Open Journal of Soil Science, 2015, 5, 287-298
Published Online December 2015 in SciRes. http://www.scirp.org/journal/ojss
http://dx.doi.org/10.4236/ojss.2015.512027

Tillage and Irrigation Requirements of Sorghum (*Sorghum bicolor* L.) at Hamelmalo, Anseba Region of Eritrea

Ramesh P. Tripathi*, Isaac Kafil, Woldeselassie Ogbazghi

Department of Land Resources and Environment, Hamelmalo Agricultural College, Keren, Eritrea
Email: *rp.tripathi52@gmail.com, nrd70hnk@yahoo.com, wogbazghi@gmail.com

Received 5 July 2015; accepted 13 December 2015; published 17 December 2015

Abstract

Most Eritrean farmers do not adopt soil conservation measures and till even sloppy fields 2 - 4 times for planting sorghum (*Sorghum bicolor* L.) with a view to facilitate rainwater intake. Field experiments were conducted at Hamelmalo to optimize tillage and irrigation requirements of sorghum in loamy sand. Tillage treatments were conventional tillage (4 times) on existing slopes (CTf), conventional tillage on managed plots (terraced) with residue (CTm + R) and without residue (CTm − R), reduced tillage (single tillage 4 days after heavy rainfall) on managed plots with residue (RTm + R) and without residue (RTm − R) and no tillage (direct planting) on managed plots with residue (NTm + R) and without residue (NTm − R) randomized in four replications. Tillage in CTm and CTf was same. Experiment was repeated in year II along with a new experiment in split plot design with same tillage treatments in main plots and 4 irrigation treatments in subplots in 3 replications. Irrigation treatments were rainfed (I_0), 70 mm irrigation at 50% depletion of soil moisture in CTm − R from 1 m profile after end of monsoon (I_1), 70 mm irrigation 7 days after irrigation in I_1 (I_2), and 70 mm irrigation 7 days after irrigation in I_2 (I_3). Bulk density increased and infiltration rates decreased by harvesting due to tillage but changes were lower in residue plots of NT and RT than CT. Optimum soil moisture for emergence of sorghum was within 0.145 ± 0.002 $m^3 m^{-3}$ at which soil strength was well below critical level for root growth. Soil strength in tilled layer due to intermittent wetting and drying following planting exceeded 2000 k Pa when dried below 0.143 $m^3 m^{-3}$ moisture. Soil profile in CTf did not recharge by rainfall even by end of the rainy season, whereas it was fully wetted in level and terraced plots. Conservation measures resulted 80 - 150 mm of residual moisture per 2 m of soil profile at sorghum harvesting. Residual moisture was relatively more in residue and irrigated plots than in nonresidue and CTf plots. Soil bunding and levelling alone raised sorghum yields in RT + R to 2887 kg ha^{-1} under rainfed and 3980 kg ha^{-1} under 70 mm irrigation 21 days after last rainfall of the season (I_1). Corresponding yields in CTf were 501 kg ha^{-1} under rainfed and 1161 kg ha^{-1} under irrigation. Single

*Corresponding author.

How to cite this paper: Tripathi, R.P., Kafil, I. and Ogbazghi, W. (2015) Tillage and Irrigation Requirements of Sorghum (*Sorghum bicolor* L.) at Hamelmalo, Anseba Region of Eritrea. *Open Journal of Soil Science*, **5**, 287-298.
http://dx.doi.org/10.4236/ojss.2015.512027

preplanting tillage 4 days after heavy rainfall (RT) was as good as 2 - 4 tillage (CT) practiced by farmers. Sorghum yields in Hamelmalo could be about 2752 kg ha^{-1} by water use of 344 mm and 4009 kg ha^{-1} by 432 mm. Water use in CTf was lowest (208 mm) under rainfed.

Keywords

Rainwater Conservation, Residue Mulch, Semiarid, Soil Properties, Sorghum Yield, Tillage

1. Introduction

Farmers in Hamelmalo region generally till twice before and once after broadcasting of sorghum (*Sorghum bicolor* L.) and once again about 25 - 30 days from planting on slopes <2% - 35% [1]-[3]. Farmers partly practice contour tillage on existing slopes but do not adopt any other conservation measure to prevent runoff and soil loss. Sorghum yields were relatively higher (0.8 - 1 t ha^{-1}) in the initial years than now (0.2 - 0.6 t ha^{-1}) perhaps due to release of nutrients by rapid oxidation of organic matter by tillage and relatively improved rainwater intake in soils [1] [3]-[5]. High yields in the initial years encouraged farmers to over-till the land without questioning its actual need and consequent deterioration of soil structure, organic matter and soil biota, accelerated soil erosion and overall declining soil quality [6]-[12]. However, it was slowly realised that conventional tillage practice without any conservation measures on the fragile land slopes in the region was unsustainable in terms of production and resources conservation [2] [13]-[16]. The conventional tillage on steep slopes resulted significant loss of top soil (>150 t ha^{-1} y^{-1}) and consequently crop yields in various parts of Africa [1] [3] [13] [15] [17]. Many smallholder farmers' fields in Anseba region are severely affected by sheet and gully erosion, which is greatly accelerated by repeated tillage. Degree of soil degradation can be assessed from the fact that average sorghum yields even in good rainfall years were less than 0.2 - 0.6 t ha^{-1} [1] [18].

Temesgen *et al*. [5] reported that traditional tillage in Ethiopian highlands was precisely to improve rainwater infiltration and reduce runoff and evaporation. However, only 30% - 40% of rainwater infiltrated in the tilled plots on 1% - 6% slopes and about 10% - 25% in non-agricultural lands on slopes > 10% - 30% under the conventional practice of management at Hamelmalo farm [3]. Regardless of the tillage system, almost 100% rainwater could infiltrate only on level and properly bunded fields covered 100% by plant residue mulch [2] [9] [12] [19].

No-till system has been advocated for more than 3 decades as effective option to combat land degradation, increase rainwater conservation and raise yields in semiarid regions like that of Eritrea [12] [20]-[23]. Rockstrom *et al*. [24] observed that minimum tillage increased water productivity and crop yields due to better water harvesting and improved fertilizer use from applications along the ripped and sub-soiled planting lines. Improved field water harvesting through bunding, levelling and mulching under no-till system has also shown to reduce soil erosion, increase biomass production and soil organic matter [2] [25]-[29]. Slower organic matter mineralization in reduced-till than conventional-till systems and consequent nutrient releases was important for resource-constrained farmers of Hamelmalo who suffer most from the consequences of poor soil fertility and soil degradation [3] [30]. Limited field experiments to evaluate tillage requirement of crops to date have been conducted in Eritrea. Ministry of Agriculture initiated research on conservation agriculture in collaboration with FAO [31]. The results were highly encouraging. Another experiment on no-till system with sorghum and groundnut was initiated in 2008 at Hamelmalo Agricultural College in collaboration with Australia. Results substantiated the potential of reduced and no-till systems in resources conservation and raising crop yields. However, as suggested by Giller *et al*. [30], conservation tillage practices must be evaluated to quantify benefits and role of different competing uses of crop residue and other inputs to raise crop yields and arrest soil degradation under local ecological and socio-economic conditions. Reports also indicated decreased yields with conservation tillage, increased labour requirements when herbicides were not used, increased labour burden to women and lack of mulch due to poor productivity and priority given to feeding of livestock with crop residues [30]. Effort to raise crop yields through optimization of tillage and supplementary irrigation requirements have shown potential in resolving many social and soil conservation issues [2] [3].

A preliminary survey of area in 2007 showed that more than 90% of the agricultural land in sub Zoba

Hamelmalo has some form of degradation, including severe soil erosion, sparse vegetation, poor rainwater infiltration, structural degradation and compaction [2] [3]. Rocks and stone pieces outcropping in a large proportion of the land surfaces all around speak of the severity of erosion. More than 90% of the land in Zoba Anseba is uncultivated due to steep slopes, which contributes 70% - 90% of the rainfall as runoff [3]. Whereas much of the runoff goes to neighbouring country and Red sea, it also raises groundwater table along the rivers and their tributaries criss-crossing the area. The groundwater is of good quality and is traditionally being used by farmers for drinking and irrigating orchards and vegetable crops. Farmers generally practice irrigation at every 4 - 6 days interval. Sorghum and pearl millet are common rainfed crops raised during the monsoon season. Although rainfall is sufficient for a good crop, yields are poor due to severe water stress during the grain filling stage (September to October first week) at which supplementary irrigations may increase grain yield prospects significantly [3] [32]. Objective of this research was thus to optimize tillage and supplementary irrigation requirements of sorghum at Hamelmalo to obtain sustainable high yields.

2. Materials and Methods

2.1. Soil

Soils of the Hamelmalo region have developed from fluvial deposits. Experimental soil was loamy sand with 83% sand, 11% silt and 6% clay overlying a layer of sandy loam down to 1.3 m followed by sand (89%) with <20% cobbles and boulders forming a porous bed (**Table 1**). Soil organic matter was 0.65% in the surface layer, which reduced by 50% in lower layers. Soil pH ranged from 7.82 in the surface layer to 8.4 below 1.3 m and electrical conductivity ranged from 0.08 - 0.15 d Sm^{-1}. Available nutrients were low but Ca^{2+}, Mg^{2+} and Na^{+} contents increased with depth. Average bulk density of the surface soil was 1.59 Mg m^{-3}, which increased to 1.69 Mg m^{-3} in 0.2 - 0.5 m layer but reduced underneath to 1.54 Mg m^{-3}. Field capacity moisture was 0.195 m^3 m^{-3} and groundwater table fluctuated from <2.5 m during rainy season to >5 m in dry season.

2.2. Experimental Details

Experiments were conducted during 2007 and 2009 at Hamelmalo Agricultural College farm on predominantly occurring loamy sand in the area. The Hamelmalo Agricultural College is located at 15˚52'20.6''N and 38˚27'57.6''E and 1280 m above msl in the Anseba region of Eritrea. It is about 12 km north of the Keren town on the Keren-Nakfa road adjacent to the river Anseba. Mean annual rainfall in the past 7 years was 488 mm with a minimum of 370 mm and a maximum of 663.1 mm. Total rainfall was 460 mm in 2007 and 390 mm in 2009. Highest mean monthly temperature occurred in May (35.7˚C) and lowest in January (11.1˚C).

In 2007, effect of 7 tillage treatments viz., conventional tillage farmers practice (CTf, slope < 3% - 6%), conventional tillage on managed plots with residue (CTm + R) and without residue (CTm − R), reduced tillage on managed plots with residue (RTm + R) and without residue (RTm − R) and no tillage on managed plots with residue (NTm + R) and without residue (NTm − R), randomized in four replications in 8 m × 6 m plots, were evaluated on rainfed sorghum. Managed plots refer to terraced or level plots with bunds all around. CTf refers to

Table 1. Important properties of the experimental soil.

Depth, m	Soil fractions, %			Texture	pH (1:5)	EC (1:5), dS m^{-1}	OM, %	N, %	P, mg kg^{-1}	Exchangeable cations, cmolc kg^{-1}			
	Sand	Silt	Clay							Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}
0 - 0.2	83	11	6	Loamy sand	7.8	0.08	0.65	0.06	9.32	11.5	3	0.15	0.35
0.2 - 0.5	70	14	16	Sandy loam	8.2	0.08	0.42	0.05	3.71	15.0	5	0.10	0.47
0.5 - 0.3	61	20	19	Sandy loam	8.2	0.14	0.42	0.05	2.91	20.0	5	0.14	0.55
>1.3	89	7	4	Sand	8.4	0.15	0.32	0.04	3.61	29.0	8	0.11	0.51

3 preplanting tillage followed by another 25 days after planting. Tillage in CTm was same as in CTf. RT refers to single preplanting tillage 4 days after heavy rainfall and NT refers to direct planting on managed plots. Except in CTf, bunds of height 0.30 m were made around each plot to prevent runoff. Entire experimental area was surrounded by trench to avoid any run-on. Each plot was separated by 2 m passage, which was sloping towards the main drain. Residue of the previous crop, chopped to 0.1 m, was applied uniformly @ 2.5 t ha^{-1} before tillage operations. The residue cover after planting was 66%, 33% and 63% in NT + R, CTm + R and RT + R plots, respectively.

Sorghum variety PP290 Shambuko was planted on 11 July 2007 at a seed rate of 12 kg ha^{-1} in rows 0.6 m apart at an average depth of 0.03 m using a seeder developed for this purpose. Wherever necessary, plants were thinned to about 0.2 m distance within row in about 20 days after planting. Diammonium phosphate (DAP) was applied @ 100 kg ha^{-1} and urea @ 50 kg ha^{-1} as per recommendations of NARI, Halhale, Eritrea. Entire DAP was applied at the last tillage before sowing and urea was top-dressed around 22 and 45 days from planting following rainfall. Weeds were removed manually on 15 and 35 days from planting. Except smut no major pests and diseases were observed. All infested plants were removed and destroyed after weighing their dry biomass.

Results of the 2007 experiment showed that supplemental irrigations after cessation of monsoon in September may cause significant increase in sorghum yield in the region as dry period coincides with milk to grain development stages. The experiment was thus repeated in 2009 along with a new experiment in split plot design with same 7 tillage treatments in main plots and 4 irrigation levels in subplots in 3 replications. The irrigation treatments were rainfed (I_0), 70 mm irrigation at 50% depletion of soil moisture in CTm − R from 1 m profile (I_1), 70 mm irrigation 7 days after irrigationin I_1 (I_2), and 70 mm irrigation 7 days after irrigation in I_2 (I_3). The crop was planted on July 9, 2009 with similar seed rate and management levels. Plot size of the repeated experiment was same but that of new experiment in split plot design was 5 m × 4 m. The crop was harvested from the central 3 m × 3 m area of the plots. The panicles of mature plants were cut, dried, threshed manually, cleaned and the grain was weighed on a precision electronic balance from each treatment and reported in kg ha^{-1} at 14% moisture content. Biomass yield was reported separately after air drying.

2.3. Measurement of Soil Properties

Soil properties determined were bulk density by core method, infiltration rate using double ring infiltrometer and soil moisture content by gravimetric method at planting, about a month after planting, end of monsoon, harvesting and before irrigations. Sampling for moisture determination was done in 50 mm cylindrical soil cores in duplicate from centre of the 0.2 m layer down to 1 m in one of the replications. High bulk density and low infiltration rates due to intermittent wetting and drying after planting prompted us to determine soil strength in the tilled layer by penetrometer to optimize soil moisture content during germination and emergence. For this reason, series of soil strength measurements were made at different moisture contents following rainfall to establish the relationship between soil moisture content and soil strength.

2.4. Water Use

Crop water use (ET, mm) in n days was calculated from the soil moisture data using water balance equation appropriate for the experimental conditions.

$$ET = RFe + IR - RO - DR \pm \Delta S \quad (1)$$

where RFe, IR, RO, DR and ΔS refer to effective rainfall (mm), irrigation depth (mm), runoff (mm), drainage (mm), and change in soil water storage or loss (mm). Estimation of DR was done from the following considerations [33].

$$DR = 0 \text{ for } S < Sp, \text{ and } DR = S - Sp \text{ for } S > Sp \quad (2)$$

where Sp is potential water storage capacity, considered as soil moisture storage at field capacity. RO was zero from all the plots except CTf in which it was estimated using the rainfall-runoff relationship Equation (3) developed on 3% slope from measurements made in the model watershed [3].

$$\text{Runoff} = 0.52 \times \text{rainfall} - 2.0, \quad (3)$$

Both rainfall and runoff are in mm.

3. Results and Discussion

3.1. Soil Properties

3.1.1. Bulk Density, Infiltration Rate and Soil Strength

Effect of tillage and crop residue on bulk density and infiltration rates at planting and harvesting were not significant (**Table 2**). But bulk density at harvesting increased by ≈6% and infiltration rate decreased by ≈12% from planting. The effect was lowest in NT and RT plots and maximum in conventional tillage farmers practice (CTf) plots followed by CTm plots. Lower effects in NT and RT plots might be due to lesser degradation of organic matter compared to CTm and CTf plots [6] [27] [34]. Presence of high exchangeable Ca^{2+} and Mg^{2+} in soil (**Table 1**) might have also contributed to formation of denser structure due to series of wetting and drying cycles before harvesting. Tripathi [35] and Tripathi *et al*. [36] reported that both tillage and residue effects may become significant after 4 - 8 years of continuous practice.

Although there was no appreciable swelling and shrinking yet soil strength was rapidly changing with drying (**Figure 1**). Soil strength was lost on wetting close to field capacity and was below 2000 kPa, critical for seedling emergence and root proliferation [2] [37], until soil drying to 0.143 $m^3\ m^{-3}$ moisture but exceeded 2500 kPa with further drying to 0.138 $m^3\ m^{-3}$ moisture at which root growth and water uptake are greatly affected [38]. Farmers also observed that emergence and early establishment of sorghum was better at higher water contents around seed zone [2] [3]. Isaac [2] reported that optimum soil moisture for emergence of sorghum was 0.145 ± 0.002 $m^3\ m^{-3}$ at which soil strength was well below the critical level. Since rainfall was low and erratic, CT was believed to optimize wetness in seed zone in the conventional sloppy fields [5] but crusting in such over till plots due to rapid drying following rainfall after planting cannot be ruled out. A number of reports also indicate that moisture conservation can be better optimized through mulching, terracing, levelling and bunding than tillage

Table 2. Bulk density and infiltration rates at planting and harvesting in different tillage and residue plots.

Treatments	Bulk density (Mg m^{-3})		Infiltration rate (mm h^{-1})	
	At planting	At harvesting	At planting	At harvesting
CTf	1.61	1.70	7.8	6.6
NT − R	1.60	1.69	8.1	7.1
NT + R	1.59	1.68	8.3	7.3
CTm − R	1.58	1.68	7.9	6.7
CTm + R	1.57	1.67	8.2	7.3
RT − R	1.60	1.68	8.0	7.2
RT + R	1.59	1.66	8.4	7.5
Mean	1.59	1.68	8.1	7.1
LSD (5%)	NS	NS	NS	NS

CTf = Conventional practice on existing slopes, NT = No tillage, CTm = CTf on managed plots, m = managed (terraced or level plots with bunds), −R = Without residue, +R = With residue, NS = Not significant.

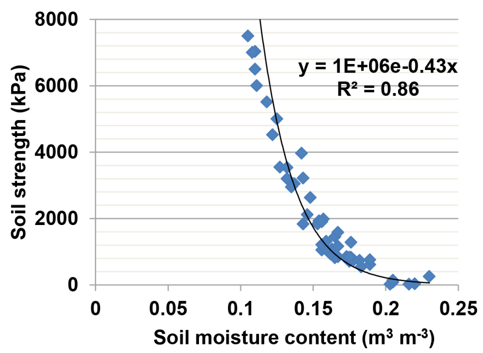

Figure 1. Soil strength as a function of soil moisture.

[3] [6] [34] [35] [39]-[41]. Optimization of tillage would not only reduce cost of cultivation but also facilitate soil and water conservation through improvements in soil structure [6] [35] [40].

3.1.2. Soil Moisture Content

At planting (July 11, 2007), soil moisture in 0 - 0.2 m layer was almost similar in all the plots and, therefore, moisture distribution only in CTf has been presented (**Figure 2**). Soil moisture at planting was about 4% below field capacity (0.195 $m^3 m^{-3}$) in 0 - 0.2 m layer and lower layers were still wetting (**Figure 2**). On 9 August (29 days from planting), all non-residue plots including CTf were still wetting in the lower layers and water content was much below field capacity but all residue plots were wetted beyond field capacity below 0.2 m depth. Total rainfall during June 27 to July 4 was 39.5 mm and that during July 10 to August 9 was 248 mm. Differences in soil moisture contents in CTf and NT-R (**Figure 2**) indicate the effect of levelling and bunding (terracing) and that in the residue plots was due to levelling, bunding and residue additions. Effect of residue on soil moisture was more in NT and RT plots perhaps because of its mulch action due to lesser incorporation in soil than in CT. Wetting in CTf and non-residue plots in lower layers continued until end of the rainy season (8 Sep) but developed uniform upward soil moisture gradient in all the plots before 23 September. The upward gradient in CTf was more because of drying of upper layers than by wetting of lower layers. Soil moisture distribution patterns (**Figure 2**) thus show that a) soil profile in the sloppy fields are not recharged by rainfall even by end of the rainy season, b) rainfall retention as soil water was unaffected by tillage and c) soil water contents in bunded and level plots of NT, RT and CT were always higher in residue than in nonresidue plots. Better capture of rainwater as soil water by crop residue than tillage has been reported by many researchers [25] [27] [34] [39] [41] [42]. Conventional tillage on sloppy fields (CTf) also encourages soil erosion compared to minimum tillage that improves water and fertilizer use [24].

In 2009, rainfall during June 28 to July 8 was 52.6 mm, which penetrated only down to 0.3 m in CTf plots but down to 1 m in the bunded and level plots (**Figure 3**). Except in CTf, wetness was greater and almost to the same depth in residue plots. In nonresidue plots, soil moisture was highest in RT – R and lowest in CTm – R.

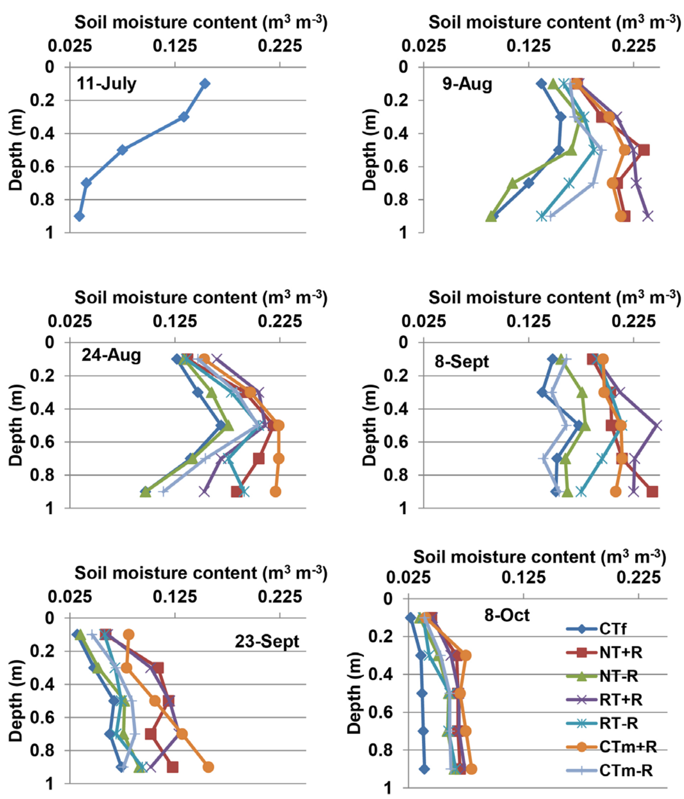

Figure 2. Soil moisture with depth in different tillage and residue plots on various dates during the crop season.

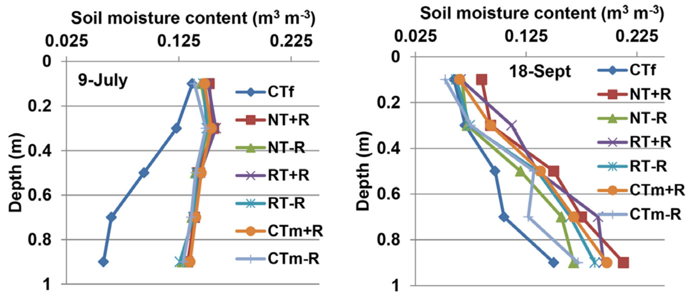

Figure 3. Soil moisture with depth in different tillage and residue plots on July 9, 2009 at planting and Sept 18, 2009 before irrigations.

Relatively more drying in CTm – R might be due to repeated tillage before planting. On September 18, surface 0.4 m soil profile in nonresidue plots dried to less than 7% moisture but wetness in the residue plots was close to field capacity below 0.6 m depth. Irrigations during September 20 to 1st week of October left more residual moisture that can be used by next crop in rotation. At harvesting, surface 0.1m layer dried almost to air dryness but, except in CTf, soil water was 40 - 80 mm m^{-1} of soil profile in lower layers (**Figure 4**). The residual moisture was relatively more in residue plots than in nonresidue plots and in I_3 (Irrigated 14 days after I_1) than in I_0. Results of 2009 confirm the observations of 2007 on tillage and residue effects on rainwater harvesting as soil water and residual moisture left in the soil profile after sorghum harvesting.

3.2. Yield

3.2.1. Tillage-Residue Effects

In 2007, highest yield of grain (2711 kg ha^{-1}) and stover (5812 kg ha^{-1}) under rainfed was observed in CTm + R, which was statistically at par with that in RT + R but significantly greater than in the remaining treatments (**Table 3**). It was lowest (1200 kg ha^{-1} grain and 3000 kg ha^{-1}stover) in CTf. All tillage treatments with residue performed significantly better than those without residue, perhaps due to better rainwater conservation (**Figure 2** and **Figure 3**). Yields were statistically equal in CTm − R and RT − R but significantly greater than in NT − R. This indicates superiority of RT over CT and NT. Similar results were also observed in 2009. Significantly lower yields under NT might be due to poor crop growth in the initial stages because of greater competition for nutrients and water with weeds compared to that under RT in which first flush of weeds that emerged in 4 days after rainfall were turned into the soil by tillage. The crop under NT also showed nitrogen deficiency, which recovered after weeding and urea applications. Two additional weedings were necessary in NT than in other plots. Results show that single preplanting tillage 4 days after heavy rainfall (RT) in well bunded and level plots that ensured rainwater conservation was sufficient to raise sorghum yields in the range of 2405 - 2797 kg ha^{-1} in Hamelmalo region. Crop yield improvements due to minimum tillage were also observed by Mbagwu [39], Steyn *et al.* [34] and Rockstrom *et al.* [24]. Despite potential benefits in crop yields, use of crop residue as mulch has been questioned by Giller *et al.* [30] in semiarid Africa due to its competing uses particularly as animal feed. The argument is valid if farmers are satisfied with current yield levels (1 - 2 t ha^{-1} sorghum stover) but if yields improve to the level obtained (>4 - 5 t ha^{-1}) through better management then at least half of the stover could be diverted back to the soil to which it belongs.

3.2.2. Tillage and Irrigation Effects

Mean grain yield due to tillage was highest in CTm + R (3823 kg ha^{-1}), which was at par with that in RT + R (3756 kg ha^{-1}) but significantly greater than in the remaining treatments (**Table 4**). Similarly mean yield due to irrigations was highest in I_1 (3548 kg ha^{-1}), which was as at par with that in I_2 (3492 kg ha^{-1}) but significantly greater than in I_0 (2416 kg ha^{-1}) and I_3 (3398 kg ha^{-1}). Interaction effects also show that grain yields in CTm + R and RT + R were at par, which further confirmed the superiority of reduced tillage. Except in I_1 and I_2 of CTm, grain yields due to residue were not significant (**Table 4**). Under rainfed (I_0), grain yield was lowest in CTf (501 kg ha^{-1}) and highest in CTm + R (2989 kg ha^{-1}), which was at par with that in RT + R (2887 kg ha^{-1}). Similar effects were observed on stover yields. First irrigation given on 21-day after last rainfall of the season (I_1) raised grain yield by 660 kg ha^{-1} in CTf and 1102 - 1408 kg ha^{-1} in the remaining treatments from that under rainfed.

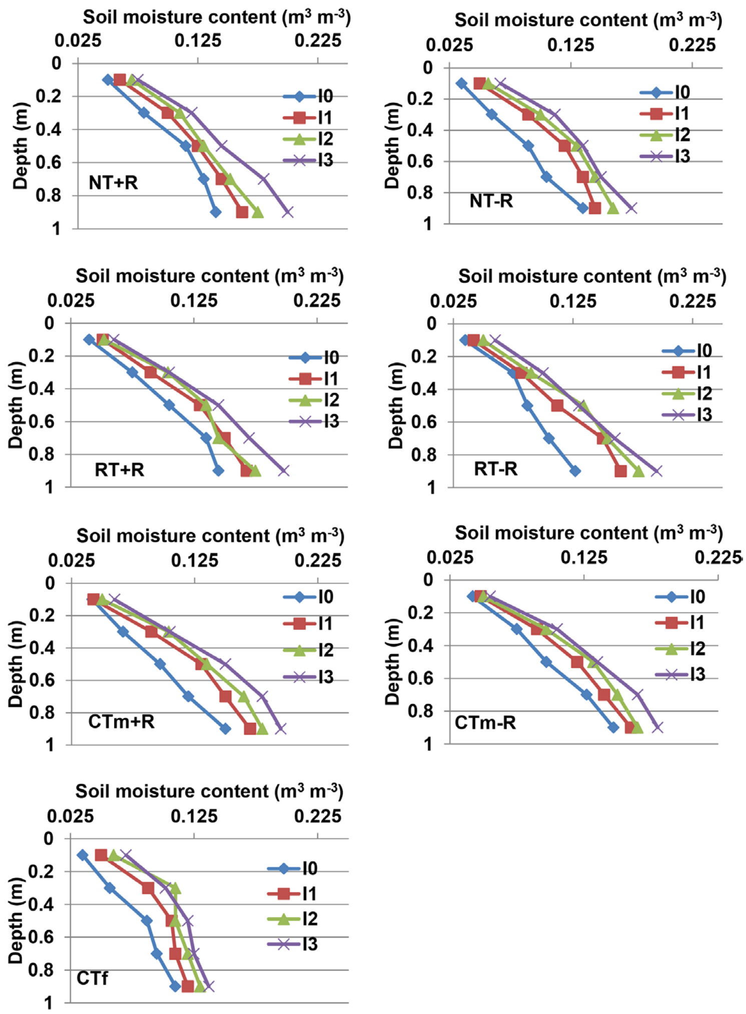

Figure 4. Soil moisture with depth at harvesting in different tillage, residue and irrigation plots.

Table 3. Grain and stover yields of rainfed sorghum in 2007 and 2009.

Treatments	Yield in 2007 (kg ha^{-1})		Yield in 2009 (kg ha^{-1})	
	Grain	Stover	Grain	Stover
CTf	1200	3000	629	1693
NT + R	2447	5474	2640	4975
NT − R	2085	5202	2450	4868
CTm + R	2711	5812	2880	5348
CTm − R	2440	5540	2676	5198
RT+R	2605	5704	2797	5301
RT − R	2405	5439	2590	5158
Mean	2270	5167	2409	4649
LSD (5%)	110	282	126	185

CTf = Conventional practice, NT = No tillage, CTm = CTf on well bunded and level plots, −R = Without residue, +R = With residue.

Table 4. Grain and stover yields of sorghum under different tillage and irrigations.

Tillage treatment, T	Grain yield (kg ha^{-1})					Stover yield (kg ha^{-1})				
	Irrigation levels, I					Irrigation levels, I				
	I_0	I_1	I_2	I_3	Mean	I_0	I_1	I_2	I_3	Mean
CTf	501	1161	983	879	881	1533	2266	2098	1983	1970
NT + R	2530	3880	3803	3731	3486	4973	5912	5872	5743	5625
NT – R	2397	3805	3657	3574	3358	4697	5815	5902	5823	5559
CTm + R	2989	4151	4156	3994	3823	5483	6310	6328	6328	6113
CTm – R	2802	3956	3893	3803	3614	5180	6008	6060.	6155	5851
RT + R	2887	3980	4108	4048	3756	5313	6285	6282	6207	6022
RT – R	2804	3906	3842	3754	3576	5188	5922	5957	5905	5743
Mean	2416	3548	3492	3398	3213	4624	5502	5500	5449	5269
Factors:		T	I	T × I		T	I	T × I		
LSD (P = 0.05)		122	64	185		174	96	271		

CTf = Conventional practice, NT = No tillage, CTm = CTf on well bunded and level plots, -R = Without residue, +R = With residue, I_0 = Rainfed, I_1 = 70 mm irrigation at 50% depletion of soil moisture from 1 m profile, I_2 = 70 mm irrigation 7 days after irrigation in I_1, I_3 = 70 mm irrigation 7 days after irrigation in I_2.

Similarly stover yields increased by 733 - 1118 kg ha^{-1}. The interaction effects justify the significance of reduced tillage (RT: one preplanting tillage 4 days after good rainfall) for optimum yields in well bunded and level plots. Maturity was delayed by 3 to 4 days in I_1 and 2 to 6 days in I_3.

Results thus show that soil bunding and levelling for rainwater conservation with single preplanting tillage can raise sorghum yields to more than 2405 kg ha^{-1} under rainfed and more than 3906 kg ha^{-1} under 70 mm irrigation 21 days after last rainfall of the season (**Table 4**). The three tillage practices (NT, RT, and CT) with residue showed lower weed incidence and produced better crop than without residue. Results also show that irrigations cannot bring significant increases in yield unless fields are level and bunded to arrest runoff and at least part of the residue is returned back to soil to maintain its quality.

3.3. Water Use and Production Function

Water use by rainfed sorghum was minimum (208 mm) in CTf and maximum (353 mm) in NT + R (**Figure 5**). Much of the irrigation water was also lost as runoff in CTf and, therefore, crop water use did not improve as much as in the other treatments. Sorghum crop at first irrigation was at grain filling stage and plants in CTf were almost drying due to inadequate soil water in the root zone but plants were perhaps within recoverable limits in other plots. Greater water use than irrigation amounts in the terraced plots (**Figure 5**) indicates improved upward flow of soil moisture into the root zone from lower layers and efficient root water extraction by mildly stressed plants [43].

A linear relationship between water use and grain yield (**Figure 6**) showed that yield increase due to single irrigation after cessation of monsoon was as important as rainfall during the crop season. Crop response to water availability in the root zone was thus crucial during September 20 to 1st week of October due to rapid drying. Irrigations raised not only the sorghum yield but also left more residual moisture for use by next crop in rotation. Production function (**Figure 6**) shows that farmers can raise rainfed sorghum yields from current <600 kg ha^{-1} [1] [18] to >2752 kg ha^{-1} with a water use of 344 mm through adoption of RT in terraced plots under dryland conditions of Hamelmalo. Grain yields may further increase to 4009 kg ha^{-1} by 70 mm irrigation about 21 days after cessation of the monsoon raising water use to 432 mm.

4. Conclusions

1) Single preplanting tillage 4 days after heavy rainfall (RT) was sufficient for optimum yield of sorghum in well bunded and level fields.

2) Soil bunding and levelling for rainwater conservation can raise rainfed sorghum yields to more than 2400 kg ha^{-1}.

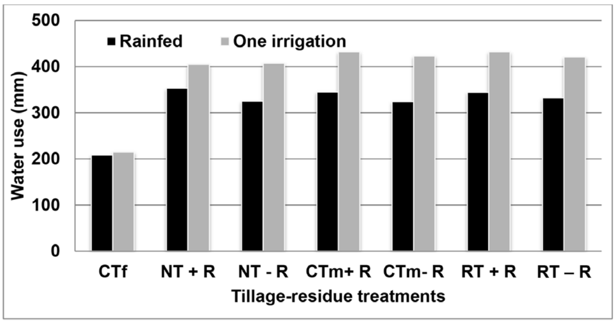

Figure 5. Water use by sorghum indifferent tillage, residue and irrigation plots.

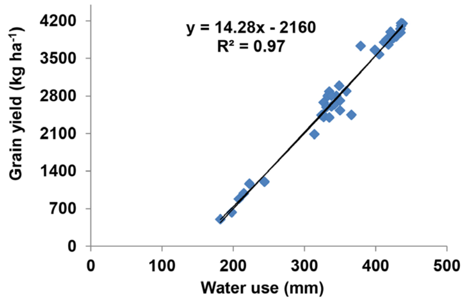

Figure 6. Sorghum yield as a function of water use.

3) Sorghum yields in Hamelmalo region can be raised to more than 3900 kg ha^{-1} by 70 mm irrigation applied 21 days after cessation of rainfall in September.

4) Grain yields would be better under residue than nonresidue conditions.

5) Crop response to water availability in the root zone is crucial for sorghum during September 20 to first week of October.

6) Sorghum root zone in the conventional cultivated sloppy fields is not recharged by rainfall even by end of the rainy season.

7) Irrigations cannot bring significant increases in yield unless fields are level and bunded.

Acknowledgements

Authors are grateful to the Centre for Development and Environment, Institute of Geography, University of Berne, Switzerland for providing financial support through Eastern and Southern Africa Partnership Programme to carry out this research.

References

[1] MOA (Ministry of Agriculture) (2005) Area and Production by Zoba from 1992-2005. Asmara, Eritrea.

[2] Isaac, K. (2008) Effect of Conservation Tillage Practices on Soil Properties, Growth and Yield of Sorghum (*Sorghum bicolour* L.) in the Semiarid Region of Eritrea. M.Sc. Thesis, Department of Land Resources and Environment, Hamelmalo Agricultural College, Eritrea.

[3] Tripathi, R.P. and Ogbazghi, W. (2010) Development and Management of a Hilly Watershed in Hamelmalo Agricultural College Farm, as a Demonstration Site for Farmers and a Study Site for Students. Final Technical Report of the Project Financed by Eastern and Southern Africa Partnership Programme (ESAAP), Hamelmalo Agricultural College, Keren, 59 p.

[4] Haile, A., Araiya, W., Omer, M.K., Ogbazghi, W. and Tewelde, M. (1995) Rehabilitation of Degraded Lands in Eritrea. Ministry of Agriculture, University of Asmara, International Development Center, Technical Paper No. 1.

[5] Temesgen, M., Rockstrom, J., Savenije, H.H.C., Hoogmoed, W.B. and Alemu, D. (2008) Determination of Tillage Frequency among Smallholder Farmers in Two Semiarid Areas in Ethiopia. *Physics and Chemistry of the Earth*, **33**,

183-191. http://dx.doi.org/10.1016/j.pce.2007.04.012

[6] Aina, P.O., Lal, R. and Roose, E.J. (1991) Tillage Methods and Soil and Water Conservation in West Africa. *Soil & Tillage Research*, **20**, 165-186. http://dx.doi.org/10.1016/0167-1987(91)90038-Y

[7] Arnon, I. (1992) Agriculture in Drylands: Principles and Practices. Elsevier Science Publishers, B.V., Amsterdam.

[8] Rockstrom J. and Jonsson, L.O. (1999) Conservation Tillage Systems for Dryland Farming: On-Farm Research and Extension Experiences. *East African Agricultural and Forestry Journal*, **65**, 101-114.

[9] Derpsch, R. (2000) Frontiers in Conservation Tillage and Advances in Conservation Practice. FAO, Rome

[10] Karlen, D.L, Andrews, S.S. and Doran, J.W. (2001) Soil Quality: Current Concepts and Applications. *Advances in Agronomy*, **74**, 1-40. http://dx.doi.org/10.1016/S0065-2113(01)74029-1

[11] Tripathi, R.P., Sharma, P. and Singh, S. (2005) Tilth Index: An Approach to Optimize Tillage in Rice Wheat System. *Soil & Tillage Research*, **80**, 125-137. http://dx.doi.org/10.1016/j.still.2004.03.004

[12] Bollinger, A., Magid, J., Amado, T.J.C., Neto, F.S., Ribeiro, M.D.D., Calegari, A., Ralisch, R. and Neergaard, A.D. (2006) Taking Stock of the Brazilian "Zero-Till Revolution": A Review of Land Mark Research and Farmers' Practice. *Advances in Agronomy*, **91**, 47-110. http://dx.doi.org/10.1016/S0065-2113(06)91002-5

[13] Elwell, H.A. and Stocking, M.A. (1988) Loss of Soil Nutrients by Sheet Erosion Is a Major Hidden Farming Cost. *The Zimbabwe Science News*, **22**, 79-82.

[14] FAO (1994) Agriculture Sector Review for Eritrea. FAO, Rome.

[15] FAO (1998) Press Release 98/42. FAO: Conventional Tillage Severely Erodes Soil; New Concepts for Soil Conservation Required. http://www.fao.org/WAICENT/OIS/PRESS NE/PRESSENG/1998/pren 9842.htm

[16] Rockstrom, J. (2001) Green Water Security for the Food Makers of Tomorrow: Windows of Opportunity in Drought-Prone Savannahs. *Water Science & Technology*, **43**, 71-78.

[17] African Conservation Tillage Network, 2008. www.act-africa.org/

[18] FAO (2005) Global Information and Early Warning System on Food and Agriculture World Food Programme. Special report FAO/WFP Crop and Food Supply Assessment Mission to Eritrea.

[19] Rockstrom, J. and Falkenmark, M. (2000) Semiarid Crop Production from a Hydrological Perspective: Gap between Potential and Actual Yields. *Plant Science*, **19**, 319-346. http://dx.doi.org/10.1080/07352680091139259

[20] Laryea, K.B., Pathak, P. and Klaiji, M.C. (1991) Tillage Systems and Soils in the Semi-Arid Tropics. *Soil & Tillage Research*, **20**, 201-218. http://dx.doi.org/10.1016/0167-1987(91)90040-5

[21] Fowler, R. and Rockstrom, J. (2001) Conservation Tillage for Sustainable Agriculture: An Agrarian Revolution Gathers Momentum in Africa. *Soil & Tillage Research*, **61**, 93-107. http://dx.doi.org/10.1016/S0167-1987(01)00181-7

[22] Hobbs, P.R. (2007) Conservation Agriculture: What Is It and Why Is It Important for Future Sustainable Food Production? *The Journal of Agricultural Science*, **145**, 127-137. http://dx.doi.org/10.1017/S0021859607006892

[23] Hobbs, P.R., Sayre, K. and Gupta, R. (2008) The Role of Conservation Agriculture in Sustainable Agriculture. *Philosophical Transactions of the Royal Society B*, **363**, 543-555. http://dx.doi.org/10.1098/rstb.2007.2169

[24] Rockstrom, J., Kaumbutho, P., Mwalley, J., Nzabi, A.W., Temesgen, M., Mawenya, I., Barron, J. and Damgaard-Larsen, S. (2008) Conservation Farming Strategies in East and South Africa: Yields and Rain Water Productivity from On-Farm Action Research. *Soil & Tillage Research*, **103**, 23-32. http://dx.doi.org/10.1016/j.still.2008.09.013

[25] Lal, R. (1998) Soil Erosion Impact on Agronomic Productivity and Environment Quality. *Critical Reviews in Plant Sciences*, **17**, 319-464. http://dx.doi.org/10.1016/S0735-2689(98)00363-3

[26] Erenstein, O. (2002) Crop Residue Mulching in Tropical and Semi-Tropical Countries: An Evaluation of Residue Availability and Other Technological Implications. *Soil & Tillage Research*, **67**, 115-133. http://dx.doi.org/10.1016/S0167-1987(02)00062-4

[27] Scopel, E., Findeling, A., Guerra, E.C. and Corbeels, M. (2005) Impact of Direct Sowing Mulch-Based Cropping Systems on Soil Carbon, Soil Erosion and Maize Yield. *Agronomy for Sustainable Development*, **25**, 425-432. http://dx.doi.org/10.1051/agro:2005041

[28] Zingore, S., Manyame, C., Nyamugafara, P. and Giller, K.E. (2005) Long-Term Changes in Organic Matter of Woodland Soils Cleared for Arable Cropping in Zimbabwe. *European Journal of Soil Science*, **56**, 727-736. http://dx.doi.org/10.1111/j.1365-2389.2005.00707.x

[29] Farage, P.K., Ardo, J., Olsson, L., Rienzi, E.A., Ball, A.S. and Pretty, J.N. (2007) The Potential for Soil Carbon Sequestration in Three Tropical Dryland Systems of Africa and Latin America: A Modelling Approach. *Soil & Tillage Research*, **94**, 457-472. http://dx.doi.org/10.1016/j.still.2006.09.006

[30] Giller, K.E., Witter, E., Corbeel, M. and Tittonell, P. (2009) Consertvation Agriculture and Smallholder Farming in Africa: The Heretics' View. *Field Crops Research*, **74**, 1-12.

[31] NARI (National Agricultural Research Institute) Eritrea (2001-2003) Reports on Introduction of Conservation Agriculture in Eritrea, and Conservation Agriculture in Eritrea.

[32] Rockstrom, J., Barron, J. and Fox, P. (2002) Rainwater Management for Increased Productivity among Small Holder Farmers in Drought Prone Environments. *Physics and Chemistry of the Earth*, **27**, 949-959. http://dx.doi.org/10.1016/S1474-7065(02)00098-0

[33] Tripathi, R.P. and Mishra, R.K. (1986) Wheat Root Growth and Seasonal Water-Use as Affected by Irrigation under Shallow Water Table Conditions. *Plant and Soil*, **92**, 181-188. http://dx.doi.org/10.1007/BF02372632

[34] Steyn, J.T., Tolmay, J.P.C., Human, J.J. and Kilian, W.H. (1995) The Effects of Tillage Systems on Soil Bulk Density and Penetrometer Resistance of a Sandy Clay Loam Soil. *South African Journal of Plant and Soil*, **12**, 86-90. http://dx.doi.org/10.1080/02571862.1995.10634342

[35] Tripathi, R.P. (1992) Physical Properties and Tillage of Rice Soils in Rice-Wheat System. In: Pandey, R.K., Dwivedi, B.S. and Sharma, A.K., Eds., *Rice-Wheat Cropping System*, Project Directorate for Cropping Systems Research, Modipuram, 53-67.

[36] Tripathi, R.P., Sharma, P. and Singh, S. (2006) Soil Physical Response to Multi-Year Rice-Wheat Production in India. *International Journal of Soil Science*, **1**, 91-107. http://dx.doi.org/10.3923/ijss.2006.91.107

[37] Da Silva, A.P. and Kay, B.D. (1997) Estimating the Least Limiting Water Range of Soil from Properties and Management. *Soil Science Society of America Journal*, **61**, 877-883. http://dx.doi.org/10.2136/sssaj1997.03615995006100030023x

[38] Phillips, R.E. and Kirkham, D. (1962) Mechanical Impedance and Corn Seedling Growth. *Soil Science Society of America Proceedings*, **26**, 319-322. http://dx.doi.org/10.2136/sssaj1962.03615995002600040005x

[39] Mbagwu, J. (1990) Mulch and Tillage Effects on Water Transmission Characteristics of an Ultisol and Maize Grain Yield in SE Nigeria. *Pedologie*, **40**, 155-168.

[40] Lal, R. (1991) Tillage and Agricultural Sustainability. *Soil & Tillage Research*, **20**, 133-146. http://dx.doi.org/10.1016/0167-1987(91)90036-W

[41] Kronen, M. (1994) Water Harvesting and Conservation Techniques for Smallholder Crop Production Systems. *Soil & Tillage Research*, **32**, 71-86. http://dx.doi.org/10.1016/0167-1987(94)90034-5

[42] Bationo, A., Kihara, J., Vanlauwe, B., Waswa, B. and Kimetu, J. (2007) Soil Organic Carbon Dynamics, Functions and Management in West African Agro-Ecosystems. *Agricultural Systems*, **94**, 13-25. http://dx.doi.org/10.1016/j.agsy.2005.08.011

[43] Kramer, P.J. (1978) Plant and Soil Water Relationships: A Modern Synthesis. McGraw-Hill, Inc., New York, 482 p.