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Impacts of conservation tillage on the hydrological and agronomic performance of *fanya juus* in the upper Blue Nile (Abbay) river basin

M. Temesgen[1,2], S. Uhlenbrook[1,4], B. Simane[3], P. van der Zaag[1,4], Y. Mohamed[1,4], J. Wenninger[1,4], and H. H. G. Savenije1[4]

[1]UNESCO-IHE Institute for Water Education, P.O. Box 3015, 2601 DA Delft, The Netherlands
[2]Civil Engineering Department, Addis Ababa Institute of Technology, Addis Ababa University, P.O. Box 380, Addis Ababa, Ethiopia
[3]Institute for Environment, Water and Development, Addis Ababa University, P.O. Box 2176, Addis Ababa, Ethiopia
[4]Delft University of Technology, Faculty of Civil Engineering and Applied Geosciences, Water Resources Section, Stevinweg 1, P.O. Box 5048, 2600 GB Delft, The Netherlands

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Correspondence to: M. Temesgen (melesse_tem@yahoo.com)

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Abstract

Adoption of soil conservation structures (SCS) has been low in high rainfall areas of Ethiopia mainly due to crop yield reduction, increased soil erosion following breaching of SCS, incompatibility with the tradition of cross plowing and water-logging behind SCS. A new type of conservation tillage (CT) involving contour plowing and the construction of invisible subsoil barriers using a modified Maresha winged "subsoiler" is suggested as a means to tackle these problems as an integral part of the SCS. We investigated the effect of integrating the CT with SCS on the surface runoff, water-logging, soil loss, crop yield and plowing convenience. The new approach of conservation tillage has been compared with traditional tillage (TT) on 5 farmers' fields in a high rainfall area in the upper Blue Nile (Abbay) river basin. Test crops were wheat [triticum *vulgare*] and tef [eragrostis tef]. Farmers found CT convenient to apply between SCS. Surface runoff appeared to be reduced under CT by 48 and 15 %, for wheat and tef, respectively. As a result, CT reduced sediment yield by 51 and 9.5 %, for wheat and tef, respectively. Significantly reduced water-logging was observed behind SCS in CT compared to TT. Grain yields of wheat and tef increased by 35 and 10 %, respectively, although the differences were not statistically significant apparently due to high fertility variations among fields of participating farmers. Farmers who tested CT indicated that they will continue this practice in the future.

1 Introduction

In Ethiopia, land degradation has become one of the most important environmental problems, mainly due to soil erosion and nutrient depletion. Coupled with poverty and the fast-growing population, land degradation poses a serious threat to national and household food security. Different literatures show an escalating threat of land degradation particularly in the highlands (Mulugeta et al., 2005; Grepperud, 1996; Hurni, 1993; Chuma, 1993; FAO, 1986). Average soil loss rates on croplands have been estimated at 42 tons ha^{-1} yr^{-1} but may reach 300 tons ha^{-1} yr^{-1} in individual fields (Hurni, 1993). This, by far, exceeds the natural rate of soil formation. The FAO (1986) report estimates some 50 % of the highlands are significantly eroded, of which 25 % are seriously eroded, and 4 % have reached a point of no return. Moreover, excessive surface runoff impacted downstream water users through a modified flow regime leading to drying up of springs during the dry season (Bewket and Sterk, 2005; Musefa, 2007). It is estimated that the trans-boundary rivers that originate from Ethiopian highlands carry about 1.3 billion tons yr^{-1} of sediment to neighboring countries (MoWR 1993) whereas the Blue Nile alone carries 131 Million tons yr^{-1} (Betrie et al., 2011) and 61 Million tons yr^{-1} (Easton et al., 2010). Poor watershed management and inappropriate farming practices have contributed to these escalating rates. A recent study (Teferi et al., 2010) conducted in the Choke Mountains has shown that between 1986 and 2005 alone 84 % of wetlands has been converted to cultivated land.

In order to reduce soil erosion, a number of soil conservation technologies have been introduced. Soil conservation technologies are generally classified as physical (mechanical) and biological measures. Physical measures include soil bunds and *Fanja Juus* (trenches following contour lines with soil bunds at the upslope side; e.g. Makurira et al., 2010). The Ethiopian government launched a massive soil conservation program beginning in the mid-1970s. However, by 1990, only limited SCS survived, viz: 30 percent of soil bunds, 25 % of the stone bunds, 60 % of the hillside terraces, 22 % of land planted in trees, and 7 % of the reserve areas still exist (USAID, 2000).

Investment in soil conservation structures is expected to lower soil erosion rates and increase grain yields in moisture stressed areas (Makurira et al., 2010; Nyssen et al., 2007; Herweg and Ludi, 1999). But for high rainfall areas, adoption of the technology has been hindered because of reduction in grain yield, accelerated soil erosion, waterlogging behind bunds and incompatibility with the tradition of cross plowing, among others (Shiferaw and Holden, 1999; Sutcliffe, 1993; Herweg, 1993; Tadesse and Belay, 2004; Hengsdijk et al., 2005).

Farmers often complain that the structures interfere with traditional practices of cross-plowing, especially when the distance between bunds is short, making turning of the plow difficult (Shiferaw and Holden, 1999; Tadesse and Belay, 2004). Cross-plowing is practiced because the traditional ard plow in Ethiopia, called *Maresha* (Fig. 1), can not be efficiently used over the same line of plowing in consecutive tillage operations (Temesgen et al., 2008). Therefore, any two consecutive tillage operations have to be carried out perpendicular to each other, which is called cross-plowing. Cross plowing increases surface runoff as a result of plowing up and down the slope, which has also been demonstrated elsewhere (Rowland, 1993). Increased surface runoff leads to either detention of too much water by the bunds leading to waterlogging or breaching of the bunds leading to accelerated soil erosion downstream.

One way of tackling the problem of breakdowns of bunds is to reduce the surface runoff reaching the structures by introducing conservation tillage. Conservation agriculture was introduced as a concept for resource-efficient agricultural crop production based on an integrated management of soil, water and biological resources combined with external inputs (FAO, 2008). To achieve this, CA is based on three principles: (1) minimum or no mechanical soil disturbance; (2) permanent organic soil cover (consisting of a growing crop or a dead mulch of crop residues); and (3) diversified crop rotations.

However, direct application of these practices of CA is constrained by several technical and socio-economic factors such as the need for dry season animal feed, high costs of herbicide (more expensive than oxen powered mechanical weed control but cheaper than tractor powered mechanical tillage), among others (Temesgen, 2007). Therefore, conservation tillage has been adapted to the local conditions by achieving the objectives but not necessarily doing the suggested practices of CA.

Thus, a conservation tillage system that involves contour plowing and subsoiling has been developed together with a modified *Maresha* plow (MST, 2008), which is now available at a price of 20USD.. Subsoiling increases infiltration by disrupting plow pans (e.g. Lampurlane and Cantero-Martínez, 2006; Busscher et al., 2002; Norfleet et al., 1996). The formation of plow pans under the traditional cultivation system has been reported (Biazin et al., 2011; Temesgen et al., 2008). *Maresha* modified subsoilers have been found to effectively disrupt the plow pan resulting in increased infiltration (Temesgen et al., 2009; McHugh et al., 2007).

It is hypothesized that the application of the new tillage system may improve the performance of the soil conservation structures by reducing surface runoff reaching those structures. As such it will reduce water-logging behind SCS, which in turn reduces soil erosion, as well as making it more convenient to plow between SCS because there is no longer a need for cross-plowing. Better moisture distribution between the upper and lower parts of the plot as well as along the soil profile with increased infiltration coupled with enhanced root growth is also expected to increase grain yield.

Therefore, the objective of this study is to assess the hydrological and agronomic impacts of integrating CT with SCS. Specifically, the study investigates the effects of CT on surface runoff and water-logging behind SCS, soil moisture pattern, convenience of plowing between SCS, rate of soil erosion and changes in crop yields.

2 Materials and methods

2.1 Study site

The experiment was carried out at Enerata (10°24.85′ N 37°44.92′ E) in the upper Blue Nile (Abbay) River basin (Fig. 1). Enerata is located 7 km North of Debre Markos town, which is about 300 km North West of Addis Ababa. The altitude ranges from 2380 m to 2610 m. The study area is characterized by sub-humid climatic condition and typically represents the "Dega" zone of the traditional agro-climatic classification system of Ethiopia. The mean annual rainfall and temperature are 1300 mm yr^{-1} and 15 °C, respectively, as recorded by Debre Markos weather station. The rainfall is unimodal occurring mainly in the months of June to September (locally known as "*kiremt*" season). The driest months are November to February (locally known as "*bega*" season) (Woldeamlak, 2003).

According to Mohar (1971) the study area is a part of the highlands that largely owe their altitude to the uplift of the Arabo-Ethiopian land mass. The geological events of the Tertiary and Quaternary periods shaped the outer part of the present highland areas of the Blue Nile River basin with an extremely large amount of lava poured to land surface to form flood (trap) basalt series and Aden series, respectively (Gurmu, 2010; Nyssen et al., 2004; BCEOM, 1998; Pik et al., 1998). Recent periods are responsible for the erosions and weathering of the various rocks formed in the Mesozoic, Tertiary and Quaternary periods yielding in situ formed or transported residual soil formation. The study area is composed of regolith with varying thickness. The younger Termaber basalt rocks (Termaber 2) constitute the parent material in the study area where the dominant soil group is Heptic Alisols (Gurmu, 2010). According to the soil classification system of FAO/UNESCO (1990) the soil type in the study area is mainly Nitosols while the textural class is clay loam.

The prevalent farming system in the study area is a subsistence mixed crop-livestock system, typical for the highlands of the country, where livestock provide the draught power needed for the farming operation and a good part of crop residues are fed to livestock. The main types of crops cultivated in the study area are barley (*Hordeum vulgare*), engido (*Avena* spp.), wheat (*Triticum vulgare*) and tef (*Eragrostis* tef). Tef, very popular in Ethiopia, is an annual cereal crop (belonging to the grass family) that has a very low canopy cover. Tef has very fine seeds that require repeated plowing of fields to prepare fine seedbeds and to control weeds, which increases the vulnerability of the soil to erosion.

2.2 Experimental setup

The experiment was laid out in a Randomized Complete Block Design (RCBD) with 4 replications (4 farmers) and 2 treatments (CT and TT). All experimental fields were treated with *fanya juus* as part of the routine soil conservation works of the local Bureau of Agriculture. Two field segments each bounded by *fanya juus* were selected from each of the 4 farmers such that they have similar slopes, which ranged between

9 and 11 %. Since the field segments do not have the same dimension and shape, runoff measurements were made from 5 m × 30 m plots delineated inside each field segment (Fig. 2). The three sides were fenced with galvanized iron sheets while the lower side was bounded by the *Fanya juus*. The iron sheets were inserted 15 cm deep while remaining 10 cm above the surface. Delineation of the plots was carried out immediately after sowing. The dates and number of tillage operations in both treatments of each farmer (replication) were made the same. All farmers plowed wheat fields 4 times before sowing while that number was 5 for tef.

Five farmers were selected and trained on the concepts and field applications of CT in addition to supervision during field works. The experimental set up was first explained to and discussed with the farmers. Each participating farmer was provided with a winged subsoiler. They were advised to keep notes of what they observe throughout the season. All other inputs such as fertilizer and seeds were provided by farmers themselves. An agreement was made with farmers such that if a CT plot gave lower yield than that of TT, the research project would pay the difference. Farmers were encouraged to make cross visits of their fields and discuss among themselves about the performance of CT. A meeting was held with farmers after they harvested the crop to discuss the results of the experiment.

A locally adapted conservation tillage (CT) has been tested in comparison with the traditional tillage system. CT involved contour plowing, subsoiling and leaving invisible barriers parallel to furrows (Fig. 3). CT employs a *maresha* modified winged subsoiler (Fig. 4), which makes it possible to undertake contour plowing while disrupting the plow pan below the depth of operation of the *Maresha*. Farmers start with contour plowing using Maresha followed by subsoiling the same furrows. During the third pass, maresha can be used along the same lines to make the furrows wider and more visible for the next subsoiling. The CT system leaves invisible subsurface barriers, in each furrow, that hinder flow along the slope thereby facilitating slow drainage parallel to the structures, increasing infiltration and percolation thus protecting the soil conservation structures.

2.3 Field measurements

2.3.1 Testing soil compaction

Soil penetration resistance was measured at randomly selected 15 places in traditionally cultivated fields at Enerata. A penetrolgger (Eijkelkamp®) was used for the study. The speed of operation was adjusted to 2 cm s^{-1} while a 1 cm^2 area 30° cone was used for ease of penetration into the lower compacted layers.

2.3.2 Assessing soil profile

The soil profile over the plow depth was assessed by measuring the distance from a horizontal line to the undisturbed surface both before and after tillage. Two pegs, spaced 1.6 m apart, were placed across the tillage direction. A rope was tied to the two pegs. In the upstream peg, the knot was placed 5 cm above the ground. The rope was kept level while tying it to the downstream peg. Height of the rope from the ground was measured at 10 cm interval before tillage. CT was applied without removing the pegs. Then the lose soil between the two pegs was carefully removed by hand. The rope was again tied to the two pegs and height of the rope from the undisturbed soil was measured at every point where the soil profile changed.

2.3.3 Agronomic data

Plant population, plant height, biomass and grain yield were measured. Samples for biomass and grain yield were taken from 5 places in each plot. A 1 m × 1 m frame was used to delineate the area for sample collection. The samples from the 5 places in each plot were mixed and weighted in the field after drying. The grain was then manually threshed and put in plastic bags. The grain samples were weighed using electronic balances in the lab and the weights were adjusted for a moisture content of 14 %.

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2.3.4 Soil moisture

Soil moisture contents were continuously monitored in both TT and CT. Moisture sensors (10HS soil moisture sensors, CaTec®) were installed at 10 and 30 cm depths in each plot. Measurements were made on soil moisture in the root zone in the lower parts of each plot bounded by two consecutive SCS in CT as well as TT.

2.3.5 Surface runoff

Runoff measuring troughs (Fig. 7) were designed, fabricated and installed at the lower corners of 4 plots (two with tef and two with wheat). The trough is divided into three main compartments. The first part retains the whole runoff until it is full. Once it reaches its capacity excess runoff is spilled through 20 pipes welded at the top of the lower side of the compartment. One of the 20 pipes is extended to deliver 5 % of the excess runoff to the second main compartment, which again spills through 10 pipes out of which one is extended to sample 10 % of the remaining excess runoff. Thus, the trough can handle up to 18 $m^3 d^{-1}$ of runoff, which is equivalent to a 10 yr daily rainfall (85 mm d^{-1} as recorded in Debre Markos weather station) with a 50 % runoff coefficient from a 400 m^2 plot, the largest plot size in this experiment.

2.3.6 Soil erosion

Sediment yield was determined as the sum of bed load and suspended load. The volume of bed load trapped in the runoff trough was determined by measuring the depth of deposited soil at four corners of the trough. Suspended load was estimated based on samples collected from the second and third compartments, after thoroughly mixing the stored water. Soil loss within the plot was determined by measuring the heights of pegs installed at randomly selected points in each plot. Increased peg height shows erosion while reduced height shows deposition.

2.3.7 Meteorological data

An automatic meteorological station was installed near the experimental plots. The equipment recorded rainfall, temperature, relative humidity and sunshine duration every 5 min. A manual raingauge was installed near the experimental plots for daily measurement of rainfall.

2.4 Data analysis

Statistical analyses were made using the SPSS version 15.0 for Windows (Julie, 2007). Hence, mean comparisons of the biomass and grain yields were made on the traditional and conservation tillage techniques using the independent sample t test ($\alpha = 0.05$). Data from only 2 replications were analyzed using simple descriptive statistics. Daily surface runoff and daily volumetric soil moisture were analyzed using time series analysis and descriptive statistics.

3 Results and discussion

3.1 Plow pans

Field tests carried out in the Choke Mountains indicate significant soil compaction revealing the formation of plow pans. Figure 6 shows penetration resistance values along the profile of cultivated soils at Enerata. A sharp rise in penetration resistance is evident below 10 cm reaching its maximum at about 20 cm, which is a typical plow pan for shallow tillage. Plow pan formation under maresha cultivation has been found elsewhere in Ethiopia with its peak located at a depth of 18–20 cm (Biazin et al., 2010; Temesgen et al., 2008).

3.2 Soil profile

Figure 7 shows the undisturbed soil profiles before and after conservation tillage. The area shaded in light brown is the plowed layer while the dark brown area represents the undisturbed layer. The average distance between the furrows is about 20 cm. Plowing up and down the slope in TT resulted in straight horizontal soil layer differentiated by a sharp line, which led to accelerated flow in TT preferentially in the furrows that are laid along the slope. Since the soil below the plow depth is less permeable, the shallow layer becomes quickly saturated and runoff is initiated at the bottom. This also causes landslides depending on the slope of the land, and the less permeable undistrubed soil serves as slip surface. However, after applying CT narrow deep trenches are made along the contour that slow down the movement of water along the slope (Fig. 7) resulting in the fill and spill flow process (Spaaks et al., 2009; Lehmann et al., 2007; Tromp-van Meerveld and McDonnell, 2006). This reduces surface runoff and soil erosion and facilitates deep percolation of soil moisture.

3.3 Soil moisture

The soil moisture measurements had been taken continuously at the lower sides of each plot, for a period of one month only (due to vandalism). Although the measurement period is short, the sample results clearly reveal that soil moisture in TT (average 34.7 % vol.) is consistently higher than that of CT (average 31 % vol.) at 10 cm depth while the reverse holds true at 30 cm depth (33.4 and 31.4 % vol., in CT and TT, respectively) (Fig. 8) . This implies a reduced surface runoff and increasing infiltration for CT compared to TT. Average values aggregate large variability of soil moisture measurements (Fig. 8a and b). Higher temporal variations in CT signifies better drainage as the soil responds to rainfall events with a rise in soil moisture followed by quicker drainage. This indicates better aeration as larger pore spaces were occupied by air in CT compared to TT. The sharp peaks in CT show that it remained unsaturated for most of the time. The pore spaces in TT were probably clogged by settling fine particles from standing water at the lower side of the plot. As a result, the air filled pore space would be less in TT than in CT leading to the negative effects of water-logging.

Unlike the upper layers CT results in higher soil moisture at 30 cm depth, i.e. below the plow pan (Fig. 8b). The high temporal variation in soil moisture at 30 cm depth shows deeper infiltration in CT than in TT, thus making more water available at lower depths in case there is a dry spell. This would also make more water available to roots growing deeper than 30 cm. Further deep percolation is also desirable as it recharges groundwater. Farmers too noticed the difference, and believe that higher soil moisture retention in the deeper layers of CT is one of the reasons for the higher biomass production (see Sect. 3.8). Field observations have also revealed deeper root growth in CT than in TT that could have contributed to increased grain yields.

3.4 Surface runoff

Results of surface runoff for CT and TT are shown in Fig. 9, for two crops wheat and tef. As can be seen, more surface runoff occurred for TT compared to CT, and that the differences between the two is more in the wheat plot than in tef. The average reduction of surface runoff was 48 % in the wheat plot due to the application of CT, with daily averages of 4.8 and 2.5 mm d^{-1} in TT and CT, respectively. In tef the surface runoff reduction was 15 % with an average of 4.5 and 3.8 mm d^{-1} in TT and CT, respectively.

A combination of hydrological processes caused reduction of surface runoff in CT, including the effect of subsoiling, contour plowing and the presence of invisible barriers. Subsoiling disrupts the plow pan thereby enhancing infiltration, the contour plowing with invisible barriers prevents water movement along the slope thereby reducing surface runoff. This result is in agreement with other investigations in similar environments: Jin et al. (2008); Sojka et al. (1993); Harris et al. (1993) and Trouse (1983) all reported significant reduction in surface runoff as a result of subsoiling, while Gebreegziabher et al. (2009) reported benefits of contour plowing in reducing surface runoff. The differences in surface runoff between CT and TT are larger for wheat than for tef (Table 1). This is because farmers let animals trample on tef seedbed during sowing for better seed-soil contact, which is crucial for germination and establishment of the small seeded crop (Teklu and Gezahegn, 2003). As a result, the compacted surface reduces infiltration, and thus undermining treatment effects. Unfortunately, surface runoff could only be monitored only after sowing. Future moisture measurements should start before sowing, since treatment effects could be significant before the sowing of tef (before seedbed compaction).

3.5 Water-logging behind *fanya juus*

Figure 10a and b show wheat crops behind *fanya juus* under CT and TT, respectively. The wheat crop under CT showed vigorous growth and greener stand while that under TT turned yellow with stunted growth. CT resulted in less surface runoff thereby reducing surface runoff that reach *fanya juus*. Moreover, disrupted plow pans in CT apparently facilitated better drainage thus avoiding water-logging behind bunds.

3.6 Sediment yield

Results of sediment yield observations (both suspended and bed load) are shown in Table 1. The results demonstrate reduced sediment yield in both wheat and tef due to the application of CT. Reduced surface runoff in CT led to reduced soil erosion. Other investigators (Kin et al., 2008; Sojka et al., 1993) have reported similar results. Farmers too noticed the differences in soil loss due to tillage treatments. The differences between CT and TT are larger for wheat than for tef. This is caused by seedbed compaction carried out during sowing of tef which undermined treatment effects in the same way as it did to surface runoff. Measurements could only be made after sowing. Larger treatment differences could be observed before sowing and hence future research should include monitoring soil loss before sowing.

3.7 Convenience in plowing between SCS

One of the main problems associated with the adoption of SCS by farmers in Ethiopia is the inconvenience created to the tradition of cross plowing. Temesgen et al. (2008) have shown that the V-shaped furrow created by the *maresha* plow is the main reason for traditional cross plowing. The winged subsoiler allows farmers to undertake consecutive tillage operations along the same line, in this case, parallel to the *fanya juus*, because the wings cut the soil on the sides of the V-shaped furrow created by the *maresha* plow. This makes it possible to control weeds between consecutive furrows by plowing only in one direction thereby making it convenient to plow in the presence of *fanya juus*. During field interviews with farmers, those who practiced CT unanimously reported that the new tillage system is more convenient than TT in fields treated with *fanya juus*.

3.8 Agronomy

Both biomass and grain yield were consistently higher in CT than in TT in both crops, wheat and tef, with 35 and 28 % increment in grain yield of wheat and tef, respectively, although the differences are not statistically significant ($\alpha = 0.05$) (Table 2). This is due to high variation in soil fertility as replications were made in different farmers' fields. Participating farmers noted the differences in biomass and grain yield. According to the interviews, farmers believe the reasons could be (1) reduced soil erosion, (2) better weed control, (3) extended period of soil wetness, and (4) reduced water logging in CT. Farmers believe that reduced soil erosion in CT led to reduced loss of soil nutrients while retention of soil moisture in deeper layers extended the growing period. Consequently, farmers harvested CT plots, on average, one week after harvesting TT plots. They believe this resulted in more biomass and grain yield. Reduced water-logging and hence better aeration in CT made the crop greener (Fig. 9a) compared to water-logged strips behind SCS in TT (Fig. 9b), which could contribute to increased biomass production in the former.

4 Conclusions and recommendations

Adoption of SCS in high rainfall areas in the upper Blue Nile (Abbay) river basin, in Ethiopia is constrained by reduced crop yield, accelerated soil erosion particularly due to frequent breaching of SCS, which in turn is caused by higher surface runoff from plowing up and down the slope. Water-logging behind SCS and inconvenience to the tradition of cross plowing were reported to be constraints for adoption as well. In this experiment, it has been shown that integration of locally adapted conservation tillage system with SCS can reduce surface runoff leading to a reduction in soil loss. Water-logging behind SCS was reduced and grain yields of wheat and tef were increased although the differences were not statistically significant ($\alpha = 0.05$), apparently due to high fertility variations among the experimental fields (replications). Farmers interviews showed that they are convinced that CT increased grain yield. They also reported increased convenience to plow between SCS. Farmers plan to continue using CT in the future. It is concluded that integration of CT with SCS can enhance performance and adoption of SCS in high rainfall areas of Ethiopia.

Further research needs to be undertaken to expand the data series spatially as well as temporally. Possibilities to reduce the number of plowing with CT and cost benefit analysis of the CT system have to be investigated. Reduced surface runoff with the application of CT opens the opportunity to increase bund spacing thereby addressing another complaint of farmers pertaining to loss of productive land. Future research should test CT with wider bund spacing than the recommended.

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Table 1. Runoff sediment concentration and total soil loss of the different farm plots during (23 August to 24 September 2010 at Enerata).

Crop type	Treatments	Average suspended sediment concentration (gm l^{-1})	Total soil loss (t ha^{-1} month^{-1})
Wheat	TT	3.46	8.55
	CT	2.21	5.41
Tef	TT	3.06	11.76
	CT	3.02	10.73

Table 2. Biomass and grain yield of wheat and tef from conservation and traditional tillage at Enerata, Ethiopia.

Crop type	Tillage	Biomass (kg ha^{-1})	Grain yield (kg ha^{-1})
Wheat	CT	5833 (±872)	2685 (±462)
	TT	4167 (±797)	1985 (±245)
Tef	CT	3960 (±340)	2396 (±440)
	TT	3470 (±429)	1868 (±367)

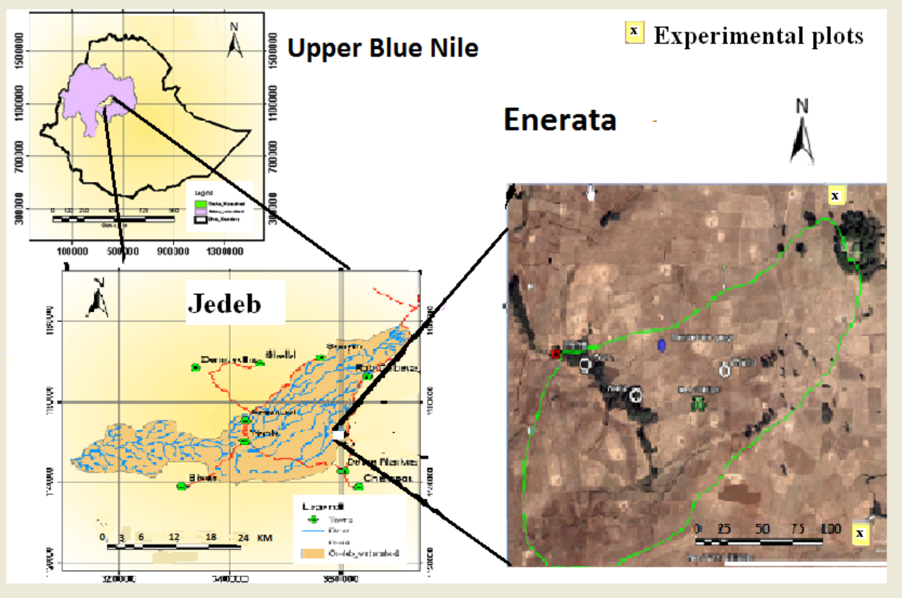
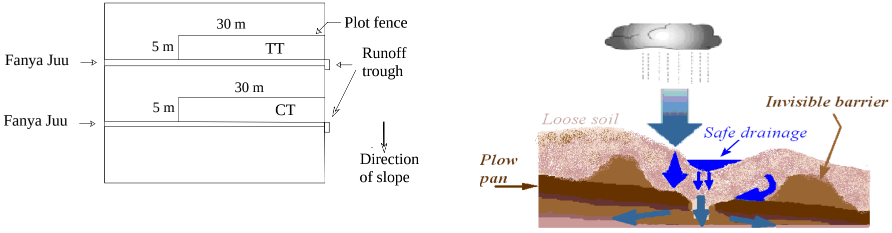


Fig. 1. Study sites at Enerata. Predominantly cultivated area in the mid altitudes of the Choke Mountains, headwaters of the Blue Nile river basin. Source of Satellite picture is Google Earth, 2009.



(a) (b)

Fig. 2. **(a)** Layout of a single replication (one farmer's field). The three sides of the 5 m × 30 m area is bound by a galvanized iron sheet fence that was inserted 10 cm in to the soil with 15 cm height above the ground. The lower side is bound by the *fanya juu*. Runoff was collected from this area. Locations of CT and TT were randomly selected for each block. **(b)** Schematic representation of the new conservation tillage system whereby surface runoff is reduced, allowing more infiltration through the disrupted plow pan and redirecting flow along the contour by the invisible barriers.

(a) (b) (c)

Fig. 3. **(a)** The traditional plow in Ethiopia, *Maresha*. **(b)** Winged subsoiler. The winged subsoiler has a vertical share and wings with sharp edges (MST, 2008). **(c)** Runoff trough used in the study. The picture was taken following a high rainfall day on 31 August 2010. About 2 m^3 (13 mm) of runoff was recorded by the trough from a 36 mm d^{-1} rainfall event on a field with TT wheat.

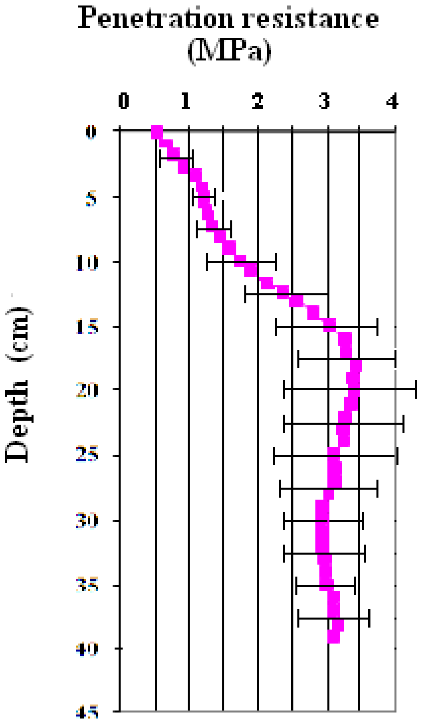


Fig. 4. Soil compaction at Enerata. Rise in penetration resistance starts at 10 cm, which is the average depth of operation of the Maresha plow. The resistance peaks at 20 cm depth. Each point is the average of ten readings.

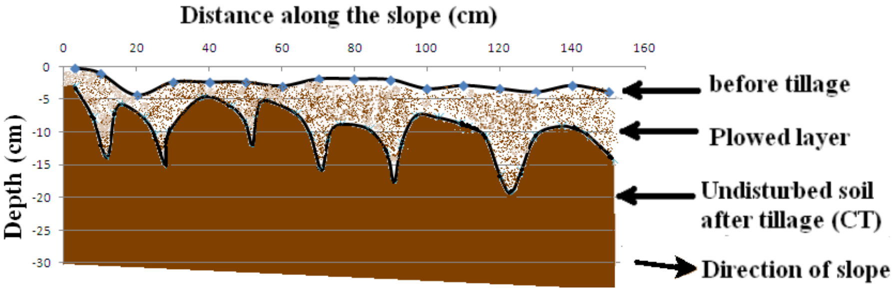


Fig. 5. Typical profiles of soil before and after the application of conservation tillage (CT). The rugged profile of the undisturbed soil beneath the plowed layer creates fill and spill type of subsurface flow. In contrast, traditional cross plowing results in sharp horizontal profile of furrow bottoms that are laid along the slope, at about 10 cm depth, thus leading to increased flow momentum and soil erosion.

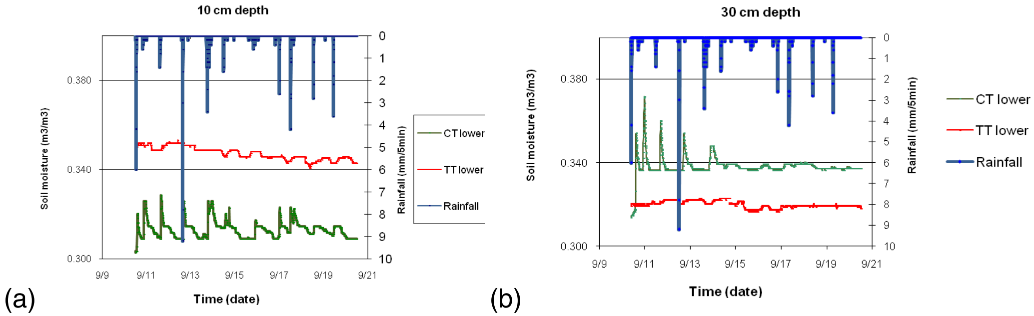


Fig. 6. Soil moisture in TT and CT plots **(a)** at 10 cm depth and **(b)** at 30 cm depth.

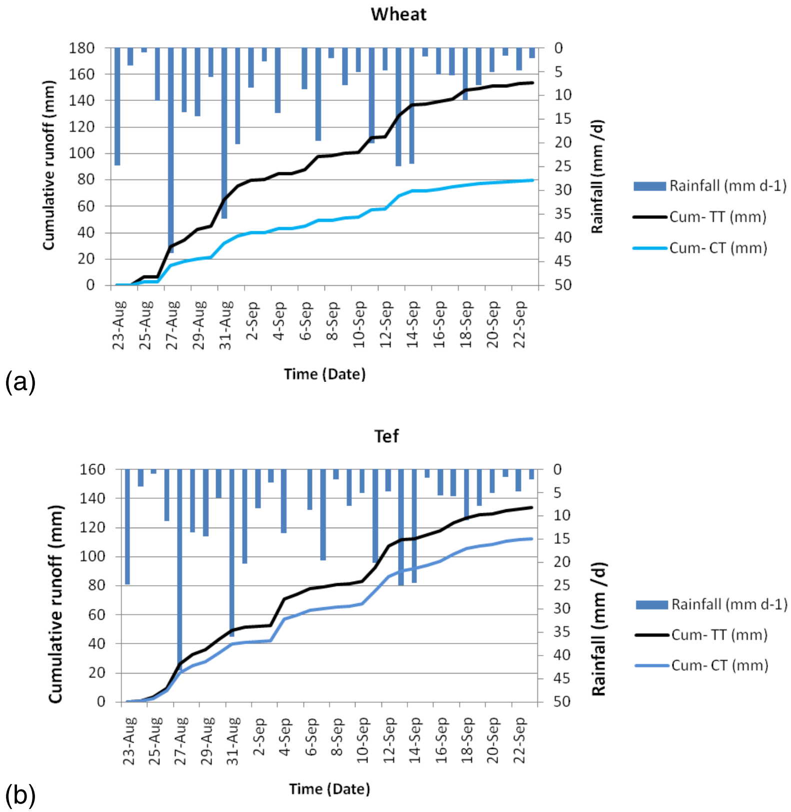


Fig. 7. Runoff and rainfall measured in TT and CT plots of **(a)** wheat **(b)** tef.


(a)
(b)

Fig. 8. Wheat fields: **(a)** conservation tillage (CT) fields are greener due to contour plowing and subsoiling, which reduced surface runoff in favor of infiltration, **(b)** traditional tillage (TT) fields with yellowish color and stunted growth, generated more surface runoff that accumulated behind SCS causing water-logging (Picture taken at Enerata on 8 September 2010).