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

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ABSTRACT

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 l 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 records 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-Sahara 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 oxidization 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 mahresha. 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 mahresha 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.

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