Effect of Winged Subsoiler and Traditional Tillage Integrated with *Fanya Juu* on Selected Soil Physico-Chemical and Soil Water Properties in the Northwestern Highlands of Ethiopia

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Abstract: Prolonged water-logging, soil degradation and decline in water productivity due to hard pans created because of repeated cross plowing using the traditional plow is the major problem in the northwestern highlands of Ethiopia. To reduce these problems, alternative tillage and soil management practices have to be implemented. Thus, the effects of winged subsoiler and traditional tillage practices on tillage depth, bulk density, infiltration, and soil moisture conditions were assessed in an on-farm experimental study in the northwestern highlands of Ethiopia. The experiment was laid out in a randomized complete block design (RCBD) with two treatments (winged subsoiler and traditional tillage) and four replicates. The study was conducted from 2011 to 2012 cropping seasons. Soil samples were collected from 0-10, 10-20, 20-30 and 50-60 cm of soil depths and analyzed for bulk density, soil texture and organic matter contents. Soil moisture was measured using 10HS automatic soil moisture sensors (CaTec®) which were inserted at 10 cm depth under both tillage types. Four readings, once every week were taken both at the lower and upper parts of the plots. Using the double ring infiltrometer, infiltration measurements were made in the experimental units treated by both tillage practices. Soil evaporation was estimated by a conceptual model whereby leaf area index, canopy cover, crop root length, moisture at saturation and field capacity were used as inputs. Substantially higher tillage depths were observed due to the winged subsoiler while dry bulk density was slightly higher in the traditional tillage. Significantly ($P \leq 0.05$) different soil moisture contents between the upper and lower sides of the *fanya juus* were observed under traditional tillage practice (0.305 ± 0.003 and 0.323 ± 0.003 m^3 m^{-3}, respectively). Infiltration rate and cumulative infiltration in the winged subsoiler treated plots exceeded that of the traditionally plowed plots. Compared with the traditional tillage, the winged subsoiler treated plots resulted in better moisture retention, high infiltration, high tillage depth and low soil evaporation. The result indicated that if the winged subsoiler is properly implemented and integrated with fanya juu, it is an important and effective conservation practice for sustainable soil and water management for smallholder farmers in the northwestern Ethiopia.

Keywords*:* Ethiopia; Plow Pan; Soil Moisture; Traditional Tillage; Winged Subsoiler

1. Introduction

The Ethiopian highlands represent one of the most productive parts of the country, but have suffered from extensive resource degradation (Hurni, 1990, 1993; Nyssen *et al*., 2007; Tewodros *et al*., 2009, Melesse *et al*., 2012) Land degradation in the form of soil erosion and declining soil quality is a serious challenge to agricultural productivity and economic growth in these highlands (Mulugeta *et al*., 2005). The northwestern highlands of the country suffer from such extreme land degradation due to repeated cross-plowing of the steep lands (Gete, 2000; Bezuayehu *et al*., 2002; Melesse *et al*., 2009). Repeated traditional tillage damages the soil structure through excessive pulverization and increased rate of mineralization leading to reduction in soil organic matter content and aggregate stability (Mwendera and Mohamed, 1997; Melesse *et al*., 2009). This results in soil compaction over the plowed layer, surface crust and plow pan formation that reduce infiltration increase both soil erosion and loss of soil moisture (Lal, 1997). Traditional tillage reduces water uptake by plants because root growth is restricted to the plowed layer. For instance, using *teff* crop in Wuolenchtiy, Ethiopia, sub-soiling resulted in the lower surface runoff (Qs = 23 mm $season^{-1}$), higher crop transpiration (T = 53 mm $season^{-1}$), higher grain yield (Y = 1180 kg ha^{-1}) and higher water productivity using total evaporation (W_{PET} = 0.42 kg m^{-3}) compared to traditional tillage (Qs = 34 mm-$season^{-1}$, T = 49 mm $season^{-1}$, Y = 1070 kg ha^{-1}, W_{PET} = 0.39 kg m^{-3}) (Melesse, 2007). Similarly, water holding capacity of the soil can be reduced due to the loss of organic matter and soil compaction, which results in less water availability for useful transpiration by crop. This suggests the need for changing and improving the tillage systems.

Based on the conservation agriculture (CA) experimental research conducted in 2006 at Gumselasa, Tigist *et al*. (2010) founded that permanent bed reduced runoff volume by 50% and Terwah by 16% compared to traditional tillage. The same author also reported that permanent bed reduced soil loss by 86% and Terwah by 53% in comparison to traditional tillage.

Soil erosion and high surface runoff due to high tillage frequency (5-6 passes) using traditional tillage and

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improper implementation of soil and water conservation structures have seriously affected over 25% of the Ethiopian highlands (Chuma, 1993; Bezuayehu *et al.*, 2002;). Such detrimental effect of soil erosion can be improved to some extent by improved management options like the use of winged subsoilers. In this study, contour plowing was made with winged subsoiler, a modified *Maresha* plow alternating with traditional *Maresha* plow that cuts soil deeper than achieved with the traditional tillage (Figure 1). This tillage system disrupts the hard pan formed due to repeated cross-plowing using traditional tillage. Winged subsoiler reduced surface runoff by 48% with the daily averages of 4.8 and 2.5 mm ha^{-1} recorded at fields plowed using traditional tillage (TT) and winged subsoiler (WS) by allowing more infiltration through disrupting plow pan and by redirecting flow along the contour using invisible barriers created by the system, respectively (Melesse *et al.*, 2012).

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Figure 1. Treatments (TT and WS) employed in the present study edges.

Winged subsoiler is aimed at altering the rainfall partitioning such that there will be more infiltration at the expense of surface runoff leading to increased root water uptake, thus more useful transpiration at the expense of evaporation (Melesse *et al.*, 2012). The objectives of this study were, therefore, to evaluate the effect of winged subsoiler on soil moisture distribution along the contour and between bunds and to assess the effect of winged subsoiler on infiltration capacity of the soil.

2. Materials and Methods

2.1. Description of the Study Area

2.1.1 Location and Climate

The study was conducted at Enerata located in East Gojjam Zone of Amhara Regional state, Ethiopia. It is situated between 10^0 25'-10^0 30' north and 37^0 42'-37^0 44' east, and located approximately 300 km north west of Addis Ababa and 7 km north of Debremarkos (Figure 2). The altitude ranges approximately from 2380 to 2610 meter above sea level (masl) and it is characterized by humid climatic condition and typically represents the 'Dega' (2300-3200 masl.) zone of the traditional agro-climatic classification system of Ethiopia. The average annual rainfall and temperature are 1300 mm and 15 ^{0}C, respectively, measured at the Debremakos Meteorological Station located 7 km from the experimental plots. The rainfall pattern is unimodal and much of the rainfall occurs from June to September, locally known as "kiremt" season (Woldeamlak, 2003).

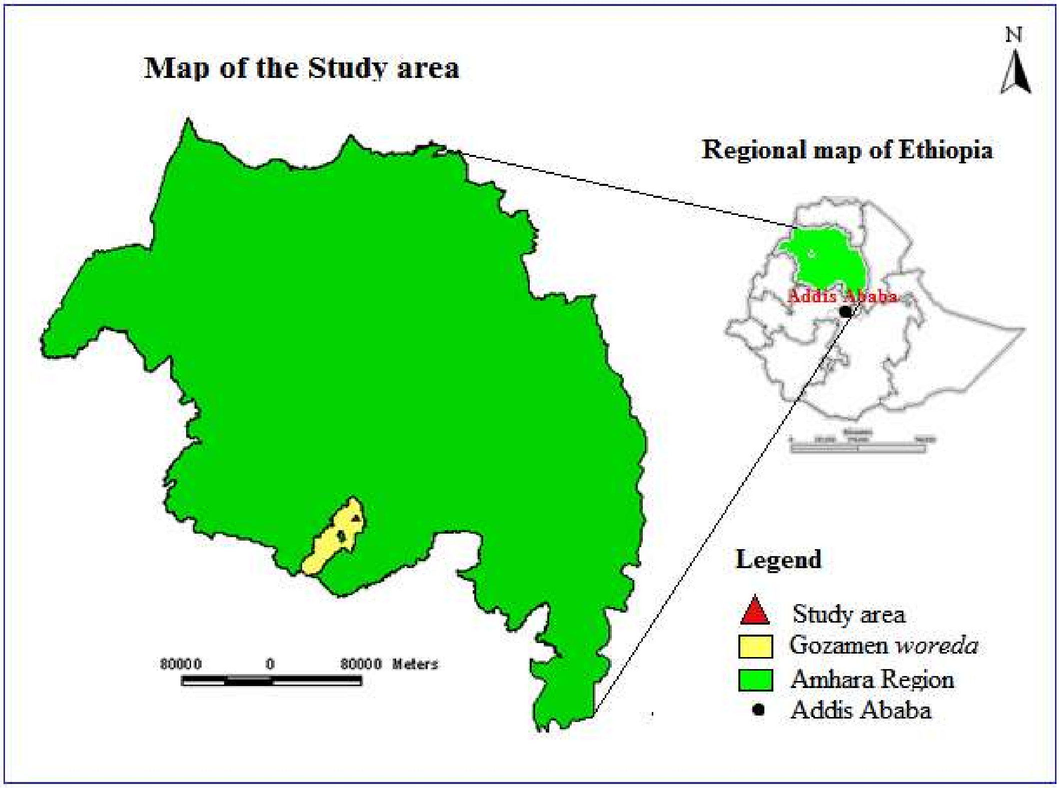

Figure 2. Location map of the study area.

2.1.2. Geology and Soil

Geologically, the micro-watershed is part of the highlands that largely owe their altitude to the uplift of the Arabo-Ethiopian land mass and subsequent outpouring of basaltic lava flows during the tertiary period (Woldeamlak and Sterk, 2005). Thus, the surface geology is of basaltic rocks, which are the parent materials for the overlying soils. The soil type that covers the micro-watershed is Nitisols (Woldeamlak, 2003) and the textural class is clay loam and uniform over the 0-60 cm layer.

2.1.3. Farming System

The farming system of the study area is typically mixed crop-livestock system of the highlands of Ethiopia, where livestock provide the draught power needed for the farming operation and a good part of the crop residues are fed to livestock. Barley (*Hordeum vulgare*), *Engdo* (*Avena Spp.*) wheat (*Triticum aestivums)* and *teff* (*Eragrostis tef*) are the dominant cultivated crops. Tillage is exclusively carried out using the traditional *Maresha* plow (Figure 1). Repeated cross-plowing is done before sowing because farmers believe that it controls weeds and improves crop yields. According to interview results and field observations, farmers plow 8 to 10 passes for *teff* crop, and 5-7 times for wheat, barley and oat crops.

2.2. Experimental Setup

Four farmers were selected and trained on the concepts and field applications of winged subsoiler (WS here after) in addition to the supervision during field works. The experimental set up was first explained to and discussed with the participating farmers. Each participating farmer was provided with a WS. The study compared the current farming practices of using traditional tillage (TT here after) versus the newly introduced winged subsoiler. The experiment was laid out in a randomized complete block design (RCBD) with 4 replications and 2 treatments (WS and TT). All experimental fields were treated with *fanya juu* as part of the routine soil conservation works of the local communities. Blocks were selected such that the two experimental plots have similar slopes in each replication, which ranged between 9 and 11%. All the experimental plots have similar plowing cropping and land cover types prior to the experimentation and found in the same micro-watershed.

Fertilizer application and controlling weed were the same for all experimental units. Experimental plots were delineated inside the fields by fencing the three sides with galvanized iron sheets (Figure 3). The fences covered the three sides while *Fanya juus* bordered the lower sides of each plot. Plot sizes were 5 m x 30 m each. Delineation of experimental plots was carried out immediately after sowing. Sowing of wheat crop was made on 23 June 2011 in both treatments. The WS treated appeared in the upper side in two of the replications while TT took that position in the other two. All experimental plots received a primary tillage by the TT plow. Then four plots were plowed twice using the WS while the remaining four plots received TT (control), with the same frequency of plowing as the former (Figure 1). During the third pass, the TT was used along the same lines to make the furrows wider and more visible for the next subsoiling. Finally, all plots were plowed as a final treatment using traditional tillage and wheat was sown by broadcasting in all plots. A total of five tillage operations had been used for the experimentation

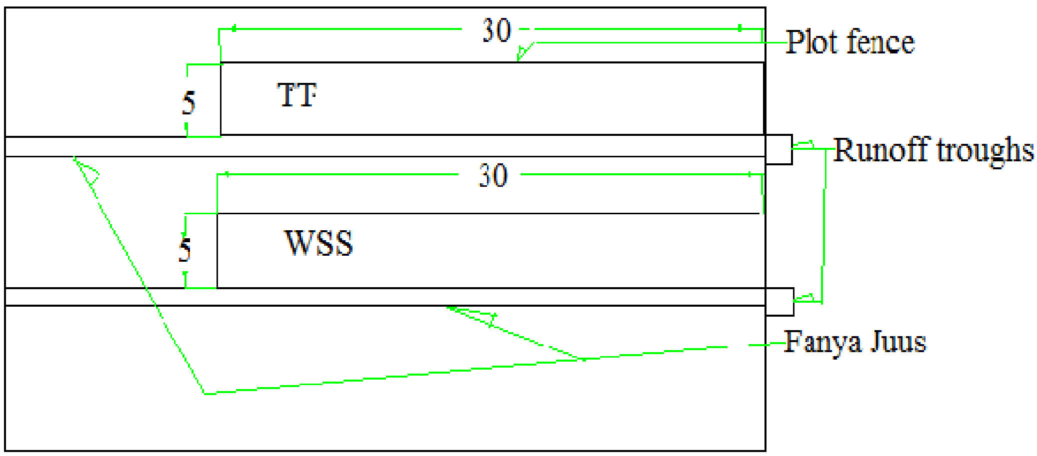

Figure 3. Layout of a single replication (one farmer's field).

2.3. Data Collection

2.3.1 Rainfall Pattern

An automatic meteorological equipment was installed at the experimental plots. The equipment recorded rainfall, temperature, relative humidity and sunshine duration every five minutes. For the triangulation of the automatic recorded data, a manual raingauge was also installed for daily rainfall measurement. A total of 338.2 mm rainfall was received during the study period at the experimental site and 38.8 mm rainfall was recorded as the maximum daily rainfall.

2.3.2. Soil Sampling and Analysis

Soil samples were collected from two randomly selected representative locations of each plot. At each location, samples were taken at four depths: 0-10, 10-20, 20-30 and 50-60 cm. Composite soil samples were collected from excavated soil pits at the respective depths for determination of soil texture, and organic matter. Soil texture was determined at Debremarkos Soil Laboratory using the hydrometer method (Day, 1965) and soil organic matter content was tested using the Walkley-Black oxidation method (Schnitzer, 1982). Soil bulk density was determined using samples obtained by core method (Blake and Hartge, 1986). Undisturbed cylindrical core samples were taken and weighed for the determination of dry bulk density. The samples were oven dried for 24 hours at 105 ^{0}C and the dry mass was determined.

2.3.3. Soil Moisture Measurement

Soil moisture was measured using 10HS automatic soil moisture sensors (CaTec®) which were inserted at 10 cm depth under both tillage systems. The sensors were programmed to record soil moisture data every five minutes. To assess soil moisture distribution between bunds, four readings, once every week, were taken both at the representative spots of the lower and upper parts of the plots (256 measurements).

2.3.4. Soil Water Infiltration

Infiltration measurements were carried out in all the experimental plots treated both under conservation and traditional tillage. Altogether, 48 measurements were taken using double ring infiltrometer. Six spots were randomly selected in each experimental plot for measurement. Both the inner and outer rings of a double-ring infiltrometer were 25 cm high and inserted 5 cm into the soil carefully using a sledge hammer, leaving 20 cm above the ground surface. The inner rings had diameters of 28, 30 and 32 cm and the outer rings had 53, 55 and 57 cm. Water was then poured into the rings to maintain the desired depth and constant head was maintained throughout all measurements. Changes in water levels were recorded at time increments of 1, 3, 5, 10, 15, 20, 30, 40, 50 and 60 minutes for calculating infiltration rate and cumulative infiltration. A pool of water was maintained approximately the same level in the outer ring to reduce the amount of lateral flow from the inner ring. The soil was moist at the time of all measurements due to the occurrence of rainfall in the previous day.

2.3.5. Measurement Evaporation

To determine the treatment effect on soil evaporation, L_{AI} was measured at 30 (bare soil cover), 60 (moderate crop cover) and 90 (maximum crop cover) days after planting of wheat crop. These days were purposely selected to measure evaporation loss of water below crop canopy cover and open field to see crop cover effect on evaporation, and water retention as evaporation is highly affected by surface cover. Leaf area index (LAI) was determined using direct method. The LAI expressed as $m^2\ m^{-2}$ was estimated by measuring the average width and length of leaves from 5 randomly selected plants using 'X' plot sampling pattern in each treatment, with a pocket meter. The leaf area (*A*) was calculated with the equation of Stewart and Dwyer (1999) as:

Thus,

$$A = aW_ML \qquad (1)$$

where *a* is coefficient, W_M is the average width of the leaf (m) and L is the average length of the leaf (m). LAI was computed by adding the areas of all the leaves in each plant, and dividing the sum by the area of land covered by each plant (Melesse, 2007), which also means multiplying the total area of a single leaf by the population P_0 as:

$$LAI = P_O \sum_{x=i}^{n} Ai \qquad (2)$$

where P_0 is plant population per m^2, n *is* the number of leaves in each plant and Ai is leaf area. Daily based meteorological data such as wind speed, relative humidity, temperature, rainfall, atmospheric pressure, and solar radiation were used as inputs. The LAI data was used to estimate the proportion of evaporation under wheat crop treated with the treatments.

2.3.6. Soil Moisture Contents at Field Capacity and Permanent Wilting Point

Moisture content at field capacity (S_{FC}) was determined at Debreziet Soil Laboratory (Ethiopia). Undisturbed soil samples were taken using core samples from two randomly selected locations in each treatment at the depth of 0-10, 10-20, 20-30 and 50-60 cm. The samples were added on a plate in the lab and water was added until the soil was completely saturated. After saturation, the soil was entered into the 0.33 bars pressure plate apparatus where it stayed until the moisture above field capacity was drained out. The wet samples were weighed before placing it in an oven at 105 ^oC. The S_{FC} in weight basis was determined as the ratio of the weights of the oven dried samples to the wet samples. The same procedure was employed to determine moisture at permanent wilting point (S_{wp}) with the saturated soil subjected to a suction of 15 bars. Moisture at S_{wp} was determined after oven drying.

Estimation of *Es* (soil evaporation) was carried out using a conceptual model (Melesse, 2007)

$$Es = \max\left((1 - L_{AI}Cc)(Ks\,Ep - I), 0\right) \max\left[\min\left(\frac{S}{(1-r)S_{FC}}, 1\right), 0\right] \qquad (3)$$

where *Es* is soil evaporation (mm-day^{-1}), L_{AI} is leaf area index ($m^2\ m^{-2}$), *Cc* is crop cover factor, *Ks* is soil factor, E_P is pan evaporation, *I* is interception (mm-day), S_{FC} is moisture at field capacity ($m^3 m^3$), *S* is stored water in the root zone ($m^3\ m^3$) and (1-*r)* is fraction of S_{FC} above which $E_{T}o = E_T$

2.4. Data Processing and Analysis

Statistical analyses were performed using SAS statistical package version 9 (TS MO), 2002. Two-way analysis of variances (ANOVA) was made for infiltration and soil physical properties using general linear model (GLM). Duncan's multiple- range test was used for mean separation were statistically significant differences at $P < 0.05$ are observed whereas one-way analysis of variance was made for soil moisture content. Tillage depth was analyzed using descriptive statistics and graphical illustrations.

3. Results and Discussion

3.1. Depth of Tillage

The overall depth of the winged sub-soiled plots was greater than the traditionally tilled ones (Figure 4). Average tillage depths for the first plowing were 17.95 and 10.1cm while average depths for the last plowing were 22.3 and 12.2 cm (420 measurements) for the winged subsoiler and the TT treated plots, respectively. Farmers commented that the draft power requirement of the subsoiler becomes higher as the depth of tillage increases. Field observations revealed that there was water logging behind conservation structures and rill formation in the upper parts of the plots in the TT plots. On the other hand, uniform moisture distribution was observed in plots treated with WS. There was a strong positive correlation between tillage depth and frequency of plowing for TT with $R^2 = 0.898$, 210 number of observation (measurements) and for WS with $R^2 = 0.986$, 210 number of observations (Figure 4).

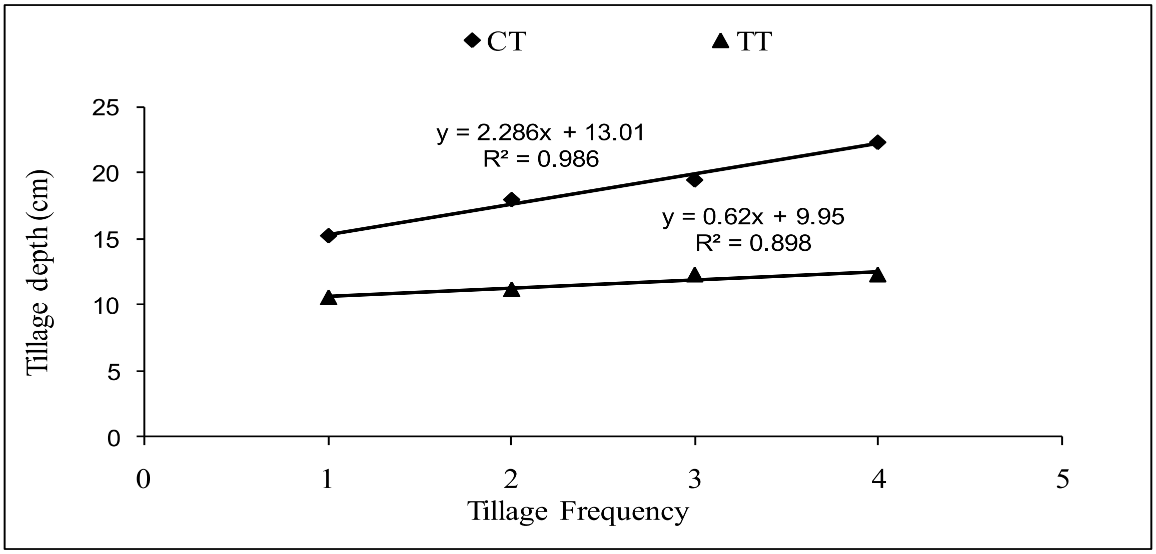

Figure 4. Plow Depth and tillage frequency in relation to winged subsoiler and traditional tillage.

The lower tillage depths of TT can be explained by the geometry of the V-shaped *Maresha* plow that creates hard pan in the plowing soil layers. Different authors have measured average tillage depths by TT (*maresha)* plow; 7 cm (Fleur, 1987); 10.1–15.3 cm (Goe, 1999); 10.1–12.5 cm (Gete, 1999); 8.1 cm (Nyssen *et al*., 2000); and 11.2 - 12.9 cm (Melesse *et al.,* 2009). On the other hand, tillage depth from winged sub-soiler was substantially higher than the depths obtained by traditional tillage (Figure 4). This is an indication that through the use of winged sub-soiler the problems of soil compaction and shallow depth could be addressed to improve the soil-water conditions of agricultural fields.

3.2. Soil Texture, Bulk Density and Organic Matter

Sand was the highest fraction at all depths across both treatments. The clay and silt fractions, on the other hand, constituted a relatively low amount in both soil layers (Table 1). Clay content tended to increase while sand content tended to decrease with depth. Moreover, clay content was substantially less in the upper most layers (0-10 cm) layer as compared with the underlying soil layers.

Table 1. Particle size, dry bulk density, organic matter under winged subsoiler and traditional tillage treated plots (Mean ±SE).

Tillage types		Soil particle size				
	Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Bulk density (g cm^{-3})	Organic matter (%)
Traditional tillage	0-10	22±0.913[a]	32±0.707[a]	45.8±0.48[a]	1.54±0.005[a]	2.503±0.008[a]
(TT)	10-20	26±0.85[a]	24±0.41[b]	50±0.93[a]	1.48±0.004[a]	2.10±0.001[a]
	20-30	36±0.29[b]	16±0.41[b]	48±0.41[a]	1.49±0.004[a]	1.77±0.008[a]
	50-60	32±0.63[b]	20±0.91[b]	48±0.41[a]	1.55±0.004[b]	1.75±0.004[a]
Winged subsoiler	0-10	22.4±0.913[a]	32±0.70[a]	45.8±0.48[a]	1.51±0.004[b]	2.51±0.002[a]
(WS)	10-20	25.75±0.85[a]	24±0.41[b]	50±0.93[a]	1.47±0.004[b]	2.12±0.005[a]
	20-30	36.5±0.29[b]	16±0.41[b]	36.5±0.41[b]	1.48±0.004[a]	1.77±0.009[a]
	50-60	31.75±0.63[b]	20±0.91[b]	48.3±0.41[a]	1.54±0.006[a]	1.75±0.004[a]
P-value						
Depth		< 0.0001	< 0.0001	< 0.0001	0.0002	0.0001
Tillage types		0.51	0.55	0.312	< 0.001	< 0.044
Depth*tillage type		0.179	0.37	0.788	0.016	0.20

Treatment means followed by the same letter(s) in the same column are not significantly different (P < 0.05).and means followed by different letters across depth at TT and WS treatments are not significant due to tillage but varied due to translocation of particles.

There were significant differences in dry bulk density in the top 10 cm soil layer between tillage systems and was less in the top 10 cm of surface soil than the underlying layers in the WS plots. There were no significant differences ($P > 0.05$) in dry bulk density in the subsurface soil layer (50-60 cm) between WS and TT.

There were no significance differences between tillage practices in soil organic matter across all depths. However, there appears a declining trend in organic matter content as soil depth increased.

Tillage practice had greater bearing on the soil physical properties, which in turn influenced soil-water relations. Accordingly, the result of dry bulk density revealed that plots treated with WS had relatively low bulk density compared to TT. This can be attributed to the breakdown of compacted soil and improved porosity at the surface layer by the subsoiler. Conversely, repeated cross plowing using traditional *Maresha* plow resulted in higher bulk density which ultimately resulted in poor water conduction.

The mean values for clay fractions indicated that there may be processes of selective erosion and migration of clay material down to the soil profile, which was evidenced by the higher clay contents at the subsurface layers than the overlying layers (Woldeamlak, 2003). However, the soil texture remained almost similar between tillage practices. This is because alteration of soil property by tillage requires longer period. The findings agreed with those of Lal (1989), Lal (1997) and Melesse (2007) also studied the effect of long-term tillage on maize crop and soil properties and concluded longer period of time is required to see the effects of tillage on soil water content.

3.3. Soil Moisture Content

Soil moisture distribution treated with WS and TT is shown in Table 2. There were significant differences ($P < 0.0001$) in soil moisture content between tillage treatments as well as in the upper and lower sides of the plots. The observed volumetric mean moisture content in the traditionally treated plots was 0.305 ± 0.003 & 0.323 ± 0.003 $m^3 m^{-3}$ for the upper and lower sides of the plots, respectively. Thus, soil moisture content was consistently higher at the lower side as compared to the upper side of the bund in the traditionally plowed plots. On the other hand, the mean moisture content in plots treated with WS was 0.275 ± 0.003 and 0.278 ± 0.002 $m^3 m^{-3}$ for the upper and lower sides of the plot, respectively. These mean values of volumetric moisture content have indicated that stored soil water under WS was nearly uniform between the upper and lower sides of the plots. The relatively lower but adequate soil moisture in the WS showed better drainage as opposed to water logging problems observed in the TT behind fanya juu (Figure 5).

Figure 5. Illustration of variation in topsoil moisture content between bunds under TT (A) and WS (B) treated plots respectively. On the left, water logging has turned the crop yellow, stunted and sparse whereas on the right greener and better stand is shown behind the *fanya juus*.

Table 2. Soil moisture content under winged subsoiler and traditional tillage treatments (Mean± SE).

Tillage types	Moisture(m^3 m^{-3}) at upper sides of the plot	Moisture(m^3 m^{-3}) at lower sides of the plot
WS	0.275±0.003[a]	0.278±0.002[a]
TT	0.305±0.003[b]	0.323±0.003[c]
P-values	< 0.0001	< 0.0001

Means denoted by the same letter(s) across row and columns are not significantly different at P > 0.05.

As it can be seen in Table 2, soil moisture at 10cm depth in the upper parts of plots under traditional tillage is significantly (P < 0.0001) lower than that in the lower part. This might be attributed to the formation of plow pan created by repeated cross plowing using traditional tillage, which hinders infiltration but encourages surface runoff and water logging behind bunds. Melesse *et al.* (2012) conducted a research with the same experimental setup and treatments and showed that surface runoff appeared to be reduced under WS by 48 and 15 %, for wheat and tef crops, respectively. The study further reported that, WS reduced sediment yield by 51 and 9.5 %, for wheat and *teff* crops, respectively. Various investigations have been carried out to observe the effect of tillage on soil erosion and concluded that intensive tillage exposes the soil to more erosion (Hoogmoed, 1999; Biamah and Rockström, 2000; Benties and Ashburner, 2001). Similarly, Babalola and Opara-Nadi (1993) and Lal (1997) noted that conservation tillage was found to double infiltration rate and increase water uptake over the traditional tillage. Conversely, under WS tillage, there was uniform moisture distribution at the upper and lower parts of the plot. The disruption of plow pan through deep contour plowing using WS tillage could be the reason for enhanced infiltration, and more uniform distribution of soil moisture leading to less water logging.

3.4. Soil Water Infiltration

There were significant differences (P < 0.0001) in infiltration rates in the soils between WS and TT treated plots (Table 3). The initial and steady state (60 min) infiltration rates under WS plots were 0.84±0.005 and 0.1±0 cm min^{-1}, respectively. On the other hand, 0.54±0.006 and 0.05±0.004 cm min at 01 and 60 min were observed under the TT treated plots (Table 4). The lowest values of the steady state infiltration rate could be explained by the occurrence of rainfall in the previous days before the measurement was taken.

Table 3. ANOVA summary for infiltration rate and cumulative infiltration under winged subsoiler and traditional tillage.

Source of variation	DF	Infiltration rate	Cumulative infiltration
		P-values	P-values
Time	9	< 0.0001	< 0.0001
Tillage type	1	< 0.0001	< 0.0001
Time*tillage type	9	< 0.0001	< 0.0001

Table 4. Infiltration rates (cm min^{-1} and cumulative infiltration under WS and TT (Mean ±SE) at initial and steady states.

Infiltration rate (cm min^{-1})	Tillage types	
	Winged subsoiler	Traditional tillage
Time (min)	WS	TT
01	0.842±0.005[a]	0.545±0.006[b]
60	0.1±0.00[c]	0.05±0.004[d]
CI I(cm)	16.92±0.17[a]	11.6±0.11[b]

Means followed by the same letter(s) are not significantly different at (P < 0.05); CI = Cumulative infiltration.

The infiltration rate in the WS treated plots was twice higher than the TT tilled plots. The time series graphical comparison of infiltration rate and cumulative infiltration also showed that the residence time for the TT treated plots was significantly higher (P < 0.0001) compared to the WS treated plots (Figure 6 and 7). Similarly, cumulative infiltration under WS was considerably higher compared to the TT with values of 16.92±0.17 and 11.6±0.11 cm, respectively.

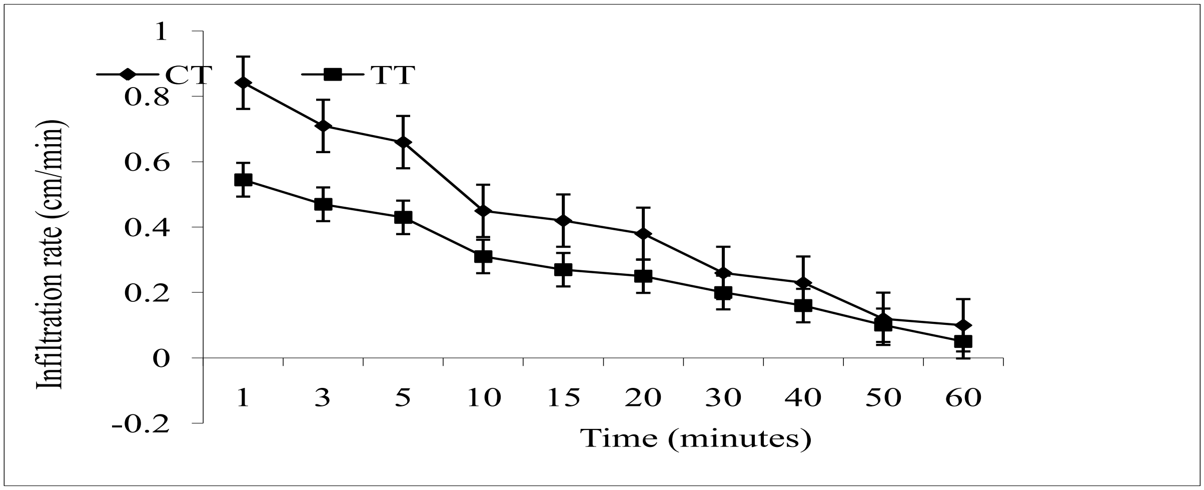

Figure 6. Infiltration rate under winged subsoiler and traditional tillage treated plots.

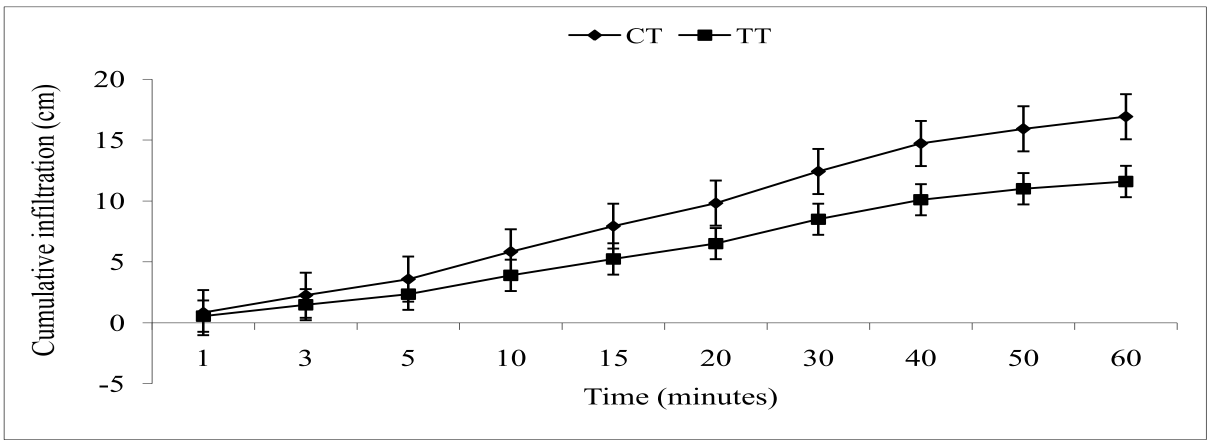

Figure 7. Cumulative infiltration under winged subsoiler and traditional tillage treated plots.

The higher values for the infiltration rate in WS treated plots might be attributable to the opening of the channel by the winged subsoiler and breakdown of hard pans thus making an easy entry of water into the root zone. Mohanty *et al.* (2006) found that subsoilers had similar effects on soil physical properties within the plowing zone and infiltration rate as well as water transmitivity increased with increasing intensity of sub-soiling. Zibilske and Bradford (2007) also indicated that increased moisture content in the root zone is associated with greater infiltration resulting from improvement of water transmission and macro porosity due to sub-soiling. A plot level tillage study showed higher infiltration rates under conservation tillage than the conventionally tilled plots (Marashi and Scullion, 2004). In addition, WS has been found to reduce surface runoff volume over TT that involves repeated passes (Mickelson *et al.*, 2001). Tillage practices can affect multiple soil physical and chemical properties including soil moisture content, mechanical resistance, and organic matter, nitrate and ammonium contents (Lal, 1989). These indicated that the wider adoption of this promising technology by resource poor smallholder farmers in northwestern Ethiopia is utmost important as it is economically beneficial due to the fact that the winged subsoiler was developed as modifications of the *Maresha* Plow, which is locally made and inexpensive.

On the other hand, the lower infiltration capacity under TT could be explained by the hard pan created by *Maresha* plow at the plowing zone, which encourages surface runoff and erosion while diminishing soil moisture storage at the root zone. The presence of plow pans in the study area has been confirmed by value of penetration resistance (Melesse *et al.*, 2012). Bailey *et al.* (1988) also confirmed that excessive compaction causes undesirable effects such as decreased infiltration of water, restrictions of root growth and increased runoff. Similarly, Abu-Hamdeh (2003, 2004) point out that the detrimental effects of soil compaction on soil physical properties is the drastic reduction of soil hydraulic conductivity, which ultimately results in soil erosion and reduced crop yields due to reduced infiltration, increased runoff, and poor drainage.

3.5. Evaporation

Soil evaporation results from the conceptual model showed that evaporation was generally low under both treatments due to summer season and Dega climate zone (Figure 8). Soil evaporation under the TT plots was higher compared to the WS treated plots. The loss of water via soil evaporation under WS and TT treated plots declined as the crop cover increased. Relatively higher soil evaporation was observed under the traditional tillage plots revealing that traditional tillage techniques using *Maresha* plow, do not promote infiltration and, on the contrary, create a hard pan on the soil in the long run and open the soil for further evaporation (Rockstrom *et al.,* 2003; Makurira *et al.*, 2009). Similar studies (Rockstrom *et al.,* 1998; Rockstrom, 2000) in the arid regions of Tanzania showed that soil evaporation can easily account for more than 50% of the rainwater. The implementation of traditional tillage does not promote infiltration and creates hard pans below the plowing layer in the long run, which encourages soil evaporation (Rockström *et al.* 2003). Considering the limitation of traditional tillage, use of winged sub-soiler could reduce soil evaporation through encouraging water holding capacity of the soil, increased infiltration, and soil moisture availability could be a viable option.

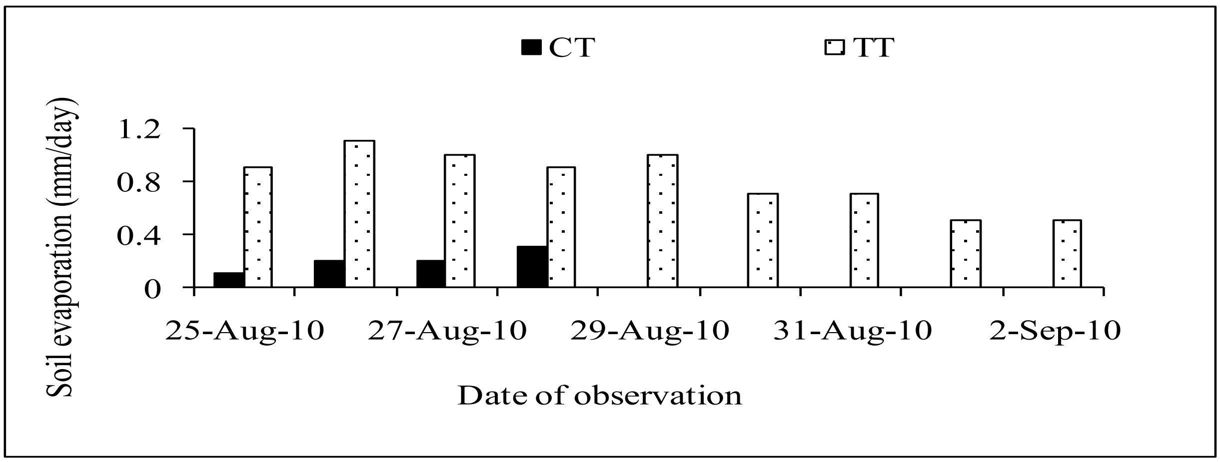

Figure 8. Effect of tillage systems on soil evaporation (mm day^{-1}) at the experimental site.

4. Conclusions

Our study demonstrated that, tillage depth using WS had been substantially higher compared to traditional plow. The WS plow through deep contour plowing and disrupt the hard pan which has been created as a result of repeated cross plowing for many years. We have found significant different silt and clay particles results across depth within TT and WS treatments independently. However, there is no significant textural change across treatments. Although its influence on soil properties reflected a less pronounced changes, the result showed that through opening up of channels by the winged subsoiler and breakdown of hard pans, an easy entry of water into the root zone was created. This in turn increased the infiltration capacity, reduced surface runoff, lowered soil evaporation at different crop growing stages and increased soil moisture availability for sufficient crop growth.

Generally, the northwestern highlands of Ethiopia are highly affected by soil compaction due to repeated cross plowing practices and consequently threatened by severe soil erosion and low land productivity. Low infiltration capacity, higher surface runoff, frequent water logging, yellowish and stunted crop growth is common features of these highlands. Therefore, the adoption and properly implementation of winged subsoiler incorporated with fanya juu soil and water conservation structure will have a far reaching impact on land productivity through improving the overall site conditions and reversing soil degradation.

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