Impacts of conservation agriculture-based farming systems on optimizing seasonal rainfall partitioning and productivity on vertisols in the Ethiopian drylands

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A B S T R A C T
Field water conservation practices are a way to build resilience against drought by increasing productive green water through reducing runoff and evaporation and thereby boosting crop yield. A field study was undertaken on permanently kept rainfed experimental plots established in 2005 on a vertisol in order to evaluate two resource saving cropping systems based on conservation agriculture (CA) that integrate in situ soil and water conservation tillage practices (derdero+ and terwah+) as compared to a conventional system in terms of soil moisture, runoff, water loss (drainage and evapotranspiration together), water productivity and crop yield. The experimental layout was a randomized complete block design with three replications and a plot size of 5 m × 19 m. The farming systems differed in tillage practice, but all had wheat, teff, barley and grass pea crops grown in rotation. The tillage treatments were (i) derdero+ (DER+), with a furrow and permanent raised bed planting system, plowed only by refreshing the furrow once at planting with no tillage on top of the permanently kept raised beds, 30% standing crop straw retention, and with ~20% of the crop residue being covered with soil during refreshing the furrow at planting, (ii) terwah+ (TER+) with furrows made at 1.5 m intervals, plowed once at planting, 30% standing crop straw retention and fresh broad beds, and crop residue being partly covered with soil during tillage at planting, and (iii) conventional tillage (CT) with a minimum of three plain tillage operations and complete removal of crop straw. All plowing as well as the maintenance of the furrows of the permanent raised beds was done using a local ard plow called mahresha. Glyphosate was sprayed at 2 ha⁻¹ to control weeds before crop emergence, starting from 2007 with DER+ and TER+. Runoff was collected at the lower end of each plot in calibrated runoff collectors after each runoff event. Soil–water content was measured using the gravimetric method at 5–6 day intervals. Normalized Difference Vegetation Index (NDVI) was measured in the field at several phenological stages, using a handheld GreenSeeker™ Optical Sensor Unit. Soil–water storage (0–80 cm soil depth) during the growing season was always highest with DER+ followed by TER+ and CT, whereas the opposite trend was observed for runoff. On the other hand, deep drainage and evapotranspiration was always highest in the DER+ compared to CT. NDVI values throughout the growing season were significantly highest with DER+ for wheat and grass pea, while the highest values were observed with TER+ when under teff. These values were directly proportional to the above ground crop biomass and yield. The grain and straw yield of wheat in 2009 was increased from 1.6 and 3.7 t ha⁻¹ with CT to 2.6 and 5.2 t ha⁻¹ with DER+, respectively. Our study demonstrates that field water conservation tillage practices that incorporate CA principles are effectively increasing green water in the root zone available for crops and thus, improve crop productivity and yields substantially on vertisols in drylands without other inputs.

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1. Introduction

Food security remains a major concern in sub-Saharan Africa (SSA) (FAO, 2011). The food shortages are largely due to the often insufficient and highly erratic nature of rainfall (Falkenmark and Rockström, 2008) and poor soil–water holding capacity and infiltrability problems because of increasing land degradation that causes deterioration of soil’s physical quality (Stroosnijder, 2009; Heng et al., 2007). Human-induced drought and thus, land degradation mainly due to conventional land management practices that resulted in desertification constitute one of the greatest environmental challenges (Falkenmark and Rockström, 2008; Nyssen et al., 2004). United Nations University warned that about 2 billion people are threatened by encroaching desertification (UNU, 2007). A major cause of cropland degradation in Ethiopia is repeated plowing continuously for several years combined with complete removal of crop residue at harvest followed by aftermath grazing of cropped fields. The latter is due to overgrazing by a large number of cattle required for repeated plowing (Gebregziabher et al., 2006), burning of crop residue, use of crop straw and animal dung for fuel and repeated droughts (Tilahun, 1999). These activities have reduced the biomass return to the soil, resulting in a deteriorated physical quality of the soil. Depletion of soil organic matter, due to intensive tillage which contributes to oxidation of organic matter in the soil, reduces infiltration and water holding capacity, and increases rainwater losses and soil erosion.

Over 95% of the agriculture in Ethiopia is rainfed, and more than 80% of the population depends on agriculture for their livelihood. The distribution of rain, rather than the total amount of rainfall in the semiarid areas, is of major importance because dry spells in the rainy season strongly depress crop yield (Segele and Lamb, 2005). Seleshi and Camberlin (2006) reported that in northern Ethiopia (Mekelle) the length of dry spells reaches 20 days on an average, with a concentration at the beginning of the main rainy season. There is a high risk of soil–water scarcity in crop production in the semiarid areas of Ethiopia leading to drought-associated food shortages as reported by Tilahun (1999). The scarcity is associated with spatial and temporal rainfall variability and is often human induced as a result of long-term cropland degradation that deteriorates the physical quality of the soil or arises from the absence of physical structures thereby affecting the soil rainwater balance in the crop root zone (Stroosnijder, 2009).

Vertisols cover a large crop production area in many countries and are the second most dominant soil type used in Ethiopian agriculture, covering 24% of the highland crop land soils (Woldeab, 1988). The current low yields in the semiarid areas of Ethiopia are related to on-farm blue water losses through surface runoff, limited infiltration to the root zone, and deep percolation below the root zone. White water losses also occur due to evaporation (non-productive water loss), limiting water availability for transpiration (productive green water loss) and, thus, for crop production (Rockström, 1997). Fox and Rockström (2003) reported that in SSA 70–85% of rainfall is lost in conventional farming systems as through white and blue water flow. On the other hand, periodic waterlogging is also problematic in vertisols (McHugh et al., 2007).

To restore the productivity of degraded lands and to overcome crop failure, efforts have been made to launch afforestation and conservation programs in Eastern Africa; success to date, however, has been limited. Recent policy in this region favors further in situ water conservation, stubble management and the abandonment of free grazing (Nyssen et al., 2011). Water productivity in rainfed agriculture will have to increase appreciably in SSA, if food production is to feed the current and fast growing population in the region. Therefore, farming systems that improve physical soil quality and promote conservation of water by physical structures hence increasing water productivity can assist in alleviating the impacts of water scarcity for crop production purposes. In previous papers, we demonstrated that conservation agriculture (CA) that integrates in situ soil and water conservation practices greatly reduces runoff and soil loss (Araya et al., 2011, 2012) and improves physical quality of vertisols (Araya, 2012). CA comprises three principal components: (1) minimum soil disturbance, (2) permanent organic soil cover, and (3) use of crop rotation (FAO, 2014). The fourth principle added in the current study of CA-based system is the integration of CA principles with in situ soil and water conservation of bed and furrows structures (terwah and derdero) using the local ard plough mahressa. According to Derpsch et al. (2014), if the soil surface is disturbed >50%, it cannot be termed as no-tillage system and thus not CA system.

In northern Ethiopia, farmers use indigenous in situ soil and water conservation practices on their cropland. Among these are terwah and derdero to tackle rainwater shortages. Acknowledging such local practices enables local farmers to more easily adopt new soil and water conservation technologies like CA. The conventional terwah tillage practice has contour furrows at 2–4 m wide intervals and is used usually only on teff (Eragrostis tef) fields. In derdero planting systems, beds and furrows are prepared along the contour after having broadcasted the seeds over the surface and are mainly practiced on vertisols for fenugreek (Trigonella foenum-graecum), wheat (Triticum sp.), lentil (Lens culinaris) and teff. Both the terwah and derdero practices store rainwater to be used later by the crop during dry spells instead of being lost as runoff. Crops in derdero are grown on the ridges where they are protected from waterlogging in vertisols (Nyssen et al., 2011). In both systems all straw is traditionally harvested, the stubble grazed and the furrows and beds destroyed yearly by tillage. Therefore, to develop sustainable farming systems, two modified versions of the traditional in situ water conservation tillage practices derdero and terwah which use the traditional mahressa ard plow, i.e., “derdero*” and “terwah*” where the ‘*’ refers to integration with CA, were introduced on vertisol in northern Ethiopia from 2005 under a wider range of crops as those for which they are typically applied.

Although the effects of these newly developed CA-based versions of traditional soil and water conservation farming systems on runoff, soil loss and soil quality have been reported previously (Araya et al., 2011, 2012), this study deals with their medium-term effects on the root zone water balance and water productivity of wheat, teff and grass pea cropping. We hypothesized that CA in combination with other in situ conservation practices can improve the soil hydrology/root zone water balance and crop productivity of vertisols in a semi-arid setting.

Table 1 Monthly rainfall (mm) distribution at the experimental site during the study period as calculated from 31 years. NEP: non-exceedance probability.

<table>
<thead>
<tr>
<th>Year</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>NEP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>8</td>
<td>0</td>
<td>10</td>
<td>180</td>
<td>160</td>
<td>5</td>
<td>6</td>
<td>3</td>
<td>2</td>
<td>28</td>
</tr>
<tr>
<td>2010</td>
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<td>1</td>
<td>52</td>
<td>22</td>
<td>12</td>
<td>171</td>
<td>246</td>
<td>94</td>
<td>3</td>
<td>0</td>
<td>4</td>
<td>78</td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>0</td>
<td>0</td>
<td>15</td>
<td>105</td>
<td>59</td>
<td>159</td>
<td>148</td>
<td>12</td>
<td>4</td>
<td>3</td>
<td>0</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>Av. (31 years)</td>
<td>1</td>
<td>2</td>
<td>8</td>
<td>21</td>
<td>19</td>
<td>28</td>
<td>164</td>
<td>208</td>
<td>40</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>54</td>
</tr>
</tbody>
</table>
2. Materials and methods

2.1. Study area

The mean annual rainfall for 31 years (1971–2011) in the town of Adi Gudom (3 km from the experimental plot in Gum Selasa) was 499 mm, with more than 85% falling from mid-June to mid-September (Table 1). The length of the growing season is ca. 90 days. The mean annual temperature of Adi Gudom is 19 °C with a maximum and minimum average monthly temperature of 27 °C and 11 °C, respectively, and a mean annual potential evapotranspiration of 1486 mm (Araya et al., 2011). Three to six tillage operations are conventionally done with an oxen-drawn and plow to control weeds, loosen the soil to improve infiltration and prepare a fine seedbed (Astatke and Jabbar, 2001).

2.2. Rainfall during the study period

In this study, the root zone balance is calculated for 2009 and 2010, and water productivity for 2009–2011. The annual precipitation in 2009, 2010 and 2011 was 382, 606 and 560 mm, respectively, with 93, 87 and 71% of it falling in the period from June to September. The rainfall non-exceedance probabilities (%), calculated using RAINBOW software (Razes et al., 2006) for 2009, 2010 and 2011, which was combined with 31 years of long term rainfall data in the study area, were 28, 78 and 64%, respectively. This means that 2010 was a wetter than normal year, 2011 a normal year and 2009 was drier than normal (Table 1).

2.3. The experimental field

Treatments are described in detail in Araya (2012). The experimental layout was a randomized complete block design with three replications (Fig. 1). The plot size was 5 m × 19 m with a slope gradient of 3%. The experimental plots with different farming systems were kept fixed for seven years of study since 2005. Crops grown in rotation from the first (2005) to the seventh (2011) year sequentially were wheat, teff, wheat, barley, wheat, teff and grass pea. Weed control was done by hand weeding with minimal soil disturbance (due to shallow rooted seasonal weeds) in the first two years under TER+ and DER+, whereas from 2007 a non-selective herbicide, glyphosate (N-(phosphonomethyl)glycine), was sprayed at 21 ha⁻¹ 3–4 days before planting to control weeds before crop emergence. Weed control with conventional tillage (CT) was done by combination of frequent tillage and hand weeding in a similar way to the local farmers’ land management practices.

Three farming systems that differed in tillage practices were applied: (1) in CT, the soil was plowed at least three times per year and the crop straw was completely harvested without leaving crop residues on the surface; (2) as described in Araya et al. (2011), the traditional local tillage practice terwah was applied without modification from 2005 to 2007. However, starting from 2008, terwah+(TER+) was a new farming system developed from terwah by making furrows on the contour at regular intervals of ~1.5 m, using only one plowing operation and leaving 30% of the crop straw standing stubble; (3) derdero+ (DER+), another newly developed farming system which is based on another traditional in situ water conservation technique derdero, makes beds and furrows along the contour at intervals of ca. 0.6 m. The ‘plus’ in derdero+ and terwah+ stands for the improvements made compared to their traditional versions; i.e., 30% of the crop straw standing stubble was left, and the beds with DER+ were never plowed, with only one tillage operation refreshing the furrows at planting. The level of soil surface disturbance in DER+ was less than 25% while in TER+ less than 50%.

All plots were established in a repeatedly ploughed crop field (prior to the study). Bed and furrow structures were made at planting in DER+ and TER+ systems and crop residue was retained starting in the first season in 2005. Unlike wheat, leaving 30% of the crop residue from teff and grass pea was not feasible in view of teff being too short and grass pea being harvested close to the ground to ensure grain collection. More than 60% of the soil surface was covered by the 30% of the wheat crop residue retained, and about 20% of the soil surface was covered by stubble after teff harvesting while the soil was not covered at all after grass pea cropping.

2.4. Soil–water storage

The change in soil–water storage in the root zone in the absence of irrigation water over a given period $\Delta t$ is given by:

$$\Delta S = RF - R - ET - D + (L_i - L_f)$$  \hspace{1cm} (1)

where $\Delta S$ is the change of soil–water storage in the root zone between two consecutive volumetric water content measurements, $D$ is capillary rise (if negative) or drainage (if positive) at the maximum rooting depth, $R$ is surface runoff, ET is evapotranspiration, RF is precipitation, and $L_i$ and $L_f$ are the lateral inflow and outflow, respectively. All components are expressed in units of length (mm per day). $L_i$ and $L_f$ were considered to be negligible. The maximum rooting depth for cereal crops grown in the study area was considered to be 80 cm as determined by digging the root profile of the crop.

Soil–water content readings using a Trime® T3 tube probe (IMKO Micromodultechnik GmbH, Ettlingen, Germany), which is a quasi time domain reflectometry (TDR) device, and matric potential readings using tensiometers (SDEC, Reignac sur Indre, France) were found to be non-consistent (see Section 3) and, consequently, they were not used in the data analysis. Therefore, volumetric soil–water content was measured on grab samples taken using an Edelman clay auger (Eijkelkamp Agrisearch Equipment, Giesbeek, The Netherlands) using the gravimetric method with 5–7 days intervals in the months of August and September in 2009 and 2010 (not in 2011) at soil depths of 20, 40, 60, 80 and 100 cm. To convert gravimetric to volumetric water content, a soil shrinkage characteristic curve (SSCC) was used, which relates bulk density with gravimetric water content. Conversion of gravimetric water content to volumetric water content using bulk density was calculated by combining Eqs. (2)–(4).

2.4.1. Soil shrinkage characteristic curve

The SSCC, describing the volume changes of vertisols with changes in moisture content, was determined using the balloon

![Fig. 1. The layout of experimental plots at Gum Selasa in Tigray, Ethiopia. DER+: derdero+, TER+: terwah+, CT: conventional tillage practice.](image-url)
method (Cornelis et al., 2006a) on samples taken at 10, 20, 30, 40, 60, 80, 90 and 100 cm soil depth. A simple four-parameter model as presented by Cornelis et al. (2006b) was then fitted through the observed void ratio $e$ to moisture ratio $\theta$ data pairs:

$$e(\theta) = e_0 + a \left( \exp \left( \frac{-b}{\theta - \theta_i} \right) \right)$$

(2)

where $e_0$ is the void ratio at oven-dryness ($m^3 m^{-3}$), and $a, b$ and $c$ are fitting parameters determined by curve-fitting to observed SSCC data, for which we used Mathcad (2000) software.

The moisture ratio $\theta$ ($m^3 m^{-3}$) was calculated as:

$$\theta = \frac{w \rho_b}{\rho_w}$$

(3)

where $w$ is gravimetric water content (kg kg$^{-1}$), $\rho_b$ is particle density ($Mg m^{-3}$) and $\rho_w$ is water density ($Mg m^{-3}$).

The void ratio $e$ ($m^3 m^{-3}$) can be written as:

$$e = \frac{\rho_b}{\rho_w} - 1$$

(4)

where $\rho_b$ is bulk density ($Mg m^{-3}$)

2.4.2. Runoff

Runoff was measured in 4.5 m long, 1.5 m wide (at the top) and 1 m deep collector trenches, which were located at the down slope end of each plot and lined with thick plastic sheets. The plots were separated by 0.5 m wide ditches to avoid surface or subsurface flow between plots. Runoff data were collected at 8:00 a.m. after each rainfall event by measuring the height of the water at three sample locations in the trenches. The volumes of the trenches were annually calibrated at the middle of the growing season by relating known amounts of water to depth at three sample locations in the trench following the method described in Araya et al. (2011). Rainfall was recorded daily at 8:00 a.m. using a rain gauge.

2.4.3. Drainage, hydraulic conductivity and evapotranspiration

In an attempt to determine the drainage component (at 80 cm depth) below the root zone, we applied the Buckingham–Darcy (1907) equation for vertical flow, similar to that in Cresswell (2002), but using the van Genuchten–Mualem equations (Van Genuchten, 1980; Mualem, 1976) rather than those of Campbell (1974), to describe the water retention and hydraulic conductivity curves. Drainage can thus be written as:

$$D = q\Delta t = -K(\theta) \frac{dH}{dz} \Delta t$$

(5)

where $K(\theta)$ is the unsaturated hydraulic conductivity corresponding to the volumetric soil–water content $\theta$ at 80 cm, $dH/dz$ is the hydraulic–head gradient, and the over bars denote time-averaged values. The hydraulic head (the sum of matric head and gravitational head) was obtained from the water content values measured at depths of 80 and 100 cm and using the Van Genuchten (1980) equation to convert them to matric head:

$$\theta = \frac{1}{\alpha} \left( \frac{\theta_s - \theta_i}{\theta - \theta_i} \right)^{1/m} - 1$$

(6)

where $h$ is matric head (cm), $\theta$ is volumetric soil–water content at a given matric head ($m^3 m^{-3}$), $\theta_s$ and $\theta_i$ are residual and saturated volumetric soil–water content, respectively ($m^3 m^{-3}$), and $\alpha$ (cm$^{-1}$), $m$ and $n$ are fitting parameters related to the bubble pressure and pore size distribution, respectively. The number of fitting parameters was restricted to four (Cornelis et al., 2005), with $m = 1 - (1/n)$.

Using RETC (2008) software, Eq. (6) was fitted to soil–water retention data determined at eight soil matric potentials: 0, −1, −2.9, −5.9, −9.8, −33, −100, and −1500 kPa, on 100 cm$^3$ undisturbed soil cores taken at depths of 60, 80, 90 and 100 cm in two replicates per depth per plot, using tension tables (Eijkelkamp Agrisearch Equipment, Giesbeek, The Netherlands) for high soil matric potentials (0 to −9.8 kPa) and pressure chambers (Soilmoisture Equipment, Santa Barbara, CA, USA) for low soil matric potentials (−33 to −1500 kPa), following the procedure outlined in Cornelis et al. (2005). Gravimetric water content was converted to volumetric water content using bulk density calculated by combining Eqs. (2)–(4).

The hydraulic conductivity curve was calculated using the Mualem–Van Genuchten equation (Eq. (7)) (Mualem, 1976; Van Genuchten, 1980):

$$K(\theta) = K_s \left( \frac{\theta - \theta_i}{\theta_s - \theta_i} \right)^{1 - \left( \frac{1}{m} \right) \left( \frac{\theta_s - \theta_i}{\theta_s - \theta_i} \right)}$$

(7)

where $K(\theta)$ is unsaturated hydraulic conductivity (cm h$^{-1}$), $K_s$ is field saturated hydraulic conductivity (cm h$^{-1}$), and $\theta$ a pore connectivity parameter set equal to 0.5 (Mualem, 1976). The single ring with constant head method (Reynolds and Elrick, 1990), in which constant head was attained using a Model 2800 Guelph Permeameter (Soilmoisture equipment, Santa Barbara, CA, USA), was used to measure the field saturated hydraulic conductivity $K_s$ (Verbit et al., 2010) at 80 and 100 cm soil depth in two replicates. The aluminum ring had an inner diameter of 32.5 cm, a height of 25.0 cm and was inserted into the soil to a depth of 3 cm (Araya, 2012). The last 10-min average was calculated as final infiltration rate after about 60 min. The infiltration rate, $q$, into the soil (cm h$^{-1}$) was calculated as:

$$q = \frac{(height_2 - height_1) \Delta q_{\text{ring}}}{t_2 - t_1}$$

with height being water height (cm) in the reservoir, $t$ is time, indices 1 and 2 indicate two successive measurements, $\Delta q_{\text{ring}}$ is the inner surface of the reservoir (m$^2$), and $A_{\text{ring}}$ is the surface of the ring (m$^2$).

Using Eq. (9) by Reynolds and Elrick (1990) for ponded infiltration from a single ring with steady flow and constant head, $K_s$ (cm h$^{-1}$) was calculated from steady state infiltration rates $q_s$:

$$K_s = \frac{\Delta q_s}{(H/(C_1 d + C_2 a)) + (1/\alpha'(C_1 d + C_2 a)) + 1}$$

(9)

with $q_s$ the steady infiltration rate (cm h$^{-1}$), height of the constant head $H$ is 0.10 m, ring insertion is 0.03 m, radius $a$ is 0.065 m, and $\alpha'$ macroscopic capillary length parameter is 0.04 cm$^{-1}$ for most structured soils from clays through loams, including unstructured medium to fine sands, as derived from Reynolds and Elrick, 1990). Calibration parameters were set as $C_1 = 0.316$ m and $C_2 = 0.184$ m, since 0.3 ≤ $d/a$ ≤ 1 and 5 cm ≤ $H$ ≤ 25 cm (Reynolds and Elrick, 1990). The average $K_s$ from measurements at 80 and 100 cm depth was then introduced in Eq. (7).

However, using this approach we found drainage values to be extremely low (less than 0.005 cm h$^{-1}$), whereas field observations based on augering and our water content profiles clearly showed that there were drainage below 80 cm depth. To avoid erroneous conclusions related to drainage, rather than calculating drainage per se, we considered it together with evapotranspiration and termed it water loss, which was then calculated from Eq. (1).

2.5. Crack size

Crack depth was determined using a metallic ring made out of wire sent to the crack inside. The width of the crack was also measured at the soil surface. Ten samples per plot were taken to determine both parameters at harvest.
2.6. Normalized Difference Vegetation Index, crop yield and water productivity

A handheld GreenSeeker™ Optical Sensor Unit (NTech Industries, Inc., USA) was used to measure Normalized Difference Vegetation Index (NDVI) at several phenological stages of wheat (2009), teff (2010) and grass pea (2011) starting 15, 42 and 35 days after planting, respectively, at 5–7 days intervals. The device measures the fraction of the emitted light in the sensed area that is returned to the sensor (reflectance). These fractions are used within the sensor to calculate the NDVI according to the following formula:

\[
\text{NDVI} = \frac{(\text{NIR} - \text{VIS})}{(\text{NIR} + \text{VIS})}
\]

where NIR is near infra red radiation and VIS is visible red radiation. Healthy vegetation absorbs most of the visible light that hits it and reflects a large portion of the near-infrared light, while unhealthy or sparse vegetation reflects more visible light and less near-infrared light (Verhulst et al., 2009). However, NDVI readings become lower as the crop reaches the grain filling stage. At that time, the chlorophyll content of the leaf starts to decrease due to translocation of assimilates from leaf to grain that leads to the conversion of the leaf color to yellow.

The sensor unit measurements were taken as the unit passed over the crop surface at a height of approximately 0.7 m above the crop canopy over the same area in each plot during emergence and with slightly smaller height at maturity. The sensor head was directed perpendicular to the crop in the plot during data collection. One measurement was taken per plot at a time. An average of about 150 individual NDVI readings was recorded per sample sequence. Travel velocities were kept at a fast walking speed.

Grain and straw crop yield were determined at harvest from 1 × 1 m areas in three replicates per plot. Rainwater productivity (kg ha⁻¹ mm⁻¹) or water use efficiency was calculated by dividing the total grain yield (kg ha⁻¹) by the amount of precipitation (mm) received from planting to harvesting.

2.7. Statistical analysis

ANOVA was used to test the statistical differences of the different parameters of the treatments. The data were analyzed using SAS statistical software (JMP version 5.0), and standard error of treatment means was used for separation of treatment means (SAS Institute Inc., 2002). Mean comparison for parameters was carried out by a Student’s t-test at \(\alpha = 0.05\).

3. Results and discussion

3.1. Trime® and tensiometer measurements in vertisols

Volumetric soil moisture content recorded with Trime® and derived using Topp’s equation (Topp et al., 1980) showed a very poor correlation with volumetric moisture content measured from grab samples using the gravimetric method in combination with the SSCC (Fig. 3). Consequently, fitting a linear regression model to the data resulted in low coefficients of determination, leading to the assumption that parts of the data are biased or erroneous. Hence, a calibration curve in lieu of Topp’s equation (Topp et al., 1980) could not be established. Evett et al. (2006) also indicated that Topp’s equation is not suitable for a clayey soil (>48%) and reported that the relationship between permittivity and moisture content is dependent on texture, temperature and salinity.

Fig. 2 shows that the Trime® readings were lower than those obtained gravimetrically, which is similar to the findings of Pozzato.
permitivity values were recorded by Trime® due to the air gaps created around the access tubes (Haverkamp et al., 1984; Fig. 4) resulting in large errors (Bronswijk et al., 1995; Rana and Katerji, 2000). The presence of dry spells during the growing season aggravated soil cracking. Usually in the month of May the crack depth can reach about 1.2 m, which was the maximum depth. However, this depends on the presence and amount of rainfall that can moisten and swell the soil before the month of May. Table 2 shows that crack width and depth recorded when the rainfall ceased in September, and thus crack volume, were significantly smaller with DER+ compared to TER+ and CT (Table 2). These cracks can further damage plant roots, favor gully erosion and evaporation while they permit preferential flow in soils with low infiltration rates. As with the Trime® readings, tensiometers were very unreliable due to the swell and shrinkage behavior of the soil. It even appeared that the presence of the tensiometers did favor crack formation in their vicinity (Fig. 4).

3.2. Effect of farming systems on water partitioning

Figs. 5 and 6 show the cumulative precipitation, cumulative runoff, cumulative soil–water storage and cumulative water loss (ET + D) over the root zone, determined up to 80 cm, for both seasons in 2009 and 2010.

3.2.1. Runoff

The results indicate that DER+ and TER+ had a beneficial effect on runoff reduction. This was similar to previous findings in the same experimental plots but within the first three years after implementing the farming systems (Araya et al., 2011) and in a nearby sub-humid and mountainous area (Araya et al., 2012). Crop residues remaining at the soil surface from prior crops combined with the furrow and bed structures slow surface runoff and thus favor infiltration (Figs. 5a and 6a; Govaerts et al., 2007; McGarry et al., 2000). With the first tillage at planting in CA, about 20% of the crop residue was buried in the soil with DER+ while partly buried with TER+ plots. The partly buried crop residue still may have the potential to increase infiltration rate. This is supported by findings of McGarry et al. (2000), who observed higher infiltration rates on zero tillage on an alluvial vertisol in Australia.

Bulk density and penetration resistance values were lower with DER+ and to a lesser extent with TER+ compared to CT, and higher soil microbial biomass carbon in the upper soil surface (0–15 cm) was observed with DER+ followed by TER+ (Araya, 2012). Soils under CA-based systems had higher soil organic matter and thus reduce the direct runoff and increase infiltration rate as compared to CT systems (Araya, 2012). The reduction in runoff, and thus the increase in infiltration, results in potentially higher water losses through deep drainage (blue water) below the 80-cm root zone of the crop and reduces green water that can be used for transpiration.

3.2.2. Evapotranspiration and drainage

The sum of evapotranspiration and drainage below the root zone was higher in the CA-based farming systems of DER+ followed by TER+ compared to the CT plots (Figs. 5b and 6b). There are several possible explanations for an increase in unproductive water losses evaporation and deep drainage and productive water losses (transpiration) over CA-based farming systems. Firstly, a significant amount of rainwater infiltrated through cracks, especially in the CA-based treatments, and moved in a process referred to as by-pass flow below 80 cm at the beginning of the rainy season in June and July. As tillage was not carried out in the beds of CA-based farming systems, cracks formed during the dry season remain longer, before they close as a result of swelling with increasing water content, whereas cracks with CT were filled with soil in the first and second tillage in May (122–152 DOY) and June (153–182 DOY), reducing the amount of water entering them.

Visual examination in the field with an auger indicated that water was percolating deeper in the soil profile hence leading to more drainage out of the root zone in DER+ and TER+ systems compared to CT systems. Soil sampling using the auger method for water content determination on August 20, 2009 (DOY 232) was possible only to a depth of 60 cm for CT, whereas auger sampling was possible up to 80 cm depth for the DER+ and TER+ systems (Fig. 7). Below those depths the soil was too hard due to the low water content. Until August 13, 2009 (DOY 225), the rainwater moistened only the upper soil layer, i.e., to a depth of 40 cm. After September 2, 2009 (DOY 245) water penetrated as deep as 100 cm due to heavy rains in the preceding period. This is further supported by water content profiles established at regular time.

![Cracks close to TDR and tensiometer](Image 34x5 to 285x735)

**Fig. 4.** Cracks in the DER+ experimental plot close to (a) Trime® access tube and (b) tensiometer immediately after harvest in January 2010 with the short standing stubble crop residue of teff retained in the furrow structure.

**Table 2**

Crack width and depth for the different treatments at the beginning of September 2010. Different letters indicate results that are significantly different.

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Depth (cm)</th>
<th>Width (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SEM</td>
<td>Mean ± SEM</td>
</tr>
<tr>
<td>DER+</td>
<td>9 ± 0.38b</td>
<td>1.9 ± 0.07b</td>
</tr>
<tr>
<td>TER+</td>
<td>11 ± 0.35a</td>
<td>2.5 ± 0.09a</td>
</tr>
<tr>
<td>CT</td>
<td>12 ± 0.02a</td>
<td>2.5 ± 0.07a</td>
</tr>
</tbody>
</table>
Fig. 5. Cumulative precipitation (RF), cumulative runoff (a), water loss (drainage + evapotranspiration) (b) and cumulative change in soil–water storage (c) at 0–80 cm soil depth from each treatment throughout the growing season (n = 6) in 2009. DER+: derdero+, TER+: terwah+, CT: conventional tillage practice. The bars shown are the standard error of mean (p < 0.05).

Fig. 6. Cumulative precipitation (RF), cumulative runoff (a), water loss (drainage + evapotranspiration) (b) and cumulative change in soil–water storage (c) at 0–80 cm soil depth from each treatment throughout the growing season (n = 6) in 2010. DER+: derdero+, TER+: terwah+, CT: conventional tillage practice. The bars shown are the standard error of mean (p < 0.05).
Fig. 7. Comparison of volumetric soil–water content in the root zone on selected dates during the growing season versus soil depth (cm) in 2009 in each treatment (n = 3). DER+: derdero+, TER+: terwu+, CT: conventional tillage. The bars shown are the standard error of mean (p < 0.05).
intervals. Fig. 7 shows the evolution of volumetric soil–water content versus soil depth as of August 20, 2009 (DOY 232), which was preceded by a period of high rainfall (235.5 mm) beginning with the onset of the rainy season on June 30, 2009 (DOY 181). On August 20, 2009 (DOY 232), water content in the top 60 cm was highest for DER+ followed by TER+ and CT. On August 26, 2009 (DOY 238), water content in the top 80 cm increased considerably due to rainfall totaling 91 mm since the previous sampling date. Again, the highest values at all depths were observed in the CA-based farming systems. The field observations and results shown in Fig. 7 suggest that water slowly percolated to deeper layers. This redistribution of water was fastest under the DER+ treatment, as illustrated by the highest changes in water content for DER+ (for example, see DOY 240). The next rainfall event (56.5 mm) resulted in increased water content, wetting the profile at least to 100 cm depth on September 2, 2009 (DOY 245). The zero to slightly positive water content gradients on September 2 and September 9, 2009 (DOY 245 and 252, respectively) suggest some drainage below the root zone, and this was most pronounced under DER+. From September 16, 2009 (DOY 259) onwards, no further drainage was observed (Fig. 7). In a silt loam soil in Canada, Azoov and Arshad (1996) reported that CA farming systems resulted in deeper drainage compared to CT. Also Tolmie and Radford (2004) found higher drainage under CA on a vertisol in Australia compared to CT practices, which was ascribed to the establishment of stable biopores that are not broken through cultivation. The increase in drainage might result in higher aquifer recharge (Jarecki and Lal, 2003; Lal et al., 2007).

Secondly, the several furrow and bed structures with DER+ and to a lesser extent TER+ plots and the cracks present in both treatments early in the rainy season might have increased the evaporating soil surface area and, thus, increase water loss by soil evaporation (Hillel, 1998). In the case of wheat, which grows on the bed while furrows remain uncovered after the weeds are cleared, direct sunlight on the furrows and increased exposed soil surface potentially increases water loss by evaporation. This effect is unlikely when growing teff, whose seeds are washed from the bed immediately after planting and grow densely in the furrow and sparsely on the beds. This is supported by the differences in water loss between the CA treatments being very low during the teff cropping season (2010), whereas during the wheat cropping season (2009) water loss observed with DER+ was rather high compared to TER+ plots. The effect of cracks is that they promote turbulent air to enter, which stimulates water vapor to be removed from the deeper reaches of the soil profile, and the exposed crack sides become secondary evaporation planes (Hillel, 1998). It should be noted, however, that with time cracks became more pronounced in CT and TER+ as compared to DER+ (Table 2) owing to more green water being present in the latter treatment. Finally, the higher amounts of green water in the soils under CA-based systems, might have increased total soil evaporation even though the evaporability of the soil might be reduced due to surface cover (as discussed below), since it takes longer before the profile-controlled falling rate phase of evaporation is reached (Hillel, 1998). On the other hand, the standing stubble crop residues in addition to residue from previous years lying on the soil surface in the CA-based farming system also reduces soil evaporation. Crop residue lying on the soil surface is more effective to reduce evaporation due to radiation than the standing stubble. However, crop straw of grass pea returned back after threshing as mulching on the soil surface can be easily blown from the crop field by wind while the standing residue resists against wind (Araya et al., 2012). Krishna et al. (2004) reported that increasing the amounts of rice residues on the soil surface reduced evaporation rates and increased duration of drying of the soil except after extended drought. Furthermore, CT using mahresha as primary tillage, followed by repeated secondary shallow tillage, can cause moist soil to move to the surface, which favors loss of water by evaporation (Aase and Siddoway, 1982). With time, however, the fraction of evaporation decreases as the crop grows and the crop canopy cover to the ground area increases. Water loss through soil evaporation is dominant when the crop is young, whereas crop transpiration is the main source of water loss, once the crop is fully developed and completely covers the soil. At the start of our water content readings, wheat was already well established, resulting in significant transpiration. Our data therefore do not enable us to deduce whether evaporation increased or decreased in the DER+ and TER+ systems compared to those under CT systems. However, Fig. 7 shows that from the end of the rainy season at about mid-September 2009 (DOY 259) onwards, the topsoil dried up first, whereas the deeper soil dried more slowly and had a higher soil–water content. As the water contents were always lower with CT systems, cracking from the soil surface became most pronounced with CT with time (Table 2), which could have aggravated water loss by evaporation.

Thirdly, higher ET values observed with DER+ might be attributed to higher crop transpiration resulting from lower water stress. Fig. 7 shows that reduction in water content as of the end of the rainy season on September 15 (DOY 258) was most pronounced with DER+ but with water content remaining higher than for CT. If we assume that wheat starts to experience water stress between a matric potential of −50 and −90 kPa (Wesseling, 1991), this corresponds with a water content of −0.45 m3 m−3 in our soil (Araya, 2012). Fig. 7 shows that at the start of sampling, water content was always lower than this value, meaning that water stress was prevailing. Moreover, with a wilting point value of 0.33 m3 m−3 for wheat in our soil (Araya, 2012), it might be that gradually only the lower depths can provide water to wheat.

Similar conclusions could be made when analyzing the water content data from 2010 (not shown). Cumulative water loss/use (ET and D) declined in September 2010 (DOY 262) and October 2010 (DOY 277). This is due to the upward movement of soil–water by capillary action to the root zone (0–80 cm) from below 80 cm, where there was a relatively higher soil–water content (Fig. 6b). The driving force for the movement of water from the lower surface to the upper surface is related to the high evaporation from the soil surface.

3.2.3. Soil–water storage in the root zone

Reduced runoff in DER+ and TER+ systems also resulted in greater soil–water storage than for CT. Fig. 7 shows almost always higher water content values for DER+, followed by TER+ and CT. As mentioned previously, water content particularly is following rainfall events (DOY 231, 237, 251). Later in the season, on October 13, 2009 (DOY 286), the increase in water content in the upper profile was more pronounced in DER+ and TER+ systems than in CT. This date was preceded by some rainy days (12.3 mm). The bed was a physical barrier against runoff and the furrow structures served as temporary storage, allowing rainwater to infiltrate slowly into the soil and potentially increase green water in the root zone. In addition, standing stubble crop residues on the soil surface created a rough surface in the plots decreasing runoff, and the mulching effect of fallen stubble and residue from previous year minimized evaporation, both contributing to the increase in green water in the crop root zone. Similar to our findings, Lenssen et al. (2007) and Jin et al. (2007) reported that zero tillage improved soil–water storage compared to CT. Also Moreno et al. (1997) reported higher replenishment of soil–water storage in CA than with CT. Lampralanis et al. (2002) reported that no tillage shows higher soil–water storage, especially in years with low precipitation. Although 2010 had higher precipitation, the cumulative change in soil–water storage was relatively lower.
during teff cropping than wheat cropping in the drier year, 2009. This may be attributable to the higher cumulative runoff and water loss (ET + D) in 2009 and to the higher wheat biomass production and canopy cover. Finally, teff grows slowly, exposing the soil to evaporation for longer periods than wheat. While transpiration flow does exhibit a linear relationship with biomass growth, evaporation flow is non-productive and, importantly, declines with biomass growth, once growing canopy covers the soil.

3.3. Water productivity and crop performance

The reduction in runoff throughout the growing season, which favored green water amounts in the DER+ and TER+ systems as demonstrated in section 3.2, may have contributed to improvements in crop yield in all years. Table 3 shows that grain and straw yield, and rain water productivity (WP) were significantly higher with DER+ for wheat (2009) and grass pea (2011) than with CT. DER+ also showed significantly higher values than CT for wheat in 2009. Although not significant, yield and WP for teff (in 2010) were also slightly higher in the DER+ system followed by TER+ than those under CT. WP for wheat was higher in each farming system than for grass pea and teff. The improvements in WP (between 9 and 40%) demonstrate the effectiveness of DER+ and TER+ farming systems in capturing rainwater, and improving green water availability and crop yield, hence reducing dry spell effects. However, as reported in Araya et al. (2012), WP for wheat and grass pea in the sub-humid areas in Hagere Selam was higher than our current values in semi-arid Adi Gudom. The relationship between improved WP and improved grain yields of cereal crops achieved through management practices is exponential for an area with yields below 4 t ha⁻¹ (Falkenmark and Rockström, 2008), whereas, at yield levels above 4 t ha⁻¹, the relationship between WP and

Table 3  
Grain and straw yield, rainwater productivity for the experimental site on a vertisol in Gum Selasa, Ethiopia. DER+: dererew+, TER+: terwah+, CT: conventional tillage practice, SEM: standard error of mean (p < 0.05), WP: rainwater productivity. Yields with different letters in the same year and column are significantly different.

<table>
<thead>
<tr>
<th>Year</th>
<th>Crop types</th>
<th>Treatments</th>
<th>Straw yield (t ha⁻¹) Mean ± SEM</th>
<th>Grain yield (t ha⁻¹) Mean ± SEM</th>
<th>WP (kg ha⁻¹ mm⁻¹) Mean ± SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>Wheat</td>
<td>DER+</td>
<td>5.20 ± 0.13a</td>
<td>2.60 ± 0.06a</td>
<td>5.9 ± 0.14a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TER+</td>
<td>4.20 ± 0.05b</td>
<td>1.90 ± 0.05b</td>
<td>5.1 ± 0.12b</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CT</td>
<td>3.70 ± 0.12c</td>
<td>1.60 ± 0.04c</td>
<td>4.2 ± 0.15c</td>
</tr>
<tr>
<td>2010</td>
<td>Teff</td>
<td>DER+</td>
<td>4.25 ± 0.08a</td>
<td>1.53 ± 0.06a</td>
<td>3.6 ± 0.1a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TER+</td>
<td>4.45 ± 0.22a</td>
<td>1.55 ± 0.04a</td>
<td>3.7 ± 0.08a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CT</td>
<td>4.03 ± 0.28a</td>
<td>1.42 ± 0.04a</td>
<td>3.3 ± 0.06a</td>
</tr>
<tr>
<td>2011</td>
<td>Grass pea</td>
<td>DER+</td>
<td>1.76 ± 0.04a</td>
<td>2.03 ± 0.07a</td>
<td>4.4 ± 0.05a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TER+</td>
<td>1.66 ± 0.04a</td>
<td>1.99 ± 0.06a</td>
<td>4.2 ± 0.08a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CT</td>
<td>1.31 ± 0.08b</td>
<td>1.59 ± 0.03b</td>
<td>3.3 ± 0.14b</td>
</tr>
</tbody>
</table>

Fig. 8. Normalized Difference Vegetative Index (NDVI) of (a) wheat (2009), (b) teff (2010) and (c) grass pea (2011). Bars shown are the standard error of mean (p < 0.05).
management returns to a linear mode, where each new ton of food requires an equal increase of water. The potential benefits offered by this window of opportunity are not only very significant for the vertisols under study, as yields currently average less than 2 t ha\(^{-1}\), but for all vertisol where yields are typically below 4 t ha\(^{-1}\) as in most SSA cropland. The grain yield of wheat in 2009, i.e., four years after implementing the new farming systems, was increased from 1.6 t ha\(^{-1}\) with CT to 2.6 t ha\(^{-1}\) (63% increase) with DER+, and its straw yield was highest with DER+ (5.2 t ha\(^{-1}\)) and lowest with CT (3.7 t ha\(^{-1}\)) (41% increase). Similarly, grain yield of teff in 2010 was increased by 8% and 9% with TER+ farming systems as compared to CT, and grass pea in 2011 by 28% with DER+ and 25% with TER+ (Table 3).

The increased biomass production in CA-based farming systems compared to CT is also supported by NDVI data. Fig. 8 shows the evolution of NDVI with time during the 2009, 2010 and 2011 growing seasons of wheat, teff and grass pea, respectively. According to the planting calendar in the study area, grass pea is sown in late August while teff in early August. Wheat can be planted starting from mid-June until about late July, if the onset of the rainy season is delayed. In this study, the length of growing season from planting to harvesting for wheat was 102 days (198–300 DOY), for teff it was 150 days (221–6 DOY) and for grass pea it was 101 days (241–242 DOY). Wheat was planted late on July 17 (198 DOY) due to the delay of ample rain for planting. The NDVI readings over time were higher in CA-based farming systems, which substantiate the presence of higher above-ground biomass in DER+ and TER+ plots (Table 3 and Fig. 8). The higher the value of NDVI, the less stress the crop experiences due to moisture deficits, disease and other constraints. DER+ had the highest NDVI for wheat and grass pea, while for teff TER+ showed the highest values. In general, for all treatments and years (2009–2011), NDVI gradually increased in the beginning of the growing season (period I), reached a stable period (period II) and then decreased toward the end of the growing season when the grains started ripening (period III). Period I (increasing stage) was shorter for wheat (less than 30 days) than for teff (57 days) or grass pea (49 days). The duration of the stages might be related to the speed of physiological development of the crops. Teff has the smallest leaf size, followed by wheat, whereas grass pea is a leguminous broad leaf crop which differs in terms of leaf area index, and thus in duration to maturity and NDVI values. The duration of period II (NDVI >0.65) of wheat was 35 days, while it was 20 days for teff in both CA-based farming systems and CT, and 35 days in CA-based farming systems and 24 days with CT for grass pea. Period II can be considered the climax of the crop vegetative stage. The crop might cease above and below ground growth at this stage. In period III, at the crop maturity stage, which is an important period for final yields, the differences between the treatments were most pronounced. Similar findings were reported by Verhulst et al. (2009). Period III, which is also called the grain filling stage, from flowering to maturity, is where translocation of assimilates occurred from source (leaves) to sink (seeds). This contributed to the appearance of yellowing of the leaf color due to degradation of chlorophylls in the leaf part and thus, low NDVI values were recorded.

The fluctuations that can be observed in NDVI data greatly reflect the crop response to water stress with changes in soil–water storage. Fig. 9 illustrates the correspondence between root zone soil–water storage and NDVI for wheat in 2009. If we assume that for the soil in this study, wheat experiences water stress at water contents less than 0.45 m\(^3\) m\(^{-3}\), which corresponds to a root zone soil–water storage of about 145 mm at 60 cm soil depth, the wheat crops in our study may have experienced water stress. The more the soil–water storage drops below the critical level for water stress, the less water the roots will take up (Feddes et al., 1978), which was reflected in a reduced NDVI value. As soil–water storage increased due to a rainfall event, NDVI values appeared to increase as well in close response to the reduced water stress experienced by the crop.

4. Conclusion

Trime\textsuperscript{e} and tensiometer are unrealistic measurement techniques for volumetric soil–water content and soil matric potential in swelling and shrinking soils in the semi-arid area of northern Ethiopia.

This study shows that improved farming systems like DER+ and TER+ that incorporate principles of CA constitute alternatives that reduce runoff and increase soil moisture on vertisols in a semi-arid setting, without further input. The CA-based farming systems of DER+ followed by TER+ had higher evapotranspiration and deep drainage than CT. The improvements in rain water partitioning with the CA-based farming systems were resulting in higher rainwater productivity, and grain and straw yield. Higher yields in the CA-based farming systems were supported by NDVI values, which were highest for DER+ followed by TER+ and lowest in CT plots for wheat and grass pea crops throughout the growing season. For teff, NDVI was highest with TER+.

Our findings indicate that CA-based farming systems have significant potential as a water management tool to increase green water availability in the root zone under rainfed agriculture. Therefore, farmers can reduce blue water flows and improve green water flow, water productivity and crop yield in vertisols by...
adopting modified and improved versions of existing field water conservation practices that utilize CA principles, without additional input. This study demonstrates that rainwater management must be used as an entry point activity starting with in situ conservation of rainwater through improved soil management for sustainable farming. The benefits of stored rainwater might potentially converge to even higher productivities by using improved cultivars, and suitable nutrient, pest and other farm management practices.

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References


