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DEEP TILLAGE IMPROVES DEGRADED SOILS IN THE (SUB) HUMID ETHIOPIAN HIGHLANDS

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Abstract: Intensification of rainfed agriculture in the Ethiopian highlands has resulted in soil degradation and hardpan formation, which has reduced rooting depth, decreased deep percolation and increased runoff and sediment transport. The main objective of this study was to assess the potential impact of subsoiling on surface runoff, sediment, soil water content, infiltration rate and maize performance. Three tillage treatments were replicated at five locations: (*i*) no tillage (zero tillage), (*ii*) conventional tillage (ox-driven Maresha plow, up to a depth of 15 cm) and (*iii*) manual deep ripping of the soil restrictive layers (deep till, up to a depth of 60 cm). Results showed that the post-treatment bulk density and penetration resistance of deep tillage was significantly lower than in the traditional tillage and zero tillage systems. In addition, the post treatment infiltration rate for deep tillage was significantly higher, which resulted in significantly lower runoff and sedimentation rates compared to conventional tillage and zero tillage. Maize yields were improved by a 6% increase under deep tillage compared to conventional tillage and a 29% increase compared to no tillage. Overall, our findings show that, deep tillage can be effective in overcoming some of the detrimental effects of hardpans in degraded soils.

Key words: Restrictive soil layers; Degraded soils; Surface runoff; Sediment; Tillage

1. Introduction

The Ethiopian highlands is suffering from extensive resource degradation[1-2]. Land degradation, hardpan formation and declining soil quality act together to decrease agricultural productivity and economic growth in these landscapes [2-3]. According to the UN Sustainable Development Goal 15 (Life on Land) [4] further land degradation should be prevented. To do this information is needed on biophysical methods that will accomplish that.

Land degradation and hardpan formation in the Ethiopian highlands has been related to repeated cross-plowing of steep slopes [5] compaction by heavy agricultural implements [6] and cattle grazing [7]. In a recent study [8] soil degradation was strongly related to continuous tillage after deforestation. Tillage increases the rate of mineralization, and the disintegration of aggregates, which subsequently results in finer soil particles that easily move down the soil profile during rainfall infiltration [8]. This movement accelerates hardpan formation in the upper 60 cm of the soil profile [8, 9]. The hardpan restricts further infiltration and reduces hydraulic conductivity as large soil pores become filled with sediment laden water [10].

Subsequently, perched water tables form when the hardpan limits deep percolation of rainfall, causing runoff and rill erosion as the soil becomes saturated. Hardpans also restrict root growth, reducing water and nutrient uptake by plants [11]. Most roots of agricultural crops will not grow in soils with a penetration resistance of greater than 2 MPa [12]. Bulk densities in soils that have not been tilled have been found to be significantly greater than that of conventionally tilled soils [13]. Farmers may opt to not till when soils are subjected to wind and water erosion, the timing of tillage is inconvenient, and /or when time and labor requirements for tillage are too high [14].

Solutions to soil compaction problems [15] to decrease the bulk density of the soil and increase the porosity include: adding manure or increasing the organic matter content of the soil; mechanical loosening such as deep ripping or deep tillage; practicing crop rotation especially with a deeply rooted crop; and controlled traffic and reduced livestock grazing.

Deep tillage is a practice that breaks up soil, usually at depths of 30-45 cm. This is undertaken in order to reduce soil compaction, rip the hardpan, reduce the soil bulk density and soil strength thereby encouraging deeper rooting of plants, and improving soil infiltration rates, plants access to water and minerals [16]. Conventional tillage can break up the soil from 10 to 15 cm, but it may be inadequate where soil compaction is a problem [7]. Deep tillage reduces soil bulk density and decreases runoff and soil loss [17]. In western Iran, plowing to a depth of 30 cm and turning under soil and crop residues resulted in longer roots, lower soil bulk density and cone index [11].

Low permeability soils are widespread in crop land areas globally, and deep plowing could greatly increase the vertical permeability in such areas [18]. Preventing hardpans from forming, ripping or loosening existing hardpans will allow more extensive root growth, increase water infiltration and reduce runoff, and may result in greater water availability for the crop. Little information is available in sub humid regions in Ethiopia on how hardpans influence hydrological processes and crop production. Hence, the main objective of this study was to assess the impact of deep tillage of degraded soils with a hardpan on surface runoff, shallow groundwater recharge, sediment loss and crop yield.

2. Materials and Methods

2.1 Description of Study area

This study was conducted in the 911-ha Robit-Bata watershed, located 10 km north of Bahir Dar near Lake Tana (Figure 1). The climate is sub-tropical (Woina Dega) with a mean annual rainfall of 1500 mm. Rural livelihoods are primarily derived from farming and rainfed agriculture and livestock production. Rainfed crops include maize, teff, millet and barley. Soils are volcanic derived and predominantly chromic Vertisols in the lower watershed with clay content ranging between 64 and 82% and organic matter ranging from 0.3 to 1.7% and Eutric Nitosols in the upper watershed with clay content between 30 and 78% and organic matter from 0.6 to 2.2%.

Depending on the crop variety, land preparation generally begins in May at the start of the rainy season with sowing in June. Land preparation was undertaken by oxen driven Maresha plough which reaches a depth of 10-15 cm. Plots were ploughed three to five times prior to planting depending on crop and soil type. Weed management is primarily manual, although some herbicides may be used. Between cropping seasons, animals are allowed to freely graze, which may contribute further to soil compaction.

2.2 Tillage treatments and monitoring

Suitable fields for this study were selected in 2014, and treatments were established in May 2015. Data were collected during the rainy seasons from July to October 2015 and June to September 2016. An overview of agricultural practices and monitoring conducted throughout the study is shown in Figure 2.

2.2.1 Identification of the restrictive, hardpan, layer

Prior to the field experiment, farmer fields were surveyed using a handheld cone penetrometer to assess the presence of a hardpan. Penetration resistance were measured 24 hours after a heavy rainfall when the soil profile was at field capacity. The penetrometer rod was driven 60 cm into the soil at a rate of 2.5 cm sec^{-1}. Plots where penetration resistance exceeded 2 MPa [12, 19], indicating the presence of a hardpan restricting root growth, were selected (Figure 1). In total, five farmer fields with hardpans, similar slopes, topographic position along the slope, soil depth and uniform presence of boulders and rocks were selected (Table 1).

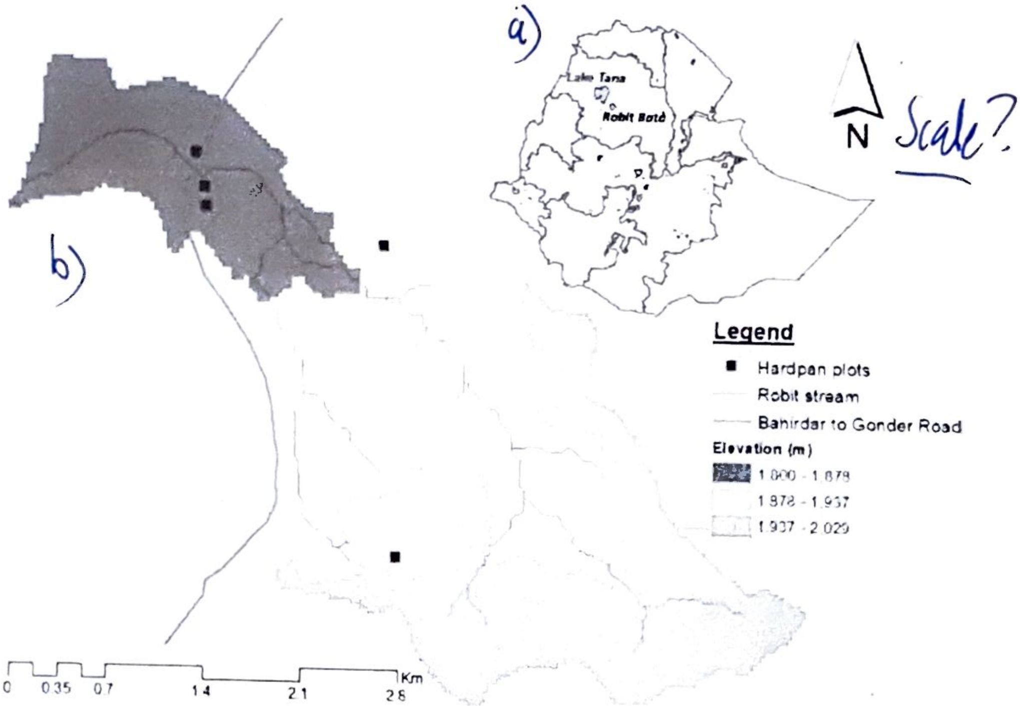

Figure 1: a) Location of Robit Bata Watershed within Ethiopia; b. The Robit Bata watershed and elevation map with the location of the five experimental trials;

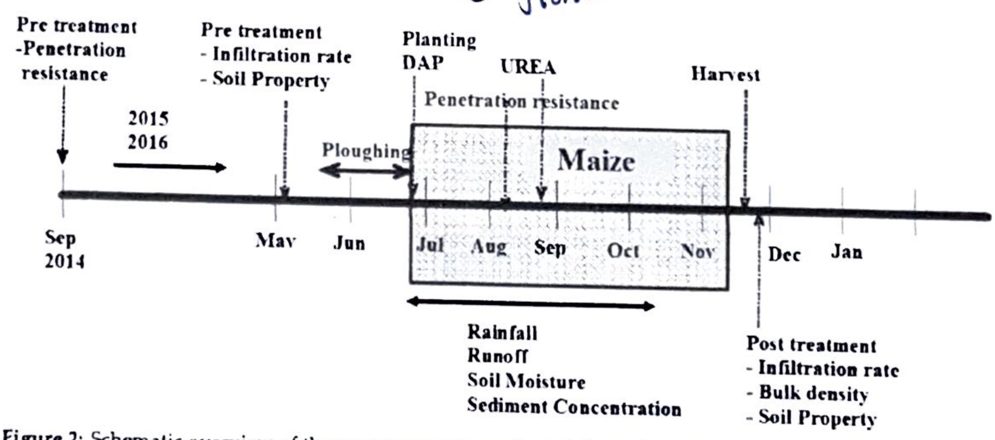

Figure 2: Schematic overview of the measurements conducted throughout the rainy season in 2015 and 2016

2.2.2. Experimental set up

In each of the selected fields, three sub-plots, each 4 m wide and 30 m long, were established in May, 2015. Sub-plots were separated using 50 cm tall 8 mm thick metal sheets. The sheets extended 35 cm depth into the soil profile. Downslope of each sub-plot, a drainage pipe was installed to collect runoff and sediments from each treatment separately. Two barrels were installed at the outlet of each sub-plot. Plot runoff was collected into barrel I (capacity 127 L) and 10% of the overflow from barrel I was directed to barrel II (capacity 110 L). Ten 2.5 cm diameter holes 5 cm below the top of barrel I facilitated run-off to Barrel II via a rubber hose. The top of the barrels was covered with corrugated iron sheet roof to prevent rainfall from entering.

Table 1. Plot characteristics and penetration resistance (MPa) from 0-20, 20-40 and 40-60 cm depths prior to and after treatment implementation (deep tillage: DT; conventional tillage: CT; and no tillage: NT) at end of the rainy season in 2015 and 2016. Values with different superscripts along the same depth within same year show a significant difference at $p<0.05$ between the tillage treatments and the pre-treatment value.

~~Plot~~ Code	Soil profile depth (m)	Elevation (m asl)	Soil depth (cm)	Pre-treatment resistance (MPa)	2015 DT (MPa)	2015 CT (MPa)	2015 NT (MPa)	2016 DT (MPa)	2016 CT (MPa)	2016 NT (MPa)
P1	0.6	1850	0-20	1.38	0.30	0.76	1.41	0.12	0.24	0.28
			20-40	2.42	0.90	1.62	2.43	1.48	1.72	1.60
			40-60	2.62	1.38	2.31	2.50	2.28	2.33	1.72
P2	>3.5	1863	0-20	1.38	0.24	1.41	2.10	0.10	0.21	0.26
			20-40	1.93	0.80	2.07	2.43	1.38	1.72	1.72
			40-60	2.21	1.42	2.36	2.40	2.07	2.33	2.24
P3	>3.5	1873	0-20	1.38	0.21	0.76	1.24	0.34	0.17	0.21
			20-40	2.07	0.50	1.66	2.18	1.29	1.72	1.64
			40-60	2.42	1.45	2.29	2.53	1.81	2.31	2.24
P4	>3.5	1930	0-20	NA	0.83	0.22	1.20	0.00	0.21	0.62
			20-40	NA	0.35	1.10	1.48	0.55	1.38	1.72
			40-60	NA	0.52	1.77	2.07	2.28	2.41	2.41
P5	0.8	1976	0-20	2.21	0.48	1.52	2.07	0.86	0.28	0.69
			20-40	2.62	0.73	1.96	2.14	0.95	1.52	2.07
			40-60	2.69	1.10	2.46	2.54	2.24	2.33	2.41
All plots			0-20	1.58^a	0.26^b	0.93^c	1.60^a	0.69^c	0.22^{bc}	0.41^b
			20-40	2.26^a	0.65^b	1.67^c	2.13^a	1.13^b	1.61^a	1.75^a
			40-60	2.48^a	1.17^b	2.24^a	2.41^a	2.13^b	2.34^b	2.21^b

Three tillage treatments [no tillage (zero tillage, NT), conventional tillage (CT) and deep tillage (DT) deep ripping of the restrictive layer] were randomly assigned to the three sub-plots (Fig 3). Plots with CT were conventionally ploughed three times to 15 cm depth with ox driven Maresha plow with fifteen days interval during both the years 2015 and 2016. Deep tillage consisted of manually digging up the soil to a depth of 60 cm using a mattock in 2015 and 2016. For NT treatment, plots were not tilled, and the weeds were removed by hand during planting.

On June 26, 2015, hybrid maize variety Konor was sown in each sub-plot using a spacing of 20 cm by 50 cm, as recommended by the farmer (Figure 3). In June 20, 2016, the sowing rate was adjusted to 20 cm by 70 cm as per the recommendation of the Office of Agricultural within the district. Fertilizer was broadcast at a rate of 200 kg ha^{-1} diammonium phosphate (DAP consisting of 18% N-NH_4^+, 46% P-PO_4^{3-}) during sowing and 200 kg ha^{-1} urea (46% N-NH_4^+) 60 days after planting. Weed management was done manually in all sub-plots four times from planting to harvest.

2.2.3 Data collected

Soil physical and chemical properties: Penetration resistance was measured prior to field experiments and in August during the rainy season in 2015 and 2016 (Figure 2) using the same methodology. Bulk density was determined by taking undisturbed soil samples using a core cutter of 5.1 cm diameter at 20 cm depth increments up to 60 cm after the rainy season in 2015 and 2016 (Figure 2). Soil samples were analyzed for cation exchange capacity (CEC), total nitrogen (N), plant available phosphorus (P), available organic matter (OM) and pH. A soil suspension with a soil-water ratio of 1 to 2.5, stirred for 30 minutes, was used to measure pH. Soil organic carbon was determined using titration with ammonium sulphate. The Kjeldahl method was used to determine total N. Plant available phosphorus was obtained from extraction of acid-soluble and adsorbed phosphorus with fluoride-containing solution according to the Bray I test (acid soil). Cation exchange capacity was determined by ~~using~~ flame photometer method.

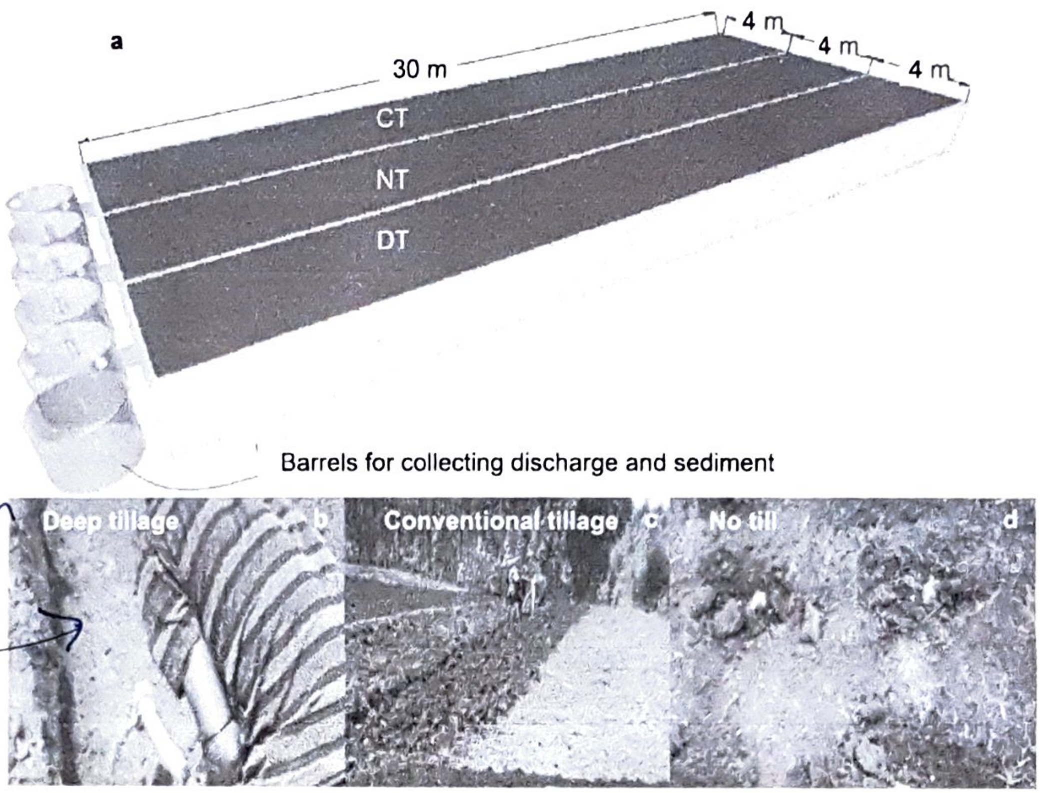

Figure 3: a) Setup of experimental plots a) Schematic diagram of the experimental runoff plots; b) photo of deep tillage (DT) with hoe; c) conventional till (CT) with traditional oxen drawn plough; and d) no-till (NT) where seed and fertilizer are placed in locally loosened soil

Infiltration rate: Steady state infiltration rates were conducted using single ring infiltrometer (30 cm height and 30 cm diameter). Pre-treatment steady state infiltration tests were conducted in the five plots. Post-treatment steady state infiltration rate measurements were conducted in each sub-plot for all the five fields after the rainy season in 2015 and 2016. In total 35 infiltration rate tests were conducted throughout the experiment.

Rainfall: Daily rainfall data was collected each morning at 08:00 hours from manual rain gauges installed at each plot during the 2015 and 2016 rainy seasons (Figure 2). The manual rain gauges were located 2 m away from the experimental plots.

Runoff and sediment yield: Runoff and sediment load generated from each plot was determined throughout the two rainy seasons. Surface runoff was measured using the installed collection barrels each day at 08:00. The water depth in each barrel was measured using a steel ruler and after thoroughly mixing, a sub sample of 150 ml was taken. Sediment concentration was determined in the lab after filtration and oven drying at 105°C. Details of the calculation are given in the supplementary material.

Soil moisture: Soil moisture profiler (Delta-T Devices Ltd, England) with an accuracy of 4% was used to determine volumetric soil moisture content at a depths of 10, 20, 30, 40, 60, and 100 cm. One moisture access tube was installed at in the lower third of each sub-plot. Measurements were taken twice weekly from planting to harvest. The reading obtained from the device was calibrated for each depth by taking 15 undisturbed soil samples, oven drying them and determining the volumetric soil moisture content.

Yield: Maize was harvested from each sub-plot separately in both years. Maize yield from each sub-plot was collected and measured using a balance. The harvested maize was dried in the field prior to separating the stem, cob and grains. Additionally, rooting depth was measured at the end of the season in 2016 in each of the treatments for all repetitions. Plant roots were carefully removed from soil and root length was determined using a ruler.

2.4 Data analysis

The effect of tillage treatment on soil physical and chemical properties was analyzed using the PROC MIXED procedure in SAS for 2015 and 2016 separately with treatment and soil depth designated fixed factors and plots were repeated measurements. Bulk density, available P and texture data were log normal transformed (i.e. log (x+1)) to ensure homogeneity of variance and normal distribution of the residuals.

Nested design with dep (ANOVA) was conducted using SPPS version 16.0 at the 5% probability level ($p<0.05$). In case the normality criteria were not fulfilled, data were log-transformed (*i.e.* log(x+1)). Differences in soil loss following the various tillage treatments were assessed using the non-parametric Kruskal- Wallis test.

3. RESULTS

The soil physical and chemical properties after the tillage treatments are presented first followed by the differences in runoff and soil loss for all the tillage treatments. The results discussed are based on the data from the 2015 and 2016 rainy seasons.

3.1. *Soil penetration resistance and bulk density*

For all of the treatments, the lowest bulk densities were observed in the surface 0-20 cm soil depth, while the highest were observed from 40-60 cm depth. Bulk density for all treatments increased slightly with increasing soil depth (Table 2). Bulk density values for the DT treatment were significantly less than

Table 2. Bulk density (g cm-3) from 0-20, 20-40 and 40-60 cm depth intervals at the end of the rainy season in 2015 and 2016 for deep tillage (DT), conventional tillage (CT) and no-till (NT).

Plot Code	Soil depth (cm)	2015			2016		
		DT	CT	NT	DT	CT	NT
P1	0-20	1.27	1.45	1.53	1.27	1.50	1.56
	20-40	1.32	1.52	1.63	1.28	1.60	1.56
	40-60	1.33	1.54	1.66	1.28	1.65	1.71
P2	0-20	1.23	1.57	1.55	1.21	1.53	1.68
	20-40	1.26	1.38	1.67	1.28	1.54	1.67
	40-60	1.27	1.54	1.64	1.3	1.59	1.70
P3	0-20	1.15	1.45	1.45	1.21	1.54	1.57
	20-40	1.19	1.44	1.42	1.19	1.60	1.60
	40-60	1.27	1.50	1.44	1.22	1.63	1.62
P4	0-20	1.05	1.22	1.33	1.10	1.53	1.39
	20-40	1.01	1.23	1.23	1.10	1.56	1.64
	40-60	1.02	1.19	1.30	1.10	1.58	1.75
P5	0-20	1.28	1.46	1.50	1.21	1.53	1.55
	20-40	1.15	1.41	1.58	1.21	1.57	1.63
	40-60	1.22	1.52	1.56	1.24	1.61	1.67
All plots	0-20	1.20^{a}	1.43^{b}	1.47^{b}	1.20^{a}	1.53^{b}	1.55^{b}
	20-40	1.20^{a}	1.40^{b}	1.51^{b}	1.21^{a}	1.57^{b}	1.62^{b}
	40-60	1.22^{a}	1.46^{b}	1.52^{b}	1.23^{a}	1.61^{b}	1.69^{b}

those measured in the CT and NT treatment for the three soil depths in both years (p<0.01). Almost all deep tillage sub-plots (at all depths), showed bulk densities remained constant in 2015 and 2016. On the other hand, in the conventional and no tillage sub-plots bulk density increased in 2016. The higher bulk density values of the no tillage treatments, which can be assumed to represent the bulk densities of the plots before the application of the tillage treatments is a good indication of the presence of hardpans in the experimental agricultural plots and in agricultural fields of the wider Robit-Bata watershed.

The penetration resistance at the onset of the experiment down the soil profile was on average 1.58 MPa (20 cm), 2.26 MPa (40 cm) and 2.48 MPa (60 cm) (Table 1). At the end of the rainy season in 2015 and 2016, the penetration resistance at the three different depths was lowest in the DT followed by CT and NT (Table 1). As expected, soil penetration resistance was significantly (p<0.05) lower for deep tillage treatments than for the conventional and no tillage treatments across the soil profile in both years. For all treatments the penetration resistance values increased with depth and the lowest average value was recorded in the surface 20 cm whilst the highest average value was at the depth of 40-60 cm which is consistent with the bulk density results and shows that the restrictive, hardpan layer is mainly located at this depth. The lower penetration values obtained for the deep tillage treatments from 20 to 40 and 40 to 60 cm were related to the restrictive, hardpan layers being broken during tillage, enabling crop root penetration. In 2015, the SPR values in the deep tillage treatment were less than the critical threshold value of 2 MPa for all depths; with CT most of the sub-plots exceeded the critical threshold value of 2 MPa at depths greater than 20 cm and for NT, the critical threshold value of 2 MPa was exceeded in the surface 20 cm in two of the sub-plots.

3.2. Changes in soil chemical properties

Medium to high variability in organic matter, sand content, total nitrogen, CEC and available phosphorus was observed between the five selected plots for a specific soil depth (Table S1). Overall, soil chemical properties within the soil profile were minimal. Aside from slight increases in pH in the surface 20 cm (p<0.05), the treatments did not have an effect on the pH, CEC, P, clay, silt or sand fraction along the soil profile over a two year period (Table S1). There was a slight increase in organic matter compared to the pre-treatment measurements over two years with highest values being reported in the CT treatment compared to the DT and NT. Total nitrogen followed similar trends for the first two soil layers but showed slightly greater concentration in the DT treatment at the 60 cm compared to the other treatments at the same depth.

3.3 Infiltration rate and soil moisture content

The mean infiltration rates observed for the years 2015 and 2016 were: 223 mm hr^{-1} and 262 mm hr^{-1} (DT), 138 mm hr^{-1} and 120 mm hr^{-1} (CT) and 118 mm hr^{-1} and 115 mm hr^{-1} (NT), respectively. The infiltration rates in DT were significantly higher in 2015 and 2016 compared to CT and NT treatments (Figure 4).

Median soil moisture contents in 2015 and 2016 are given in Figure 5. Differences were minimal in 2015. In 2016 soil moisture content under DT increased in the entire soil profile compared to the NT and CT. This is most likely related to the lower bulk density and greater pore space observed in the DT compared to the CT and NT treatments.

3.4. Runoff and soil loss

The cumulative surface runoff fluctuated significantly between the various treatments and replicates (Table 3, Figure 6). Runoff was the least under the DT treatment (0-65 mm in 2015 and 0-47 mm in 2016). The greatest runoff was found under the NT treatment (0-229 mm in 2015 and 0.5-233 mm in 2016). The no tillage treatment produced the highest average surface runoff (2015: 92 mm; 2016: 113 mm) while the deep tillage produced the least surface runoff (2015: 36 mm and 2016: 34 mm) (Table 3, p<0.05). The surface runoff from the deep tillage was likely significantly reduced due to greater infiltration rates and the disruption of the hardpan from 40 to 60 cm.

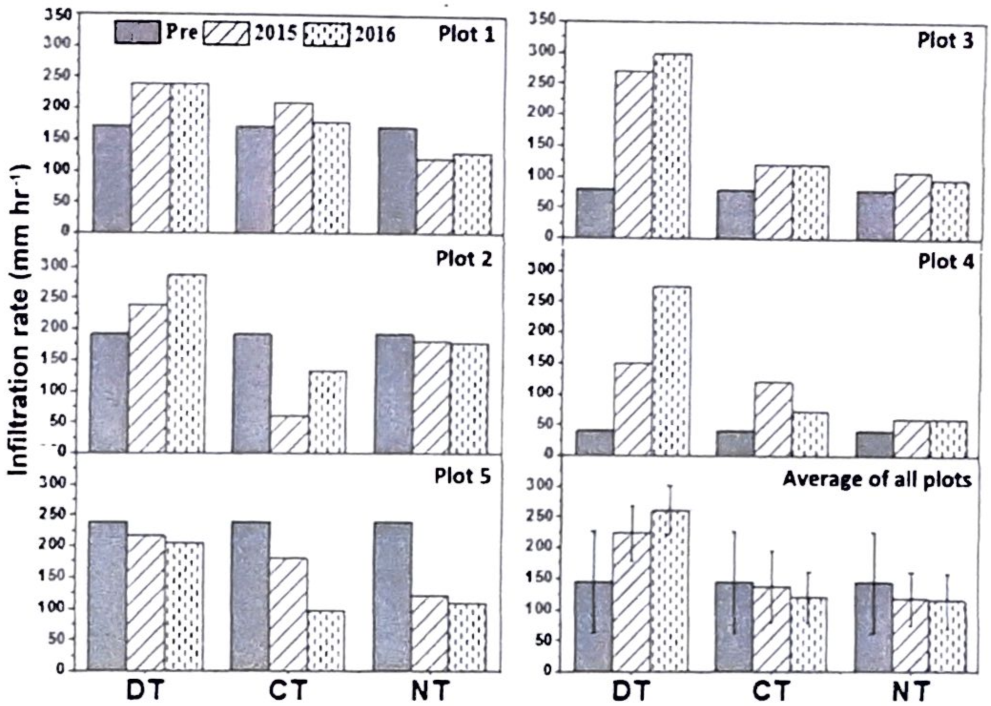

Figure 4. Steady state infiltration rates before tillage and after harvest for deep tillage (DT), conventional tillage (CT) and no till (NT) in 2015 and 2016

Table 3. Average and standard deviation of the surface runoff (mm) for the three tillage treatments (deep tillage (DT); conventional tillage (CT) and no-tillage (NT)) for the 2015 and 2016 rainy seasons.

Tillage treatment	2015	2016
DT	36±23.80[a]	34±12.60[a]
CT	85±76.76[b]	82±35.02[b]
NT	91±87.45[b]	113±70.80[b]

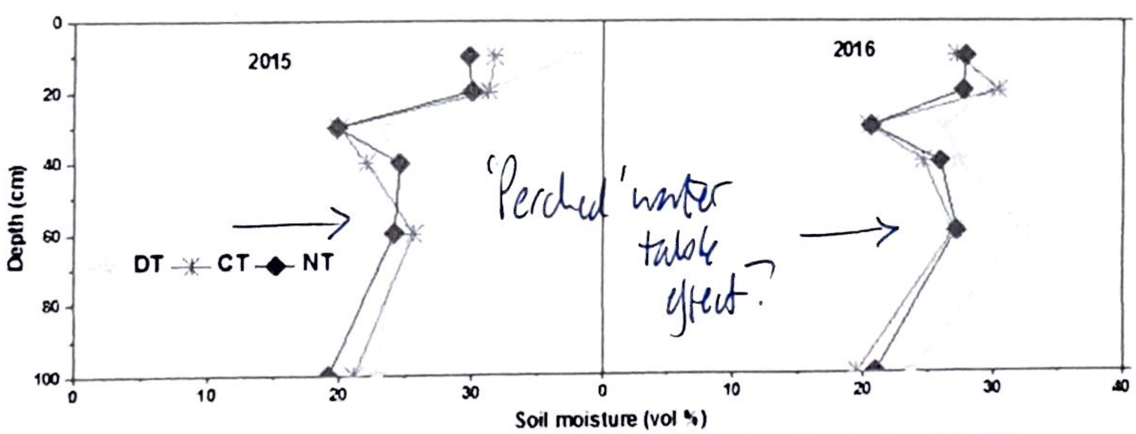

Figure 5. Plot of the soil volumetric water content versus the soil depth for the three tillage treatments in 2015 and 2016.

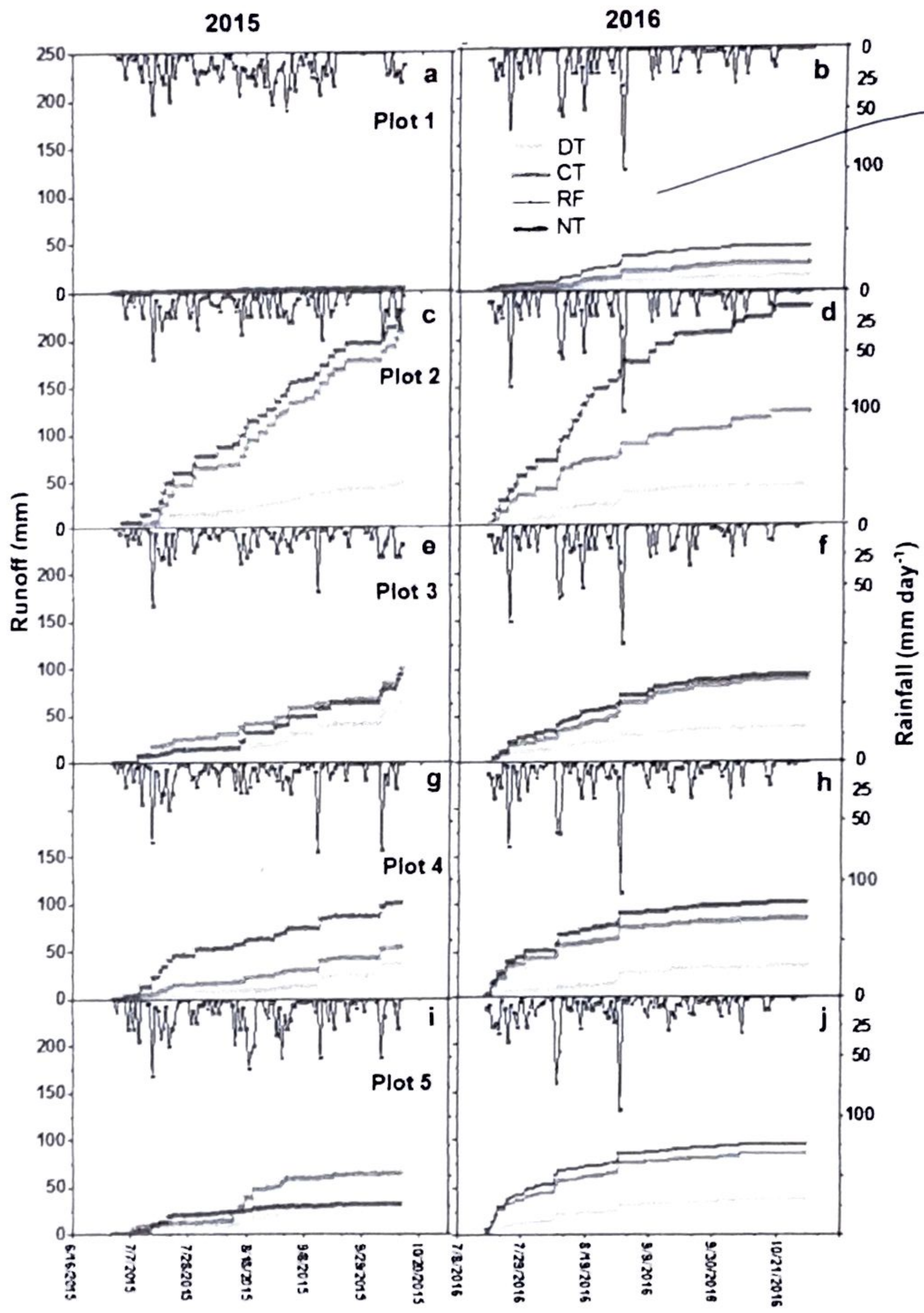

Figure 6. Rainfall and cumulative runoff for conventional tillage (CT), deep tillage (DT) and no till (NT) in 2015 (left) and 2016 (right): ~~a) plot 1, 2015; b) plot 1, 2016; c) plot 2, 2015; d) plot 2, 2016; e) plot 3, 2015; f) plot 4, 2016; g) plot 4, 2015; h) plot 4, 2016; i) plot~~ 5, 2015; j) plot 5, 2016; the locations are given in Figure 1

Measured soil loss followed a similar trend to runoff among the years and treatments. Similarly, soil loss observed between the fields varied strongly. The majority of the soil removed lost/eroded? from the treatments occurred prior to August. Soil loss in 2015 and 2016, respectively, was 1.45 Mg ha^{-1} and

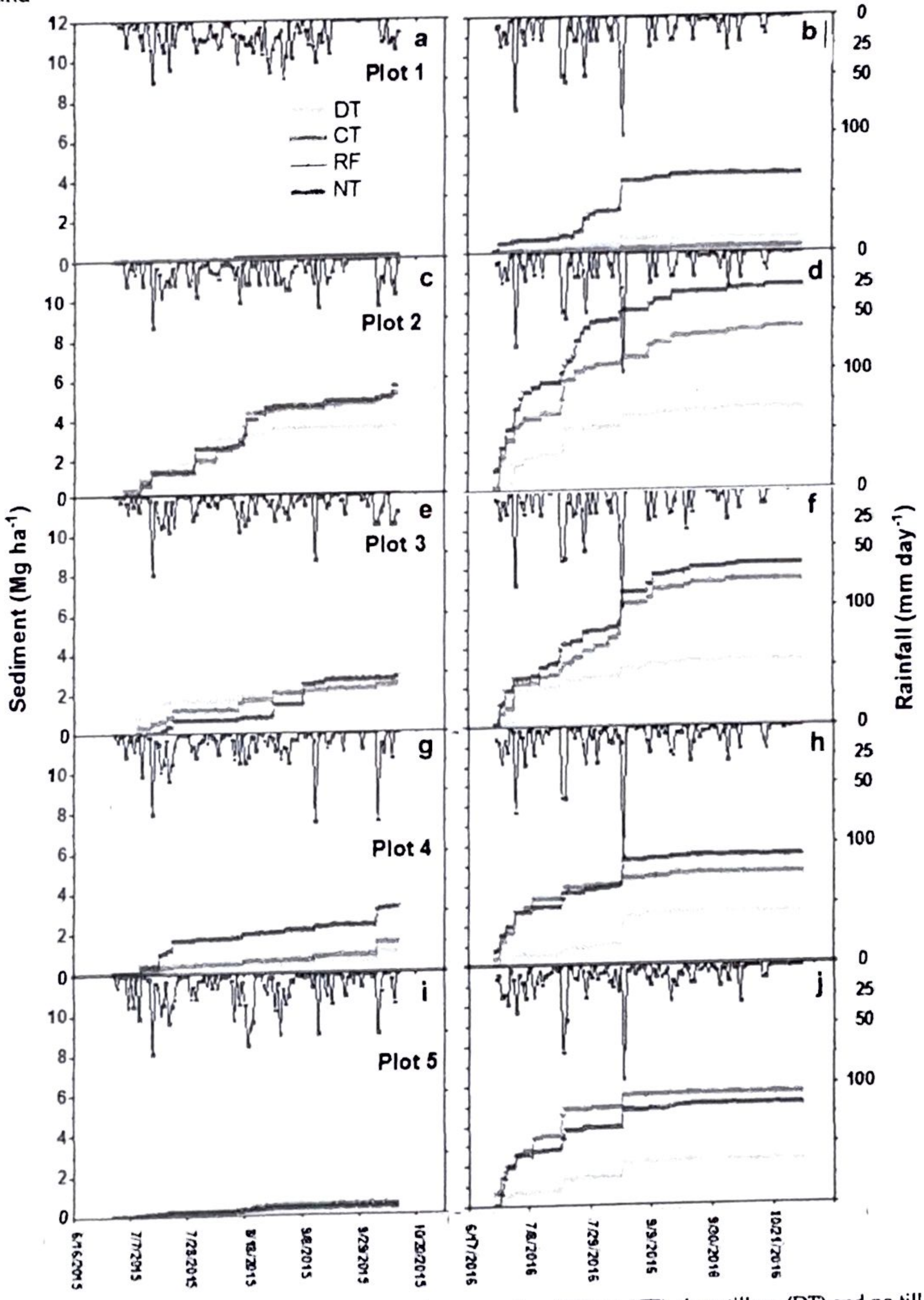

Figure 7. Rainfall and cumulative sediment loss for conventional tillage (CT), deep tillage (DT) and no till (NT) in 2015 (left) and 2016 (right): a) plot 1, 2015; b) plot 1, 2016; c) plot 2, 2015; d) plot 2, 2016; e) plot 3, 2015; f) plot 4, 2016; g) plot 4, 2015; h) plot 4, 2016; i) plot 5, 2015; j) plot 5, 2016; the locations are given in Figure 1

2.55 Mg ha^{-1} in DT, 2.03 Mg ha^{-1} and 5.06 Mg ha^{-1} in CT and 2.35 Mg ha^{-1} and 6.66 Mg ha^{-1} in NT (Figure 7). Among the three tillage treatments NT lost more soil and DT lost the least (Figure 7). Soil loss was 42% and 54% greater in CT and 64% and 62% higher in NT compared to DT for 2015 and 2016, respectively.

3.5. Agricultural productivity of maize as function of tillage treatments

~~The average rooting depth in 2016 was 51±6 cm in DT, 29±3 cm in CT and 23±4 cm in NT (Table 4).~~ The rooting zone in DT was almost double that in NT and CT. Maize yield obtained for 2015 was on average 4.9 ± 2.1 Mg ha^{-1} under DT, 4.1 ± 1.6 Mg ha^{-1} under CT, and 3.4 ± 2.1Mg ha^{-1} under NT. Similar trends were to CT and noted in 2016 (Table 4). In 2015, maize yield under DT produced on average 14% greater yields compared to conventional till and 35% compared to the NT treatments. In 2016, however, maize yields under DT declined by 2% compared to those observed under the CT treatment. The conventional tillage produced 23% greater maize grain yield than the no till.

Table 4. Measured maize yield (Mg ha^{-1}) and rooting depth observed under the various treatments deep tillage (DT); conventional tillage (CT) and no-tillage (NT)).

Plot	Yield (Mg ha^{-1}) by treatment						Root depth (cm) by treatment		
	2015			2016			2016		
	DT	CT	NT	DT	CT	NT	DT	CT	NT
P1	4.2	3.6	3.2	3.7	2.2	2.2	57	25	21
P2	6.3	5.7	6.1	2.8	3.8	2.7	52	28	28
P3	7.8	6.0	4.9	5.3	6.2	3.2	49	34	17
P4	2.9	2.6	1.6	3.5	3.7	2.7	56	29	25
P5	3.1	2.8	1.3	3.5	3.3	3.1	43	27	23
Average	4.9±2.1	4.1±1.6	3.4±2.1	3.8±0.9	3.8±1.5	2.8±0.4	51±6	29±3	23±4
CV %	44.1	38.8	60.6	24.7	38.0	14.5	11	12	18

4. DISCUSSION

4.1 Effect of deep tillage on soil erosion and runoff

The soil bulk density and penetration resistance obtained with DT is likely because of the deeper ripping of the soil profile disrupting the hardpan and creating more pore space. The results are in agreement with [20] who reported lower bulk density with deep tillage treatments and higher bulk density with NT. Other studies such as [21] reported that deep tillage resulted in lower bulk density and penetration resistance than conventional tillage. [22] also found that application of deep tillage ~~up~~ to 90 cm depth in soils with a fragipan resulted in a significant reduction in bulk density and penetration resistance.

The positive effects of deep tillage on penetration resistance and bulk density corresponded with the higher infiltration rates found with DT in both years. The infiltration rates in DT increased with time, but in CT and NT rates decreased. The increase in filtration rates can be attributed to the increase in total pore space. Njùs and Bùrresen (1988 cited by [23]) showed that deep ploughing resulted in a higher number of macro pores and increased the total number of pore spaces to a depth of 10cm. Because the restrictive soil layer disintegrated with deep tillage, more rainfall was able to infiltrate into the soil profile resulting in higher moisture content. This result is consistent with other studies, such as [21] in which DT resulted in a significantly higher water content at a depth of 20-30 cm than CT on a loam soil. [24] also reported that tilling soils resulted in improving water holding capacity and transmittivity ability of the soils and this was attributed it to high roughness and depression storage.

The increase in pore space following the deep tillage treatment resulted in a reduction in surface runoff and soil loss in the DT treatment. The reduction in soil loss for deep tillage treatment was primarily due to the reduction in surface runoff because of improved infiltration. This result is in agreement with the findings of [17]. In addition, the reduction in sediment with deep tillage could possibly result in the higher roughness caused by tillage at the onset of the season, which reduces the erosive potential of raindrops.

Whilst the trends of the surface runoff followed those observed in soil loss, the annual surface runoff was lower than those reported by other studies, such as [25] who reported a higher total runoff (32% and 20% of monsoon rainfall in 2010 and 2011, respectively) in Debre Mawi watershed before implementation of soil water conservation practices. After application of practices the reported runoff in Debre Mawi watershed was 10% and 11% of monsoon rainfall in 2012 and 2013, respectively. In our study the observed surface runoff was 3.9 and 3.6% of total rainfall for DT, 9.1 and 8.8% for CT and 10 and 12.2 % for NT in 2015 and 2016, respectively, primarily because of the higher infiltration rates. The median pre-treatment infiltration rate in this study was 171 mm hr^{-1} whilst [25] reported an median infiltration rate for Debre Mawi watershed of 33 mm hr^{-1} y^{-1} in 2010, 24 mm hr^{-1} in 2012 and 31 mm hr^{-1} in 2013. In Robit infiltration rates increased to 242 mm hr^{-1} under deep tillage, further reducing the expected runoff and soil loss. As the sub-humid mountainous region of Amhara is characterized by saturation excess flow [26, 27], breaking the hardpan in the upland area could increase sub-surface water availability and therefore, shallow groundwater recharge by decreasing surface runoff.

4.2 Effect of deep tillage on maize production

The lower grain yield in NT may have been due to unfavorable soil conditions for crop growth such as higher bulk density, higher penetration resistance, less soil moisture content and less air diffusivity. The results were in agreement with [20]; [21] and [28] who reported that subsoiling resulted in higher grain yield than NT and CT. A meta-analysis by [29] reported that deep tillage resulted in a 6% increase in grain yield. [30] reported that deep tillage resulted in improved seed emergence and grain yield than CT and NT, with the improvement attributed to better drainage during wet period.

The relatively greater soil moisture in the soil profile for deep tillage corresponded to the higher infiltration rates. As the root zone depth was larger with DT, it is likely that the maize was able to access more water and nutrients from the soil profile [12]. Furthermore, the lower runoff and soil loss observed in the deep tillage treatment may have reduced fertilizer runoff. The high variability in organic matter, sand and available phosphorus between the fields may have masked the response of maize to increased soil moisture and available nutrients. Though the changes in hydrological processes and maize performance showed similar trends among all the fields, results were variable. This variation may be partially attributed to the location of the fields in the watershed. Event runoff was higher in downslope subplots compared to upslope because of higher soil moisture contents limited infiltration. Upslope, subsurface lateral flow is higher and the soil is not saturated, thus there is room for more water to infiltrate [31]. Saturation downslope occurs more rapidly because of rainfall and subsurface flow from the upper or hill slopes [26], and thus will generate more runoff.

5. CONCLUSION

Based on the two years of experimental data, we conclude that in the sub humid conditions of Robit-Bata, Ethiopia, breaking up a soil hardpan using deep tillage (60 cm depth) increased infiltration rates and soil moisture throughout the profile whilst reducing runoff and soil loss. Pore space was increased and both bulk density and penetration resistance decreased but soil chemical properties were not affected significantly by deep tillage. These improvements in soil physical properties may have influenced the higher maize yields obtained under the deep tillage compared with the tillage with the traditional Maresha plow. No-till reduced crop yields and increase runoff. Significant dry spells did not occur in this study. Therefore, the increased soil moisture content with deep tillage most likely will have a greater effect on maize yields in semi-arid areas where the interval between rain events is larger than in the humid areas and rainfed crops experience water stress.

Taking the results of this study together with [25] reinforce the evidence to promote interventions relating to tillage techniques that improve livelihoods for farmers through greater productivity. At the same time these interventions contribute to sustainable intensification (more produce per unit of natural resource), increasing shallow groundwater to contribute to extending availability of water for use downstream as well as reducing negative off-site impacts through reduction in soil loss and suspended solid loads in surface waters and meet thereby the goals of UN Sustainable Development Goals (SDG) 15 and specifically SDG 15.3 that aims at achieving Land Degradation Neutrality

Supplementary Materials: The following are available online at www.mdpi.com/xxx/s1, Text S1: Calculation of runoff; Table S1. Soil chemical properties of the top 60 cm before and after the application of the tillage treatments; Figure S1. Bulk density at the various depths after the implementation of tillage treatments measured after harvest in 2015 and 2016.

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