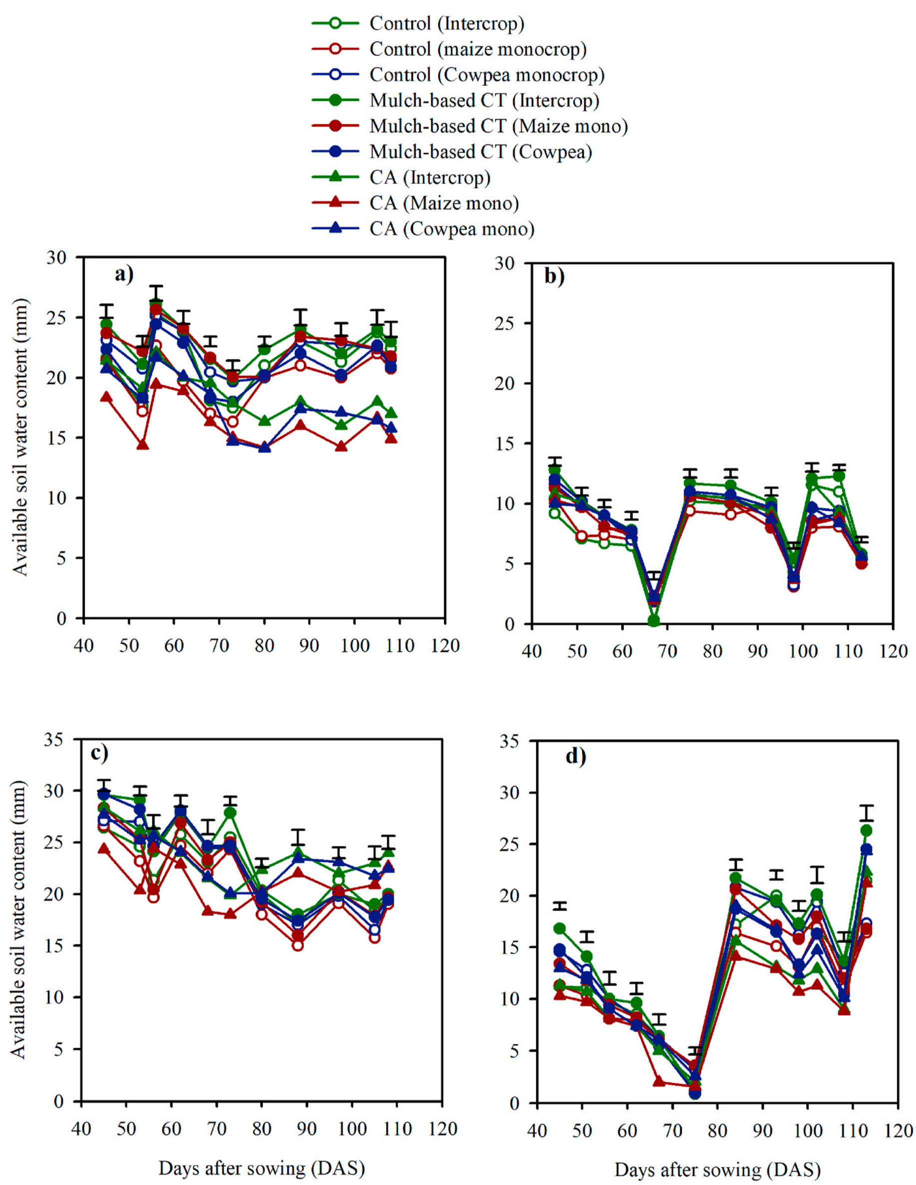

Fig. 2. Plant available soil water content (0–45 cm) under different soil water conservation and, maize and cowpea cropping options on sand (a and b) and clay (c and d) soil, respectively, during the 'wetter' and 'drier' season in Hwedza, eastern Zimbabwe. Error bars represent $LSD_{0.05}$.

greatest plant available soil water content ($P \leq 0.05$) particularly on the sand soil (Fig. 2 a). For clay soil, such was the case up to 80 DAS before intercrop + CA gave the highest moisture retention for the remainder of the season (Fig. 2c). The greatest values of 26 mm and 22 mm for CT and CA, respectively, were achieved at 56 days after sowing (DAS) maize on the sand soil (Fig. 2a). On the clay site, the highest soil moisture content of 30 mm was recorded at 42 DAS maize (Fig. 2c). Maize monocrop under CA had the least available soil water content throughout the 'wetter' season on sand soil (Fig. 2a) and up to around 80 and 66 DAS of maize and cowpea, respectively, on the clay soil (Fig. 2c). Overall, CT treatments had approximately 10–31% (sand soil) and 27–40% (clay soil) more soil water content than CA. Mulching increased plant available soil water content, particularly during the early part of the season (i.e. between 42 and 80 DAS of maize). For example, on the sand soil the increase in soil water due to mulching under intercrops ranged from 13 to 39%, with more increase under CT than CA treatments. On the clay soil, mulching increased soil water by 15 and 45% under the CT and CA treatments, respectively. The mulching effect was less apparent later in the season (i.e. after 80 and 66 DAS of maize and cowpea, respectively) as most of the grass mulch cover had been destroyed by termites.

During the 'drier' season, the first soil water content measurements coincided with the beginning of the longest dry spell which lasted 29 days. Treatment differences were only observed during the first two weeks of that dry spell. The CT + mulch + intercrop treatment recorded the greatest amount of plant available soil water, amounting to 18% and 14% more than the corresponding CA (RT + mulch + intercrop) treatment on sand and clay soil, respectively (Fig. 2b and d). Intercrop and maize monocrop without mulch treatments had generally the least available soil water content (Fig. 2b and d). On the clay soil, mulching increased available soil water by 51% and 44% in intercrops under CT and CA, respectively (Fig. 2d). On the sand soil, the equivalent increases were 39% and 34% (Fig. 2b). After the first two weeks of the 29-days dry spell, available soil water content, declined to near zero mm, especially in intercrops (Fig. 2b and d). After the dry spell, the intercrop + mulch + CT treatment recorded the highest plant available soil water regardless of soil type. Consistent with the 'wetter' season, there were no significant differences in plant available soil water content between intercropping with and without mulch treatments around 80 and 66 DAS of maize and cowpea, respectively.

3.2. Leaf area index (LAI)

Overall, leaf area indices under intercrops almost doubled that of monocrops (Table 3). During the 'wetter' season (sand soil), the CA treatment (RT + intercrop + mulch) had the greatest LAI (3.5), which was 70% more than for the CT + intercrop + mulch treatment (Table 3). However, on the clay soil, the difference between CT and CA treatments was not significant (Table 3). Similarly, mulching did not influence LAI on the clay soil. During the 'drier' season, CT + intercrop + mulch had the greatest LAI of almost 3 at grain (maize)/pod filling (cowpea) stages (Table 3). Mulching increased LAI by about 20%, especially in intercrops.

3.3. Maize grain yield

Overall, maize grain yields were higher during the 'wetter' than the 'drier' season (Table 4). During the 'wetter' season on the sand soil, CA (RT + mulch + intercrop) attained the highest maize grain yield of 2.3 Mg ha^{-1}, which was 50% more than under CT + mulch + intercrop. The CT + mulch treatment under maize monocropping achieved the least yield of 1.0 Mg ha^{-1} (Table 4). Mulching suppressed maize yields in the conventionally-tilled treatments. The low yields could have been due to waterlogging following incessant rains around 60 DAS (field observations by the first author). On the clay soil, CT + mulch + intercrop achieved the greatest grain yield of 2.4 Mg ha^{-1} (Table 4). Mulching increased maize grain yield by approximately 15% across treatments on the clay soil. Maize yield penalty was recorded in CT + mulch + intercrop on sand soil during the 'wetter' season (Table 5). The benefits of treatment combination on the sand soil followed the order: CA (62.4%) > CT without mulch (8.5%) > CT + mulch (−9.2%) (Table 5). On clay

Table 3
Leaf area index (LAI) of maize and cowpea at different crop development stages under different soil water conservation and cropping options on sand and clay soil during the 'wetter' and 'drier' season.

Treatment	Leaf area Index (LAI) (m^2 m^2)					
	Sand soil			Clay soil		
	Vegetative	Reproductive	*Grain filling	Vegetative	Reproductive	Grain filling
'Wetter' season						
CA						
Intercrop	2.22 a	3.00 a	3.50 a	2.11 a	2.84 a	3.06 b
Maize	1.10 c	1.44 c	1.56 d	0.94 c	1.38 e	1.47 ef
Cowpea	1.20 b	1.54 b	1.73 c	1.38 b	1.57 f	1.73 cd
CT + mulch						
Intercrop	1.11 c	1.84 b	2.06 b	2.24 a	3.10 a	3.40 a
Maize	0.84 e	1.08 d	1.17 ef	1.10 c	1.44 de	1.56 de
Cowpea	0.84 e	1.17 d	1.27 e	1.43 b	1.64 b	1.79 c
CT only (control)						
Intercrop	1.02 d	1.42 c	1.68 cd	2.10 a	2.98 a	3.36 a
Maize	0.69 f	0.85 e	1.03 f	0.88 c	1.15 f	1.29 f
Cowpea	0.87 e	1.19 d	1.31 e	1.40 b	1.61 cd	1.77 c
'Drier' season						
CA						
Intercrop	1.11 c	1.84 c	2.06 c	1.31 c	1.84 c	2.06 c
Maize	0.84 d	1.08 e	1.10 e	0.84 e	1.08 e	1.18 f
Cowpea	0.84 d	1.17 e	1.29 e	0.84 e	1.17 e	1.29 ef
CT + mulch						
Intercrop	2.10 a	2.70 a	3.10 a	2.10 a	2.65 a	2.91 a
Maize	1.20 c	1.60 d	1.74 d	1.10 d	1.50 d	1.64 d
Cowpea	1.25 bc	1.47 d	1.69 d	1.25 cd	1.47 d	1.69 d
CT only (control)						
Intercrop	1.93 a	2.33 b	2.6 b	1.73 b	2.13 b	2.40 b
Maize	0.86 d	1.23 e	1.52 d	0.80 e	1.23 e	1.40 e
Cowpea	1.35 b	1.54 d	1.68 d	1.35 c	1.54 d	1.68 d

*Grainfilling for maize or pod filling for cowpea. Different letters within each column indicate significant differences ($p < 0.05$) within each season.

Table 4
Grain yield (Mg ha^{-1}) of maize and cowpea intercrops and sole crops under different soil water management options on sand and clay soils during the 'wetter' and 'drier' season in semi-arid Zimbabwe.

Treatment	Grain yield (Mg ha^{-1})							
	'Wetter' season				'Drier' season			
	Sand soil		Clay soil		Sand soil		Clay soil	
	Maize	Cowpea	Maize	Cowpea	Maize	Cowpea	Maize	Cowpea
CA								
Intercrop	2.29 a	0.43 b	2.13 b	0.23 c	1.11 b	0.30 bc	0.93 b	0.26 bc
Maize sole	1.81 b		1.86 cd		0.83 c		0.81 b	
Cowpea sole		0.49 ab		0.36 b		0.36 b		0.37 a
CT + mulch								
Intercrop	1.28 d	0.37 cd	2.43 a	0.37 b	1.45 a	0.22 c	1.38 a	0.24 bc
Maize sole	1.01 e				1.01 b		1.03 b	
Cowpea sole		0.31 d	2.02 bc	0.41 b		0.47 a		0.33 ab
CT only (control)								
Intercrop	1.53 c	0.51 a	2.11 b	0.39 b	0.69 c	0.28 b	1.02 b	0.18 c
Maize sole	1.41 c		1.71 d		0.68 c		0.74 b	
Cowpea sole		0.55 a		0.48 a		0.35 b		0.22 c

Different letters within each column indicate significant differences ($p < 0.05$).

Table 5
Overall intercropping effect on maize and cowpea grain yield advantage (+) or penalty (−), and water capture (WC) and use efficiency (WUE) relative to maize sole crop during the 'wetter' and 'drier' cropping seasons in Hwedza, eastern Zimbabwe.

Water conservation option	Sand soil				Clay soil			
	Maize	Cowpea	WC	WUE	Maize	Cowpea	WC	WUE
'Wetter' season								
CA	62.4	−21.8	24	56	24.6	−52.1	31	−3
CT + mulch	−9.2	−32.7	23	−26	42.1	−22.9	55	36
CT only (control)	8.5	−7.3	12	−3	23.4	−18.8	9	46
'Drier' season								
CA	63.2	−34.3	50	34	−9.7	18.2	88	51
CT + mulch	113.2	−20.0	78	38	34.0	9.1	65	62
CT only (control)	1.5	−37.1	30	1	−1.0	−18.2	12	47

soil, CT + mulch recorded the best intercropping maize yield advantage of 42% (Table 5).

During the 'drier' season, CT + mulch + intercrop had the greatest maize grain yield regardless of soil type (Table 4). Under this treatment the maize yields were 1.5 Mg ha^{-1} on the sandy soil and 1.4 t ha^{-1} on the clay soil (Table 4). On the sand soil, mulching increased maize grain yield by between 49 and 131% (Table 4). Similarly on the clay soil, yield increase due to mulching ranged from 35% to 107% (Table 4). The intercropping benefits followed the order CT + mulch (113%) > CA (63%) > CT without mulch (2%) on sand soil (Table 5). On clay soil the benefits followed the order: CT + mulch (34%) > CT + no mulch (−1%) > CA (−9.7%) (Table 5).

3.4. Cowpea grain yield

Cowpea productivity was generally higher during the 'wetter' than 'drier' season although grain yields did not exceed 1 Mg ha^{-1} (Table 4). On the sand soil, the non-mulched treatments recorded the best yield of 0.56 Mg ha^{-1} in the 'wetter' season (Table 4). However, on the clay soil, there were no significant differences among treatments, with grain yields not exceeding 0.40 Mg ha^{-1} (Table 4). During the 'wetter' season, mulching resulted in cowpea grain yield penalties of 33% and 52% on the sand and clay soil, respectively (Table 5). Conversely during the 'drier' season, yield penalties were highest in the unmulched treatments (Table 5).

3.5. Crop water capture and use efficiency

Crop water capture was generally greatest in the CT + intercrop + mulch treatment during both seasons (Fig. 3). During the 'wetter' season on the sand soil, only cropping system showed significant differences with intercrop capturing about 39% more than the monocrops (Fig. 3a). For the clay soil, 59% and 44% of the in-crop rainfall received was captured under CT and CA treatments, respectively. Mulching significantly ($P < 0.05$) increased crop water capture in the intercrops. A similar trend was repeated on the clay soil. During the 'drier' season, CT and CA treatments captured 53% and 44%, respectively, of the in-crop rainfall received on the sand soil. For the clay soil, corresponding values were 52% and 42%. As was the case in the 'wetter' season, mulching increased crop water capture in the intercrops during the 'drier' season (Fig. 3b and d).

Crop water use efficiency (WUE) in the 'wetter' season was generally highest in intercrops, and least in the cowpea monocrop (Fig. 4). Overall, CA treatments on the sand soil were approximately 21% more efficient in utilizing water than CT treatments, particularly in intercrops. In contrast, CT was 39% more efficient than CA on the clay soil (Fig. 4c). During the 'drier' season, tillage did not significantly ($P > 0.05$) influence WUE. However, mulching increased WUE, particularly in intercropped treatments. For instance, on the sand soil, mulching increased WUE by 36% and 52% in CT and CA treatments, respectively (Fig. 4b). A similar trend was observed on the clay soil (Fig. 4d).

The changes in water capture/use in maize-cowpea intercropping relative to the maize mono crop (common cropping practice) were smaller during 'wetter' season compared to 'drier' season on both soil types (Table 5). Overall, crop water capture was improved through intercropping regardless of the season. Contrarily, WUE was negatively impacted under CT (−3%) and CT + mulch (−26%) on sand soil during the 'wetter' season. On clay soil, negative effect was only recorded under CA (−3%). During the 'drier' season, CT + mulch was the most efficient treatment in utilizing water on both the sand (38%) and clay (62%)

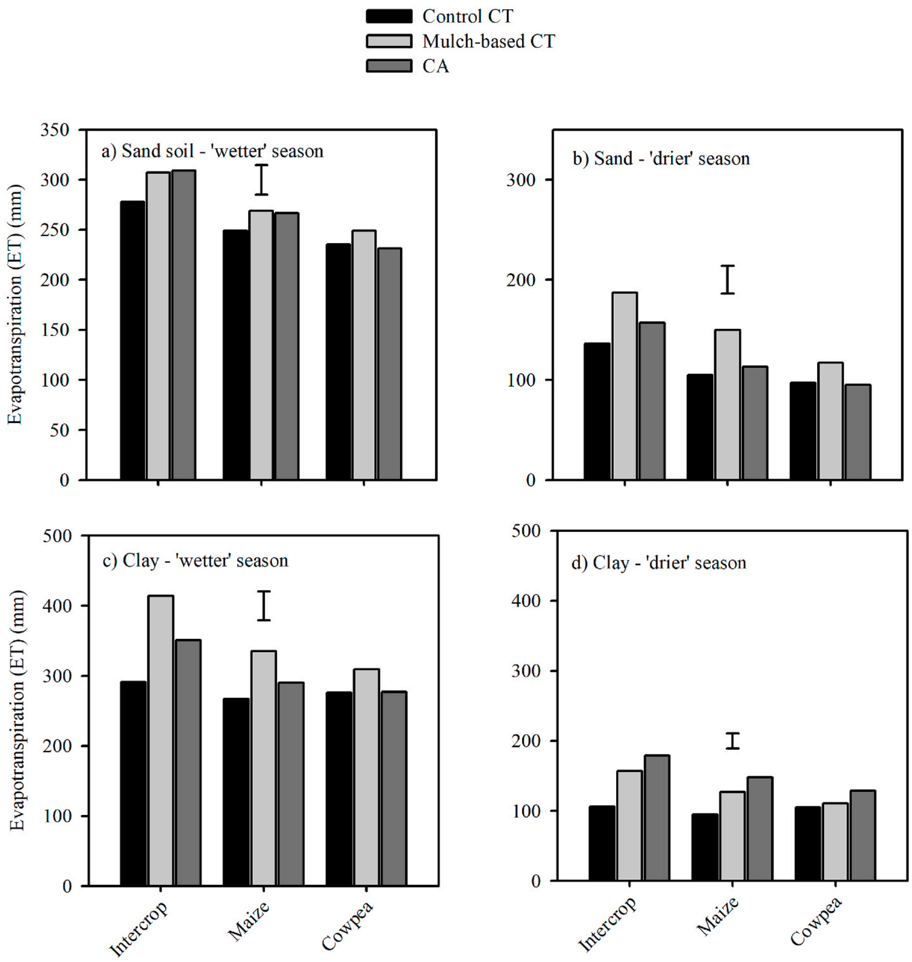

Fig. 3. Total crop water use of maize-cowpea intercrop and monocrops under different soil water conservation and cropping options on sand (a and b)) and clay (c and d) during the ‘wetter’ and ‘drier’ season, respectively. Error bars represent $LSD_{0.05}$.

(Table 5).

4. Discussion

4.1. Effects of soil type and seasonal rainfall distribution on crop productivity in intercrops

Available soil water content was greatest under the combination of conventional tillage (CT), mulching and maize-cowpea intercrop during all seasons under both soil types. This was most likely due to maximized rain water infiltration from loosened soil coupled with reduced evaporative loss owing to mulch and denser canopy cover. Increased soil water retention under mulching has also been confirmed in other studies [30, 44–48]. In this study, the mulching benefit was more under CT than CA, a result which is of utmost importance for smallholder farmers who usually prefer interventions that provide immediate benefits [49]. Benefits under CA tend to be evident in the long term [50]. The need to adapt CA principles to suit different biophysical and socioeconomic settings has been emphasized in a number of studies [11,50,51]. With greatest soil water content, the conventional tillage (CT) + mulching combination resulted in increased grain yields and WUE in maize/cowpea intercrop on the clay soil during the two contrasting seasons and on sand soil during the ‘drier’ season. Denser canopies in intercrops increase water uptake and transpiration capacity thereby increasing WUE [48,52]. Competition for water between crops in intercrops is a common challenge under water-limited environments [24,25], and under extreme conditions, total crop failure can occur [22,25]. Contrarily, the CA treatment was the most productive on the sand soil during the ‘wetter’ season despite achieving lower plant available soil water content. Plants in mulch-based CT plots showed waterlogging symptoms which were not showing under CA plots, suggesting some shedding of excess water under the later practice. Reduced tillage practices under CA can shed excess water through increased runoff [10, 11]. These results therefore indicate reduced intercrop productivity when mulch is added to conventionally-ploughed soils during seasons with high amounts of rainfall, particularly on sand soils. Similarly, in South Africa, Tsubo and others [53] reported no significant differences in WUE between maize-bean intercrop and the monocrops during a high rainfall season. Our results suggest that, in the wake of the increasing rainfall variability being experienced in the region due to climate change, both CT and CA are critical for increasing crop productivity, particularly on sand soils. Farmers could designate CA and conventional tillage options to different fields and soil types each cropping season to minimize risk of total crop failure. This points to need for designing tillage and mulching typologies that integrate CA concepts with conventional practices taking into consideration such factors as soil type, rainfall zone and farmer resource endowment.

4.2. Complementarity between ‘dead’ and ‘live’ mulch improves soil water conservation in intercrops

Overall, the intercrop + mulch treatment had the greatest plant available soil water content even after the grass residue cover had been destroyed by termites. This result suggest that during the early crop

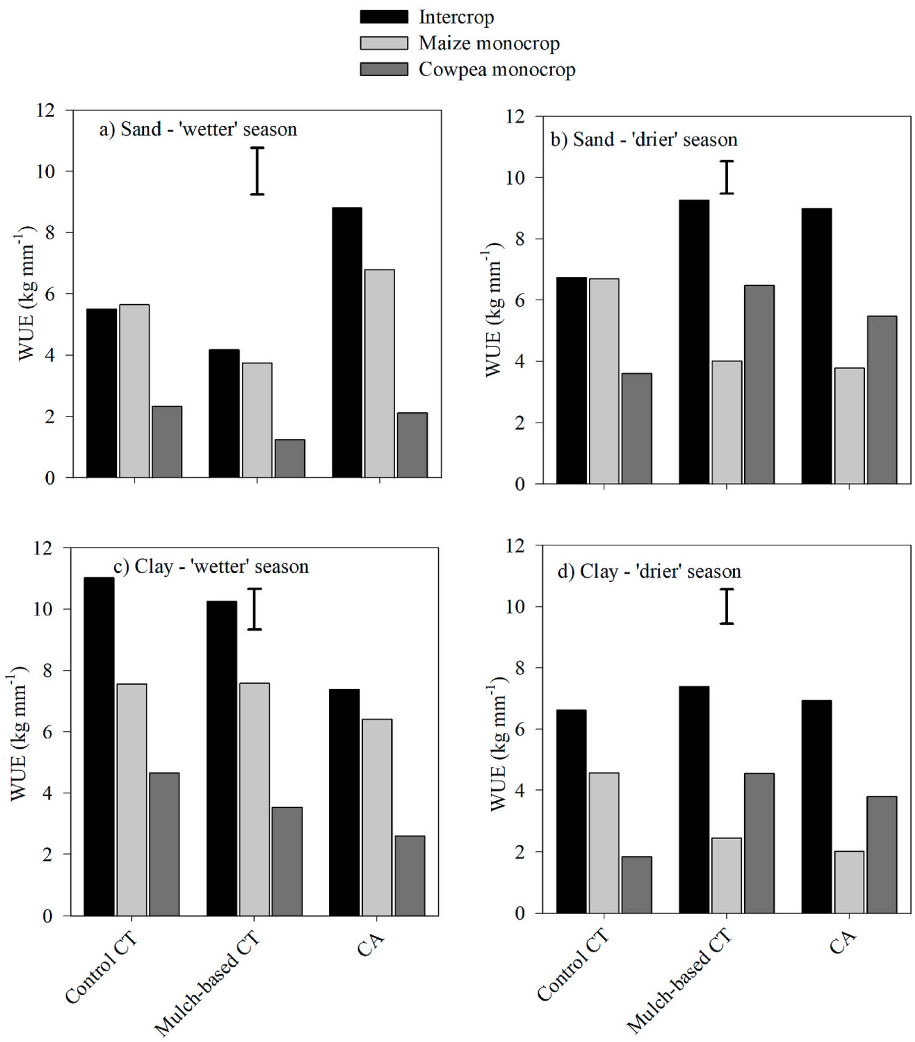

Fig. 4. Grain water use efficiency (GWUE) of maize and cowpea in intercrops and mono crops under different soil water conservation options on sand and clay soils during the 'wetter' and 'drier' season in Hwedza, eastern Zimbabwe. Error bars represent $LSD_{0.05}$.

growth stages the presence of 'dead' mulch could have minimized evaporative soil water loss, while cowpea canopy cover provided 'live' mulch during the latter part of the season. The gradual increase in soil water content in intercrops without mulch during both seasons further confirms the 'live' mulching effect in intercrops. With increased LAI in intercrops, productive soil water loss through transpiration is facilitated rather than non-productive surface evaporation. This is in agreement with the findings from Shackel and Hall [52] where relay cropping sorghum with cowpea reduced soil water evaporation by almost 70%. Cowpea is known to have high ground cover when planted at high population densities [49,54]. Thus, in this study, the maize-cowpea intercrop could have allowed for 'permanent' mulching leading to enhanced soil water conservation. The combination of 'dead' and 'live' mulch therefore prove a plausible option for enhancing soil moisture retention on most smallholder farms of southern Africa where the available crop residues face competing uses e.g. as fuel, construction material and livestock feeding. Thus, intercropping has a significant role to play through 'live' mulching due to improved ground cover. However, there is still need to strategically target addition of available 'dead' mulching material at early growth stages of the crops before attainment of full ground cover.

5. Conclusions

We sought to evaluate, CA [reduced tillage (RT) and mulching] against other farmer prioritized tillage- and mulching-based option [conventional (CT) and two mulching rates (mulch vs. no mulch)] with respect to seasonal soil water dynamics, and subsequent productivity of maize and cowpea in inter- and mono-crop on sand and clay soils. Our study findings showed greatest soil water retention in mulch-based conventional tillage on both soil types during all the three seasons. This reduced the risk of inter-specific competition during periods of water stress (prolonged intra-seasonal dry spells) thereby maximizing yield advantage of intercrops over monocrops particularly during the 'drier' seasons. However, crop yields and water use efficiency were lower under CT than CA during the 'wetter' season, particularly on the sandy soil. Under such conditions, CA was rather the best option for increasing crop productivity, probably by shedding excess water from the field. These contrasting results imply that, under rainfed conditions, soil water conservation agronomic techniques that employ both CT and RT combination with mulching are key to increasing intercropping productivity, and minimizing risk of total crop failure at farm level in the wake of the changing climate in Zimbabwe and other parts of southern Africa.

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