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Berken plow and intercropping with pigeon pea ameliorate degraded soils with a hardpan in the Ethiopian highlands

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ABSTRACT

Closing the yield gap and enhancing efficiency in rainfed maize production systems in Ethiopia requires urgent action in increasing the productivity of degraded agricultural land. The degradation of land through continuous compaction and decline in the organic matter has resulted in a wide-spread formation of a hardpan that restricts deep percolation, prevents plant root development, and, ultimately can lead to increased erosion. Studies exploring practical low-cost solutions to break the hardpan are limited in Ethiopia. The main objective was to evaluate soil mechanical (i.e. modified plow or *Berken* plow) or biological intervention (i.e. intercropping with pigeon pea) effectiveness to enhance soil water management and crop yield of rainfed maize systems whilst reducing soil erosion and runoff. Five farm fields, each including four plots with different tillage treatments, were monitored during two rainy seasons in 2016 and 2017. The treatments were: (i) farmers practice under conventional (CT) tillage; plots tilled three times using an oxen driven local plow *Maresha*, (ii) no-till (NT), (iii) *Berken* tillage (BT), plots tilled three times using an oxen pulled *Berken* plow, and (iv) biological (CT + Bio), tap-rooted pigeon pea intercropped with maize on plots conventionally tilled. Results showed that mean tillage depth was significantly deeper in the BT (28 cm) treatment compared to CT and CT + Bio (18 cm) treatments. Measured soil penetration resistance significantly decreased up to 40 cm depth under BT and maize roots reached 1.5 times deeper compared to roots measured in the CT treatment. Under BT, the estimated water storage in the root zone was estimated at 556 mm, 1.86 times higher compared to CT, 3.11 times higher compared to NT and 0.89 times higher compared to CT + Bio. The positive effects on increased water storage and root development resulted in an average increase in maize grain (i.e. 15%, 0.95 t ha^{-1}) and residual above ground biomass (0.3%, 6.4 t ha^{-1}) leading to a positive net benefit of 138 USD ha^{-1} for the BT treatment compared to the CT treatment. The negative net benefit obtained under CT and CT+Bio was mainly related to the high labor cost related to plowing, weeding, planting, and fertilizer application whilst in the NT this was related to the significantly lower maize yields. The positive effects in the BT treatment, and to some extent the CT+Bio treatment show great potential for smallholder rainfed maize systems where degraded soils with hardpans and high variability in rainfall prevail.

1. Introduction

Meeting the maize demand in Sub-Saharan Africa by 2050 would require a doubling of current annual yields (van Ittersum et al., 2016). According to ten Berge et al. (2019), it is feasible to meet national self-sufficiency needs in countries like Ethiopia without significant agricultural land expansion. However, this would require urgent action in decreasing the yield gap especially in degraded land characterized by

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low nitrogen use efficiency (ten Berge et al., 2019), high nutrient depletion rates (van Beek et al., 2016), and labor constraints (Silva et al., 2019). Furthermore, large-scale oceanic and atmospheric variability and its influence on rainfall heterogeneity, poses additional water related challenges to agricultural productivity as the country's main crop livestock system remains predominantly rainfed (Taye et al., 2021).

Land and soil degradation are a major contributor to low agricultural productivity in the Ethiopian highlands. Degraded soils are responsible for the increasing trend of soil loss in the Ethiopian highlands by increasing surface runoff or indirectly for the formation of gullies (Abate et al., 2017; Steenhuis & Tilahun, 2014; Dagnew et al., 2017). These problems are widespread in the northern and central Ethiopian highlands (Biazin et al., 2011; Tebebu et al., 2015). Soil organic matter has decreased after the conversion of forest to agricultural land by continuous tillage, removal of crop residues, and replacement of animal dung to inorganic fertilizer. As a result, the loss in organic matter increased aggregate stability and structure (Rockström & Valentin, 1997; Temesgen et al., 2012; Tebebu et al., 2017) and increases fine-textured, easily erodable soil particles (Pimentel & Burgess, 2013; Tebebu et al., 2017). Subsequently, continuous plowing and translocation of fine soil particles during rainfall to the sub-surface closes the original macropores. This resulted in the formation of hardpan layers in the uppermost subsoil layer (Araya et al., 2016; Tebebu et al., 2017).

Hardpans limit deep percolation of the amount of rainwater that can be stored in the soil before the soils become saturated. Hardpans, therefore, cause saturation excess surface runoff contributing to increased soil erosion, restrict airflow, hinder root penetration, consequently reducing crop growth and yield (Busscher et al., 2001; Chen et al., 2005; Temesgen et al., 2012; Tebebu et al., 2015). They have been identified at different depths depending on soil type and tillage practices. For example, hardpan occurred in loamy sands at 20 to 40 cm depth (Gliński et al., 2011); below 17.5 cm in heavy clay soil (Chen et al., 2005), and at a depth of 8–15 cm in sandy clay loam soils (David et al., 2007). In Ethiopia, hardpans are found on average below 15 cm on silt clay soils in a semi-arid region (Biazin et al., 2011), below 20 cm on clay loam soil in the humid region (Temesgen et al., 2012), and at 10–15 cm depth under grassland and cropland in Debre Mawi and Anjeni watersheds (Tebebu et al., 2017).

Research has shown that hardpans can be ruptured with deep tillage using shank-mounted tractors every 2–3 years to keep soils free from compaction (Schneider et al., 2017; Amanullah et al., 2010; Gliński et al., 2011). Likewise, in Ethiopia hardpans can be disrupted by subsoiler implements (McHugh et al. 2007; Temesgen et al., 2007). However, smallholder farming and subsequently labor operations are predominantly manual or with animal traction, given their small plot sizes and steep slopes (Baudron et al., 2015). Abidela Hussein et al. (2019), Bayabil et al. (2017) and Tebebu et al. (2020) have tested the effect of deep tillage using hand tools (*mattock)* on water infiltration and soil erosion. While these results showed promise in terms of runoff reduction and yield improvement, the manual digging is labor intensive, limiting the adoption of deep tillage practices. The *Berken* plow, originally developed for improved weed control by Aybar Engineering PLC (Institute for Sustainable Development, 2015) could provide a less labor intensive alternative, especially in smallholder fields (<2 ha) on steep slopes were tractor driven sub-soiling remains challenging. The design modifies a local *Maresha* plow where the wooden plowshare component is replaced by a metal plowshare. The design allows a deep center cut of approximately 28 cm, which is deeper than the 10–15 cm of the standard oxen plow used in Ethiopia.

Intercropping of staple crops with tap-rooted legumes could provide a biological alternative for improving agricultural production on degraded soils with a hardpan (Mallikarjuna et al., 2011). Tap rooted crops like pigeon pea form biopores which are used by crops such as maize to tap into the subsoil (Kautz, 2015; Lynch and Wojciechowski, 2015). Furthermore, depending on crop type and prevailing soil moisture conditions, hydraulic lifts through plant-root systems have varied in magnitude (Zegada-Lizarazu and Iijima, 2004 and references therein). Singh et al. (2019) showed that the presence of microbes (e.g. arbuscular mycorrhizal (AM) fungi) supports a common mycorrhizal network in the root zone, enabling pigeon pea (*Cajanus cajan*) to hydraulically lift water, so-called *bio-irrigation*. The cultivation of pigeon pea provides additional benefits such as its dual purpose for fodder/grain consumption, soil conservation, nitrogen fixation, and increase in organic matter (Smith et al., 2016; Snapp et al., 2019).

Limited studies are available in Ethiopia using low-cost mechanical and biological methods suitable to smallholder farming systems to improve soil physical conditions in degraded soils with a hardpan presence. Hence, the objective of this study was to assess low cost and less labor-intensive technologies alongside conventional and no-tillage systems and evaluate their impact on soil penetration resistance, soil water storage, runoff generation, maize performance, and economic benefits.

2. Methods and materials

2.1. Description of Robit Bata watershed

The experiment was carried in the Robit Bata watershed (Fig. 1) on the south-eastern edge of Lake Tana, Amhara Region, around 10 km north of Bahir Dar city in Ethiopia. The watershed has a strong undulating landscape with steep slopes up to 44% and with over 60% of the 911 ha watershed being cultivated farmland. The subsistence mixed crop-livestock system in the area is typical for the Ethiopian highlands, where livestock provides draught power and is fed a large amount of the crop residues. Maize (*Zea mays*), finger millet (*Eleusine coracana*), and tef (*Eragrostis tef*) are the main crops cultivated during the rainy season (June to September). Smallholder irrigation is increasing with 13% of the croplands being additionally cultivated with vegetables during the dry season (October to May). Depending on the crop and soil conditions, farmers plow three to five times to prepare seedbeds. The lower parts of the watershed are comprised of Chromic Vertisols (60%) whereas Eutric Nitosols (40%) dominate in the upper watershed. The climate is subtropical (Woyina Dega) with a mean annual rainfall of 1500 mm y^{-1}, temperature range from 12 to 27 °C, and on the average 8 h of sun per day.

2.2. Experimental setup

The study by Abidela Hussein et al. (2019) selected 5 fields with a hardpan to study the impact of deep tillage (DT) on the hydrological performance of degraded soils. In May 2015, three plots each 4 m wide and 30 m long were established in each farmer's field corresponding to the CT, NT and DT treatments. The physical characteristics of the five fields prior to the implementation of the tillage treatments is described in Table 1. In 2016, two plots, each with the same dimensions, were randomly added to explore less labor-intensive treatments (Table 2, Fig. 2). Hence, three treatments CT, DT and NT, were initiated in 2015 whereas BT and CT + Bio were established in 2016. The treatments were monitored during the rainy season of 2016 and 2017. The study focused on assessing the *Berken* tillage (BT), and biological treatment (CT + Bio) alongside the conventional tillage (CT) and no-till (NT) treatments (Table 2, Fig. 2).

In CT (Fig. 3, left), clods form as the soil is pushed by the *Maresha plow*, necessitating repeated cross plowing up to five times as contour ploughing is not feasible. This treatment is referred to as farmer practice. The *Berken* plow results in a deep center cut allowing for the water to infiltrate, requiring farmers to plow only one time along contour lines (Fig. 3, right). As a result, the mean tillage depth differs between the two treatments where the *Berken* plow results in ripping the soil up to 28 cm whereas the *Maresha* plow penetrates the soil up to a maximum of 18 cm. The biological treatment CT + Bio combines the traditional CT with intercropping of the main crop with a tap-rooted crop. In this study

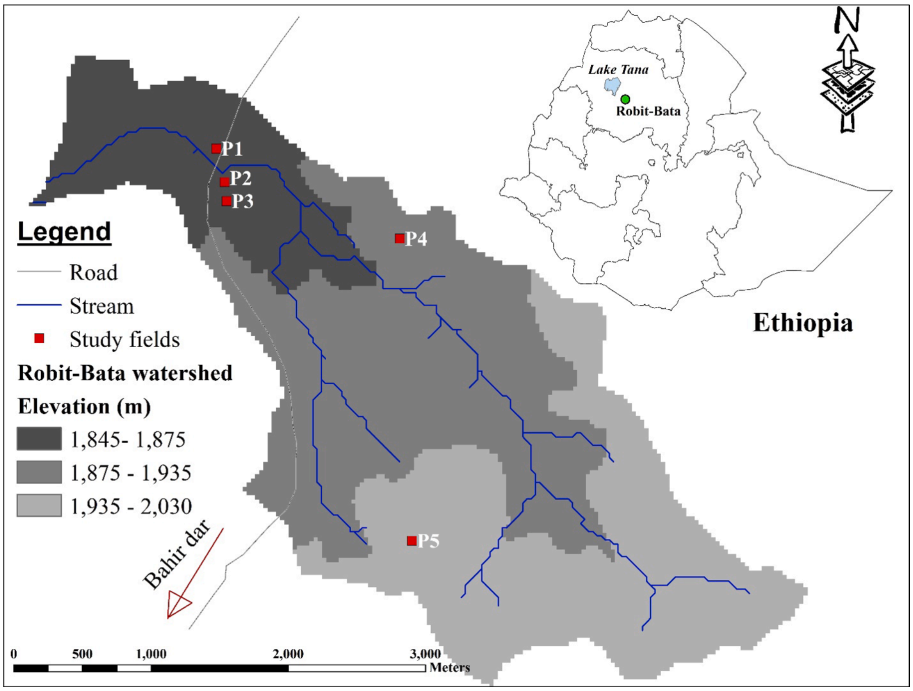

Fig. 1. Location of the five study fields selected in Robit Bata Watershed and the relative location of the watershed to Lake Tana and Ethiopia (top right).

Table 1
Physical characteristics of the farm fields prior to study (source: Abidela Hussein et al., 2019).

Field code	Soil depth (m)	SPR at 20 cm depth (MPa)	Slope (%)	Elevation (m a.s.l)	Soil pH (-)	OC (%)
P1	0.6	3.01	6.0	1850	5.51	0.59
P2	>3.5	2.39	9.4	1863	4.98	0.25
P3	>3.5	2.99	10.0	1873	5.44	0.325
P4	0.8	2.23	8.0	1976	4.98	0.42
P5	>3.5	2.96	8.3	1930	5.34	0.825

Key: SPR - soil penetration resistance; OC - organic carbon.

Table 2
Description of implemented tillage treatments.

Treatments	Descriptions
No tillage (NT)	• No ploughing for three consecutive years (started in 2015)
Conventional tillage (CT)	• Plots cross ploughed using ox-driven *Maresha* (started in 2015) • Soil tilled twice before sowing: before the onset of rain, and after first rain • One superficial tillage to cover the seeds with soil
Berken tillage (BT)	• Plots contour ploughed (i.e., perpendicular to slope of plots) using ox- driven *Berken* (started in 2016) • Soil tilled twice before sowing: before the onset of rain, and after first rain • One superficial tillage to cover seeds with soil
Biological tillage (CT + Bio)	• Plots cross ploughed using ox-driven *Maresha* (started in 2016) • Soil tilled twice before sowing: before the onset of rain, and after first rain • One superficial tillage to cover the seeds with soil • Intercropped with tap rooted *pigeon pea*

pigeon pea (*Cajanus cajan*) was used given its multi-purpose benefits for household and livestock consumption as well as improvements on soil fertility and ability of the taproot to penetrate through the hardpan.

Following Bayabil et al., (2017) the four plots were demarcated with 8 mm thick galvanized iron sheets (Fig. 2). The iron sheets were inserted 20 cm into the ground with 15 cm left above the surface. At the bottom of the plots, a PVC pipe transported runoff and sediment into a barrel with a diameter of 60 cm and a height of 50 cm resulting in a capacity of 127 L (Fig. 2). Ten 2.5 cm holes were drilled 5 cm from the top in each barrel. One of the ten holes was connected through a pipe with a second barrel (60 cm diameter × 40 cm height) with a capacity of 110 L. Therefore, the second barrel received 10% of the overflow volume from the first barrel.

Hybrid maize seeds were sown in all plots with a spacing of 20 by 75 cm. The hybrid variety was selected because the farmers liked the excellent yield potential (ESA, 2014). At sowing, Diammonium Phosphate (DAP) containing 18% N and 46% P_2O_5 was applied in each plot at a rate of 200 kg ha^{-1} followed by a urea (46% N) application at a rate of 200 kg ha^{-1} 60 days after sowing. No pesticides were applied throughout the growing season and weeds were removed two times manually during the cropping season in all plots. For the CT + Bio treatment, pigeon pea seeds were intercropped 7 days after maize sowing with a spacing of 50 cm between plants.

2.3. Data collection

2.3.1. Soil physical and chemical properties

To assess the effect of tillage treatments on soil properties, a total of 180 soil samples were collected from the top, middle, and bottom parts for all treatments in all five fields. Samples were taken along the soil depth at 20 cm increments up to 60 cm before and after the cropping season in 2016 and 2017. Prior to laboratory analysis, three bulk samples taken at the same depth in the same treatment and same plot were mixed thoroughly in a plastic bucket and air dried at room temperature. Samples were analyzed at the Amhara Design and Supervision Enterprise. Soil parameters were measured both before and after the cropping season (Table 3). Overall, the soil profiles showed a high clay content ranging between 54 and 66% (Table S1). Mean total nitrogen contents in all tillage treatments were from low to moderate ranging from 0.05 % to 0.14%. Available phosphorus in all treatments was low (5–10 mg kg^{-1}) to very low (<5 mg kg^{-1}).

Soil penetration resistance was measured using a handheld cone

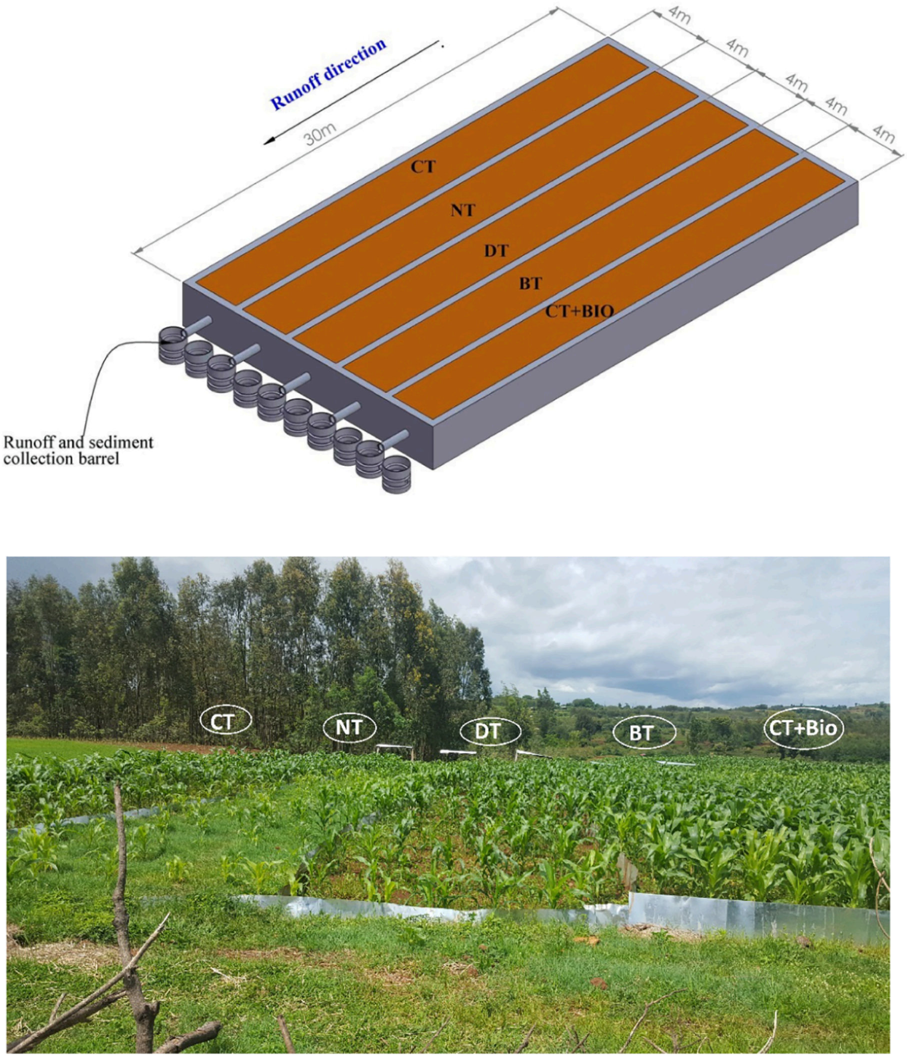

Fig. 2. A schematic representation (top) and actual experimental layout of the five tillage treatments within a farmer field reflected by a photograph taken at 30 days after planting. (CT - conventional tillage; NT - no-till; DT- Deep tillage; BT - tillage using the Berken plow; and CT + Bio - conventional tillage with maize intercropped with tap rooted pigeon pea. As deep tillage was found to be too labor intensive by smallholder farmers, we omit the DT results in this paper.

Fig. 3. Conventional *Maresha* plow (left) and *Berken* (right) tillage implements.

penetrometer. Weekly pressure measurements were carried out at 20, 40, 60 cm, 24 h after a heavy rainfall before the rainfed cropping season for summer of 2016. During the 2017 rainy season, penetration resistance was measured weekly.

2.3.2. *Meteorological and hydrological data*

Rainfall was measured manually daily at 08:00 h with five rain gages (i.e., one for each field) during the rainy season in 2016 and 2017. The total rainfall in 2016 was 956 mm and in 2017 1646 mm (Fig. 4). Rainfall intensities ranged in 2016 between 3 mm hr^{-1} and 204 mm hr^{-1}. Rainfall intensities could not be calculated for 2017 due to the failure of the automatic rain gauge. From the rainfall data measurements, 2016 and 2017 were considered as a dry and wet year.

Steady state infiltration rates were measured using a single ring infiltrometer (30 cm height and 30 cm diameter) at three locations in all treatments before the experiment setup in 2016. The infiltrometer was

Table 3

Description of methods used during the soil analysis.

Parameter	Method	Reference
Soil texture analysis	Hydrometric	Black, 1965
Soil organic carbon (SOC)	Walkley-Black oxidation	Nelson and Sommers, 1982; Pribyl, 2010
Total nitrogen (TN)	Kjeldahl digestion method	Bremner and Mulvaney, 1982
Available Phosphorous (Av-P)	Olsen's extraction (UV/visible spectrometer)	Olsen and Dean, 1965
Available potassium (Av-K)	Atomic absorption spectrophotometry using ammonium acetate (pH 7)	Black, 1965
Cation Exchange Capacity (CEC)	Extraction with Ammonium acetate	Chapman, 1965
Soil pH	Potentiometric at 1:2.5 soil:water ratio	Sahilemedhin and Taye (2000)

inserted 10 cm deep from the surface. The decline in water depth was measured over time until a steady state was reached. Measurements were repeated in 2017 after two cropping seasons. Throughout the paper we will use the term infiltration rates to discuss the steady state infiltration findings.

A soil moisture profiler from Delta-T Devices Ltd was calibrated and used to measure changes throughout the soil profile during the rainy season for all treatments. Access tubes were installed 10 m from the bottom of each plot at the onset of each season. The probe with an accuracy of ± 4% was used to measure volumetric soil moisture content weekly at 10, 20, 30, 40, 60, and 100 cm depth. Undisturbed soil cores with 100 cm^3 cylinders were taken in each plot to calibrate the soil moisture profiler and to determine the bulk density. The soil was dried in the lab at 105 °C. The readings were corrected following an established calibration curve between the profiler readings and volumetric moisture measurements derived from the core samples.

Daily runoff and suspended sediments were measured for all plots. The water height in the collection barrels was measured starting each day at 8:00 AM. The daily collected surface runoff for each plot was computed as:

$$V = \frac{\pi D^2}{4} * (H_1 + 10H_2) \tag{1}$$

where V is the runoff volume from the plot (l), D is the barrel diameter (cm) and H_1 is the water height (cm) in the first barrel and H_2 the water height (cm) in the second barrel. In some cases when the barrels overflowed, the runoff was estimated with the soil conservation service (SCS) curve number method with calibrated curve numbers for each plot (see supplementary material).

Suspended sediment samples were collected separately from the two barrels at each plot using one-liter sampling bottles after steering the collected runoff and sediments in the barrel for 30 s. The one-liter samples were filtered in the laboratory using pre-weighted dried filter paper with 100 μm pore size. The filters with suspended sediments were dried in the oven at 105 °C for 24 h and then reweighed to determine the sediment concentration. Sediment yield was determined as a product of concentration and runoff.

Sediment collected from each treatment were aggregated monthly for the analysis of total nitrogen (TN), PO_4^{3-} and K^+. Laboratory analysis was performed using standard wet analysis as described in Table 3. Sediment nutrient loss was computed as the product of sediment yield and measured sediment-associated nutrients.

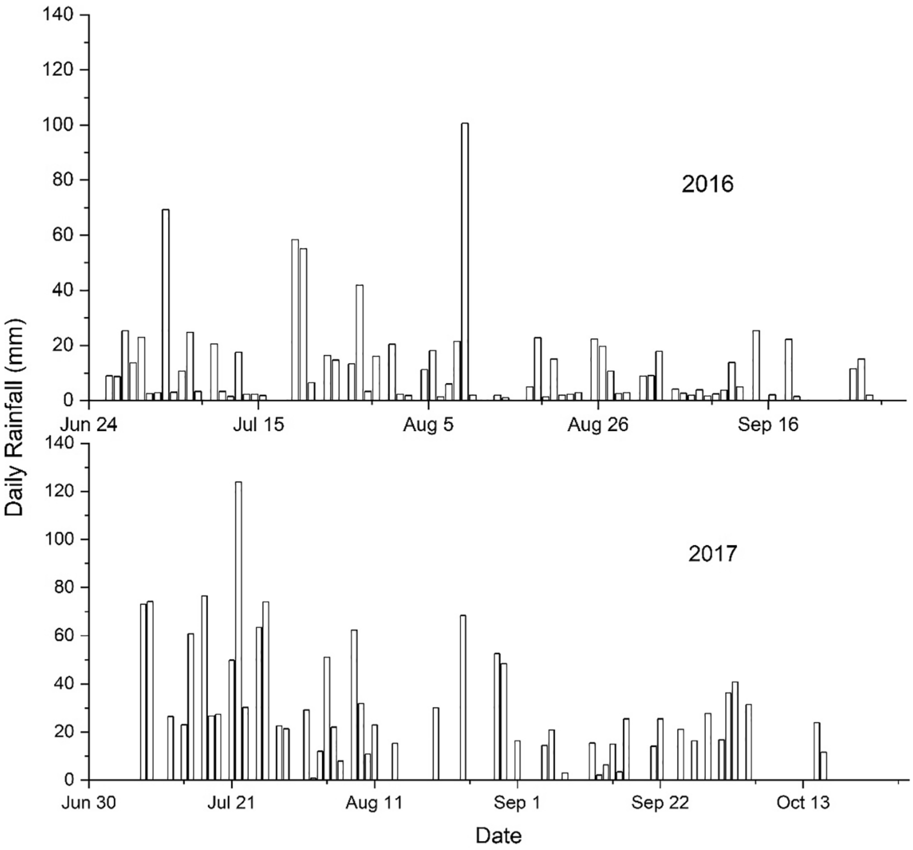

Fig. 4. Daily rainfall distribution (mm) during rainy seasons in 2016 (top) and 2017 (below). The maize was planted on 24th and 30th of June and harvested at the 2nd and 3rd of November in 2016 and 2017, respectively.

2.3.3. Crop yield and rooting depth

Maize yield was measured in upper, middle, and lower positions in each plot covering an area of 12 m^2 resulting in a total harvested area of 36 m^2. Straw and cob were separated and measured separately in the field. Hence, the weights referred to in this study are fresh weights. In the CT + Bio treatment, the pigeon pea yield was separately harvested at the upper, middle, and lower positions. Maize rooting depth was measured after reaching the reproductive stage R6 when the abscission layer had formed according to Perdue University research[3]. Maize rooting depth was determined in each plot by carefully removing the soil around three randomly selected maize plants in the upper, middle, and lower slope positions. Once the soil was removed, the plants were dug up and the vertical root length was approximated.

2.4. Data analysis

2.4.1. Effect of tillage on runoff using the SCS-CN method

The SCS-CN method, a commonly used method for estimating storm runoff can also be used for calculating storage (S) in cases where saturation excess runoff occurs (such as on our runoff plots) before the entire plot contributes to the runoff (Steenhuis et al., 1995; Schneiderman et al., 2006). In addition, the SCS equation is used to estimate the runoff for the large storms once barrels overflowed. The SCS equation, written in terms of the storage S and the effective rainfall (defined as rainfall after the first runoff starts), is given in appendix A. To find the storage S for each treatment, the SCS equation was fitted to average rainfall and storm runoff data for weekly averaged of the 2016 and 2017 observed data.

2.4.2. Economic analysis of the tillage treatments

The net benefit from tillage treatments was determined by subtracting the total cost incurred for each treatment from the total revenue. The cost included maize and pigeon seed and fertilizer (DAP and urea), *Maresha* and *Berken* plow, and family and hired labor throughout the cultivation season for 2016 and 2017[4]. The *Maresha* plow costed 3 USD and the *Berken* plow 10 USD. Based on the Input Supplier and Marketing Service Department in Zenzelma Agricultural office report (2016 & 2017), the fertilizer cost for urea was 0.77 USD kg^{-1} and 0.91 USD kg^{-1} and the price of DAP was 1.95 USD kg^{-1} and 2.05 USD kg^{-1} in 2016 and 2017, respectively. The price of blended fertilizer (K-N-P-S-B) was 0.43 USD kg^{-1} (2016) and 0.46 USD kg^{-1} (2017), respectively. Similarly, a seed price of 0.52 USD kg^{-1} (2016) and 0.56 USD kg^{-1} (2017) was taken for maize whilst 0.18 USD kg^{-1} (2016) and 0.27 USD kg^{-1} (2017) was taken for pigeon pea. Family and hired labor included the manpower spend during plowing, fertilizer, weeding, seeding (maize and pigeon pea), residual handling, and grain separation. The total number of labor hours were converted to man days at a rate of 10 h day^{-1} equivalent to 4.34 and 3.70 USD in 2016 and 2017, respectively. Additionally, the cost to replace the estimated loss of N, P, and K were considered. As NO_3^- and K^+ are very mobile and likely would be leached even if runoff were to be reduced, the study assumed that both nutrients will continue to need replenishment. Therefore, this study only calculated the cost to replace the P. The cost to supplement the loss of P was calculated according to:

$$Fertilizer_{replacement\ P\ cost} = \mathrm{P_D Q_P} \quad (2)$$

where $\mathrm{Fertilizer_{replacement\ P\ cost}}$ is the cost (USD kg^{-1}) to supplement the phosphorus lost by runoff and sediment loss P_{loss} (kg ha^{-1}) by taking into account the quantity of DAP required (Q_D, kg^{-1}) and the cost of DAP fertilizer P_D (USD kg^{-1}).

The total revenue included grain yield for maize and pigeon pea and maize straw obtained. The market price of maize and straw were 0.21 and 0.021 USD kg^{-1} (2016); 0.25 and 0.025 USD kg^{-1} (2017), respectively. For pigeon pea, only the grains were taken into account which had a market price of 0.65 USD kg^{-1} in 2016 and 0.61 USD kg^{-1} in 2017.

2.4.3. Statistical analysis

Statistical analyses were performed using SAS University Edition 2017 statistical package. The PROC MIXED module was used to assess potential differences following the treatments on soil physical and chemical parameters after two rainy seasons. A nested design was used with year, treatment, and depth as fixed effects and the plots both as a random effect and as repeated measurements. Observations with absolute standardized residuals exceeding 3 were removed. The variables pH, Sand, and K^+ were log (x + 1) transformed whereas the sqrt (x + 0.5) was taken for clay to obtain homogeneity of variance and normal distribution of the residuals. The other soil parameters were not transformed prior to the analysis. To assess potential effects of the treatments on hydrological parameters, root depth, and maize performance the PROC GLM module was used. Data were checked for normality and in case of non-normality, runoff and sediment concentrations were log-transformed using log (x + 1). The GLM was used for the analysis of variance and multiple-comparison post hoc Tukey's honest to establish a significant difference (HSD) between treatments when ANOVA showed a statistically significant difference ($p < 0.05$).

3. Results

3.1. Changes in soil physical and chemical properties

Soil parameters varied little between the various treatments for a particular depth before the start of the experiment (2016, Table S1). Similarly, no significant variations were observed between the CT and BT or CT + Bio treatment after two rainy seasons (see 2017, Table S1). Based on the 2016 data for bulk density (data not shown), a significant difference was observed before planting and after harvesting for all 3 soil depths under the BT treatment ($p < 0.05$). Whilst the BD values for CT and NT did not show significant differences at any of the depths, the CT + Bio did show a significant difference at the 20–40 cm depth (data not shown) ($p < 0.05$).

Throughout the 2017 cropping season, the weekly measured penetration resistance at 40 and 60 cm depth remained close to 2 MPa (Fig. 5). For all treatments, an increase was observed throughout the rainy season. At week 1, average penetration resistance at 60 cm depth was 1.96 MPa, 2.11 MPa, 2.18 MPa, and 2.32 MPa for BT, CT, CT + Bio, and NT, respectively. Using the same sequence of the treatments, average values in week 11 were 2.19 MPa, 2.21 MPa, 2.33 MPa, and 2.25 MPa at the same depth. Throughout the rainy season, the penetration resistance at 40 cm depth in the BT treatment remained below 2 MPa and was significantly lower compared to the other treatments where values fluctuated around 2 MPa (Fig. 5). In week 6, the measured average penetration resistance was 1.36 MPa for BT, 1.64 MPa for CT + Bio, 1.79 MPa for CT, and 1.91 MPa for NT. This increased to 1.85 MPa, 2.08 MPa, 2.21 MPa, and 2.36 MPa for BT, CT + Bio, CT, and NT, respectively in week 11. The average penetration resistances up to 20 cm, increased as well throughout the season but remained well below 2 MPa throughout the cropping season.

3.2. Changes in infiltration and soil moisture

At the onset of the 2016 cropping season, infiltration rates at the soil surface were on average 144 mm hr^{-1} for all treatments with a standard deviation of 75 mm hr^{-1} (Fig. 6). After two cropping cycles, the highest infiltration rate was measured for BT (242 mm hr^{-1}) followed by CT + Bio (187 mm hr^{-1}), CT (120 mm hr^{-1}), and NT (115 mm hr^{-1}) (Fig. 6). After two cropping cycles, significant improvements were observed in

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[3] https://extension.entm.purdue.edu/fieldcropsipm/corn-stages.php

[4] Exchange rate used in the study is 1 USD = 23 ETB for 2016 and 27 ETB for 2017.

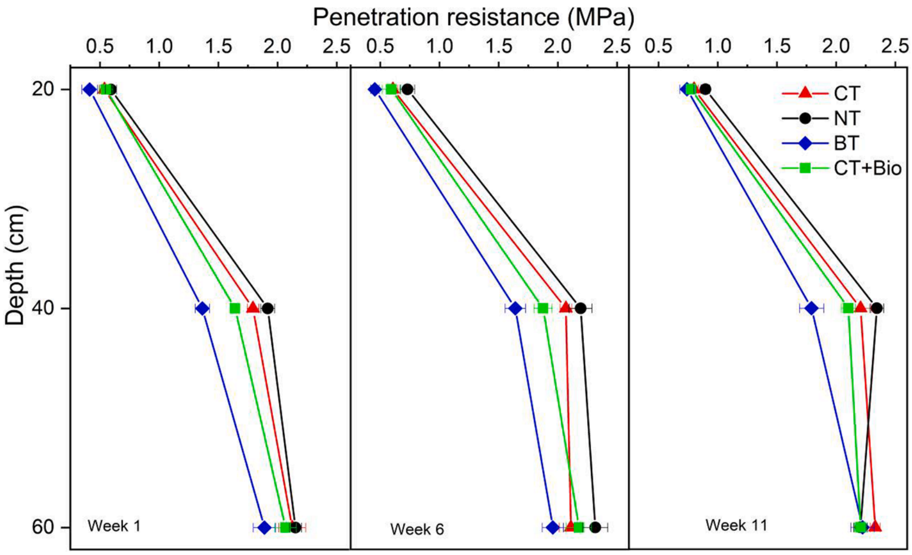

Fig. 5. Average soil penetration resistance (MPa) with standard error bars at 1, 6 and 11 weeks after planting at 20, 40 and 60 cm soil depth in 2017 (n = 15 per treatment per week). (CT - conventional tillage; NT - no-till; BT - tillage using the *Berken* plow; and CT + Bio -conventional tillage with maize intercropped with tap-rooted pigeon pea).

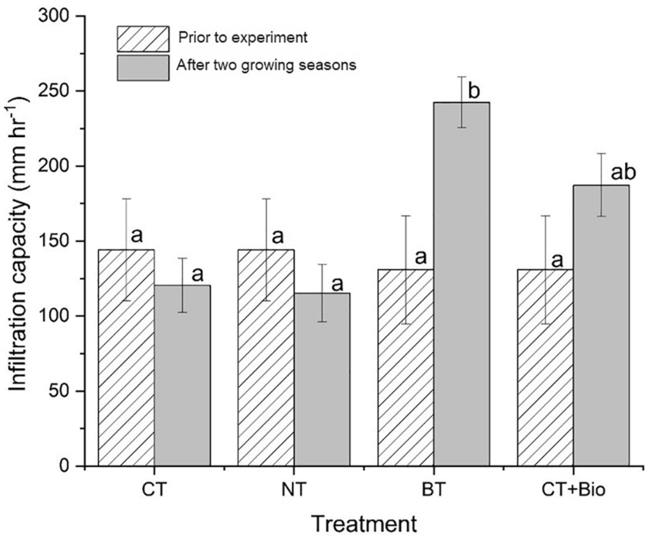

Fig. 6. Mean and standard error of infiltration capacity (mm hr^{-1}) measured under each treatment across the five experimental fields prior to the experiment in 2016 and after two cropping seasons on 6th of December 2017 (i.e. 172 days after last tillage). (CT - conventional tillage; NT - no-till; BT - tillage using the *Berken* plow; and CT + Bio to conventional tillage with maize intercropped with tap-rooted pigeon pea). Infiltration capacity for tillage treatments followed by the different letters shows a significant difference between the treatments within the year ($p < 0.05$).

the BT and to some extent in the CT + Bio treatments ($p < 0.01$). Infiltration rates increased by 47% under BT and 30% under CT + Bio. On the other hand, infiltration capacity slightly decreased over two cropping cycles by 15% and 25% for the CT and NT treatments, respectively. Less then 0.5% of the storms in the Robit Bata watershed have rainfall intensities>100 mm hr^{-1} (Tilahun et al., 2020). Thus, only the most intense storm might have a period when rainfall intensities exceeded the infiltration capacity of the soil. Most runoff is, therefore, generated when water is ponded on the hardpan and runs off when the soil is saturated till the surface.

Soil moisture between the treatments at 10 cm and 20 cm varied only slightly throughout the cropping season. From 30 cm onwards the *Berken* plow (BT) and the intercropping with Pigeon pea (CT + Bio) showed significantly greater moisture content compared to the CT treatment (Fig. 7) ($p < 0.05$). Furthermore, the increase in soil moisture at 60 cm continued to be significantly greater for BT whilst soil moisture in the CT + Bio treatment was comparable to those observed in the CT and NT treatment.

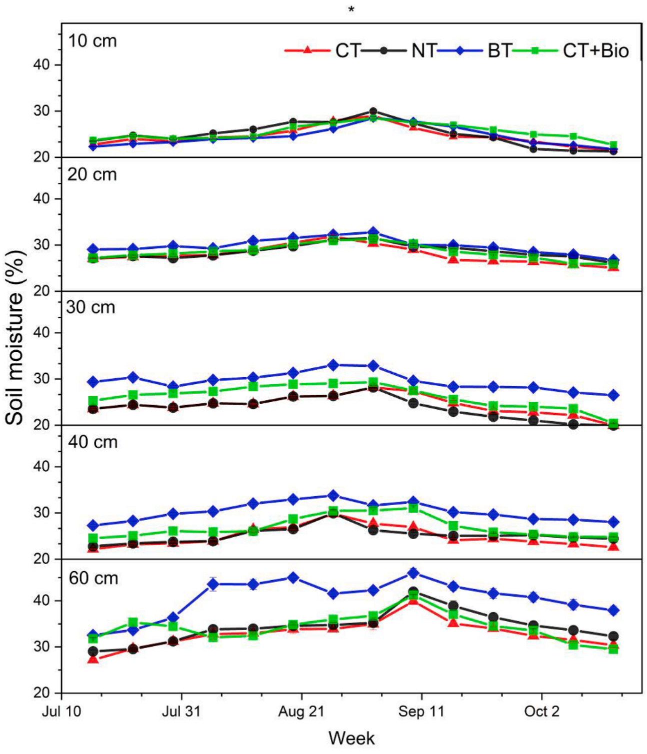

Fig. 7. Weekly changes in volumetric soil moisture measurement (%) under the various tillage treatments at 10, 20, 30, 40 and 60 cm in 2017. (CT - conventional tillage; NT - no-till; BT - tillage using the *Berken* plow; and CT + Bio to conventional tillage with maize intercropped with tap-rooted pigeon pea.

3.3. Changes in runoff and sediment transport

Runoff for all treatment was greater in 2017 than in 2016 because of the greater amount of rain in 2017 (Table 4). Total measured runoff during the monsoon phase was lowest in the plots tilled with the Berken plow (BT) treatment in both years followed by the CT + Bio and CT treatments (Table 4). The no-till (NT) had the greatest runoff in both years (Table 4). Consequently, under BT the runoff was significantly reduced by 45% compared to the CT treatment. The biological (CT + Bio) treatments reduced runoff by 20% respectively compared to CT ($p > 0.05$). The reduced runoff, and greater portion of the rainfall infiltrating, resulted in higher moisture contents as shown in the previous section (Fig. 7).

Table 5 shows the amount of water, S, which can be stored in the soil before the entire plot contributes to runoff, ranged from 60 to 700 mm. Despite the high variability among the five different plots, the storage potential increased on average by 187% under the BT and by 52% in CT + Bio treatments (Fig. 8 and Table 5). As expected, greater storage of water was directly related to a greater reduction in runoff (Tables 5 and 6). BT had the greatest average available storage of 556 mm (Table 5) and the smallest runoff of 33 mm in 2016 and 93 mm in 2017 whilst NT had the smallest storage of 135 mm and the largest runoff of 97 mm in 2016 and 197 mm in 2017.

Similar to the runoff findings, differences in soil loss and sediment concentrations were observed between the treatments in both years (Table 6). Sediment concentrations were greater at the beginning of the rainy season and decreased with time. Average sediment concentrations were highest in the CT (2016: 8.4 g l^{-1}; 2017: 14.4 g l^{-1}) and CT + Bio treatments (2016: 7.9 g l^{-1}; 2017: 14.1 g l^{-1}) compared to the BT (2016: 7.7 g l^{-1}; 2017: 8.9 g l^{-1}) and NT (2016: 6.8 g l^{-1}; 2017: 10.6 g l^{-1}) ($p < 0.05$) (Table 6). Sediment concentrations were higher in 2017 compared to 2016 corresponding to differences observed in the rainfall pattern between both rainy seasons (Fig. 4). As a result, the total soil loss observed in 2017 was 5 to 9 times greater than those observed in 2016. Average total soil loss were highest in the NT (2016: 7 Mg ha^{-1}; 2017: 29 Mg ha^{-1}) and CT treatments (2016: 5 Mg ha^{-1}; 2017: 39 Mg ha^{-1}) followed by CT + Bio (2016: 4.0 Mg ha^{-1}; 2017: 29 Mg ha^{-1}) and BT (2016: 3 Mg ha^{-1}; 2017: 16 Mg ha^{-1}) (Table 4). Soil loss was on average reduced by 40% and 20% (2016) and 58% and 25% (2017) in the BT and CT + Bio treatments compared to the CT treatment ($p < 0.05$), respectively.

Table 5
Estimated potential maximum retention (mm) and corresponding curve numbers CN using the SCS curve number method for each tillage treatment obtained for the five measured fields.

Field code	Storage (mm)				CN			
	CT	NT	BT	CT + Bio	CT	NT	BT	CT + Bio
P1	300	220	650	415	45	53	28	38
P2	80	70	300	160	76	78	45	61
P3	300	200	530	220	45	56	32	53
P4	90	60	600	175	74	81	29	59
P5	200	125	700	500	56	67	26	33
Average	*194*	*135*	*556*	*294*	*59*	*67*	*32*	*49*
St. dev.	*96*	*65*	*140*	*138*	*14*	*11*	*7*	*11*

Key: CT - conventional tillage; NT - no-till; BT - tillage using the *Berken* plough; and CT + Bio to conventional tillage with maize intercropped with tap-rooted pigeon pea.

Sediment-associated nutrient loss corresponded well with both the runoff and soil loss trends observed over both years across the various treatments (Table 6). For both years, the highest sediment-associated nutrient removal for TN, PO_4^{3-} and K^+ was recorded in June, the first month of the rainy season, while the lowest values were observed in September (i.e. the late rainy season). For sediment-associated TN and PO_4^{3-}, a significant difference was observed between BT and the other treatments for most of the months in both 2016 and 2017 ($p < 0.05$) (Table 6). The measured sediment-associated total nitrogen ranged from 1.9 kg ha^{-1} (BT treatment) to 5.7 kg ha^{-1} (NT treatment) in 2016 and from 29.6 kg ha^{-1} (BT treatment) to 68.1 kg ha^{-1} (CT treatment) in 2017. Similarly, sediment-associated phosphorus ranged from 0.02 kg ha^{-1} (BT treatment) to 0.04 kg ha^{-1} (CT & NT treatments) in 2016 and from 0.32 kg ha^{-1} (BT treatment) to 0.81 kg ha^{-1} (CT treatment) in 2017. Sediment-associated potassium varied from 0.73 to 1.59 kg ha^{-1}in 2016 and 5.29 to 13.1 kg ha^{-1} in 2017. Given the large fluctuation in potassium observed between the fields, no significant difference was observed between the treatments in most of the months. On average across both seasons, sediment-associated TN was reduced by 50% (BT) and 15% (CT + Bio) compared to the CT treatment. Likewise, the reduction of sediment-associated $PO_4^{3-}$was decreased by 50% in the BT and 13% in the CT + Bio treatments compared to CT.

3.4. Changes in maize root development and yield

The observed average rooting depth was 41 and 46 cm in BT, 35, and 36 cm in CT + Bio, 28 and 29 cm in CT, and 22 and 25 cm in NT treatments for 2016 and 2017, respectively (Fig. 9). Maize roots penetrated significantly deeper in the BT treatment ($p < 0.05$). Maize roots in the treatment were on average 1.5 times deeper compared to the CT treatment in both years while the CT + Bio treatment was on average 1.2 times greater. The effect on grain yield was less pronounced and varied considerably between the plots for the same treatment. In 2016 average observed grain yield was 6.0 ± 1.7 Mg ha^{-1} (BT), 5.0 ± 2.4 Mg ha^{-1} (CT + Bio), 5.7 ± 1.7 Mg ha^{-1} (CT), and 2.7 ± 0.6 Mg ha^{-1} (NT). Higher yields were observed in 2017 as a result of the spacing adjustments during planting with yields around 8.7 ± 3.8 Mg ha^{-1} (BT), 7.1 ± 3.6 Mg ha^{-1} (CT + Bio), 7.1 ± 3.4 Mg ha^{-1} (CT), and 4.2 ± 1.8 Mg ha^{-1} (NT). Additionally, in the CT + Bio treatments, an average of 0.15 ± 0.02 Mg ha^{-1} (2016), 0.13 ± 0.03 Mg ha^{-1} (2017) pigeon yield was obtained. As a result of the large variation observed between the fields, no significant differences between the CT, BT, and CT + Bio treatments were measured. However, results suggest a 5% (2016) and 23 % (2017) increase in the BT treatment compared to the CT treatment. The NT treatment was significantly lower for both years compared to the three other treatments (Fig. 9).

Table 4
Average and standard error of total runoff (mm) and soil loss (Mg ha^{-1}) observed and predicted in the various treatments for 2016 and 2017.

Treatment	2016				2017			
	Observed runoff (mm)	Observed soil loss (Mg ha^{-1})	Adjusted runoff (mm)	Adjusted soil loss (Mg ha^{-1})	Observed runoff (mm)	Observed soil loss (Mg ha^{-1})	Adjusted runoff (mm)	Adjusted soil loss (Mg ha^{-1})
CT	70 ± 14^{ab}	5 ± 0.8^{b}	72 ± 18^{ab}	9 ± 1.1^{ab}	178 ± 20^{a}	39 ± 6.6^{a}	164 ± 38^{a}	91 ± 21^{a}
NT	97 ± 27^{a}	7 ± 1.1^{a}	98 ± 20^{a}	10 ± 2.0^{a}	197 ± 25^{a}	29 ± 4.4^{b}	210 ± 37^{a}	78 ± 18^{ab}
BT	33 ± 6.2^{c}	3 ± 0.7^{c}	25 ± 4^{c}	4 ± 0.5^{c}	93 ± 15^{c}	16 ± 2.7^{c}	58 ± 12^{b}	25 ± 6^{c}
CT + Bio	46 ± 8b^{c}	4 ± 0.7^{b}	47 ± 9^{bc}	7 ± 1.3^{bc}	148 ± 20^{b}	29 ± 5.1^{ab}	107 ± 21^{b}	63 ± 12^{b}

Key: Different letters across a column depict a significant difference at $p < 0.05$. CT refers to conventional tillage; NT to no-till, BT to tillage using the *Berken* plough and CT + Bio to conventional tillage and maize being intercropped with the tap rooted pigeon pea. Mean with SE followed by a different superscript represent a significant difference ($p < 0.05$) between the treatments within the same year.

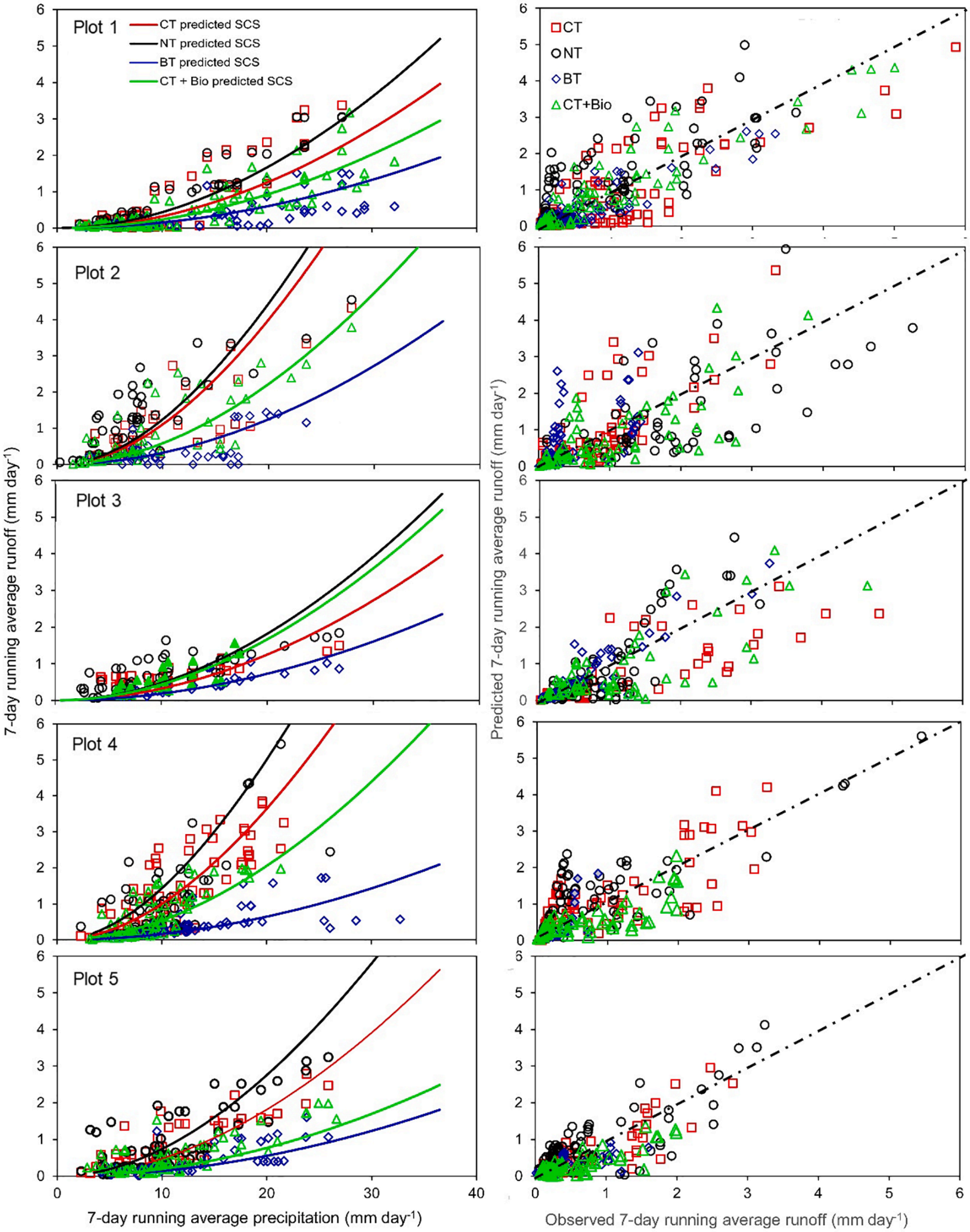

Fig. 8. Left side: the 7-day running averages fitted with the SCS runoff equation for each tillage treatment at plot level for 2016 and 2017. Right side: Scatter plot of 7-day running average measured *vs.* estimated runoff using the SCS runoff equation. The input data for the SCS equation is provided in Appendix A and the abreviations for the treatments in Table 5.

3.5. Economic analysis

The total labor cost for NT was on average 1.1 times higher compared to the CT, CT + Bio, and BT, respectively (Table 7). The higher labor requirements in the NT treatment were predominantly related to increased labor requirements for weeding. Labor for weeding was on average 2 and 4 times higher under NT compared to CT or CT + Bio and BT, respectively. Approximately a 30 % higher labor requirement was found in CT and CT + Bio compared to Berken because because CT and CT + Bio treatments were cross ploughed 5 times requiring more time and therefore higher labor. Revenues from obtained grain and straw yield were highest for the BT and the CT + Bio treatment compared to the NT and CT treatment. Increased revenues for these treatments were related to the higher maize and, in the case of the CT + Bio, pigeon pea yields as well as the significant effect both treatments had on straw yield. Taking into account the investment cost of the tool implement, the

Table 6
Event mean sediment concentration (EMSC) (g l^{-1}) and corresponding mean and standard error of the estimated total and monthly sediment associated TN, PO_4^{3-} and K^+ loss (kg ha^{-1}) per tillage treatment.

Month	Treatment	2016				2017			
		EMSC	TN	PO_4^{3-}	K^+	EMSC	TN	PO_4^{3-}	K^+
July	CT	16.4 ± 6^a	2.50 ± 2.1^a	0.02 ± 0.01^a	0.79 ± 0.2^a	36.3 ± 8^a	46.00 ± 14.6^a	0.63 ± 0.3^a	7.07 ± 5.0^a
	NT	17.8 ± 4^a	3.80 ± 1.8^a	0.02 ± 0.01^a	1.09 ± 0.6^a	29.6 ± 3^{ab}	35.28 ± 18.6^a	0.41 ± 0.2^a	7.39 ± 3.6^a
	BT	19.3 ± 2^a	1.12 ± 0.8^b	0.01 ± 0.01^a	0.50 ± 0.08^a	24.8 ± 8^b	17.24 ± 11.5^b	0.15 ± 0.1^b	2.49 ± 1.4^b
	CT + Bio	20.6 ± 4^a	2.44 ± 1.5^a	0.02 ± 0.01^a	0.68 ± 0.08^a	35.9 ± 4^a	34.95 ± 7.9^a	0.49 ± 0.2^a	11.10 ± 9.8^a
Aug	CT	8.3 ± 3^a	1.11 ± 0.8^a	0.01 ± 0.01^a	0.33 ± 0.03^a	20.4 ± 6^a	20.17 ± 3.6^a	0.14 ± 0.0^a	2.60 ± 1.7^b
	NT	6.3 ± 2^b	1.78 ± 1.2^a	0.01 ± 0.01^a	0.46 ± 0.1^a	13.9 ± 3^b	15.44 ± 6.7^{ab}	0.18 ± 0.1^a	4.10 ± 2.8^a
	BT	6.4 ± 2^b	0.76 ± 0.3^b	0.01 ± 0.00^a	0.21 ± 0.1^a	22.9 ± 9^a	11.98 ± 9.1^b	0.09 ± 0.1^b	1.87 ± 1.5^b
	CT + Bio	7.9 ± 3^a	0.68 ± 0.2^b	0.01 ± 0.01^a	0.25 ± 0.1^a	19.1 ± 7^a	22.07 ± 8.8^a	0.16 ± 0.1^a	2.79 ± 2.7^b
Sept	CT	5.5 ± 3.4^a	0.12 ± 0.1^a	$<0.01^a$	0.06 ± 0.01^a	6.8 ± 4^a	1.99 ± 1.3^a	0.012 ± 0.0^a	0.20 ± 0.1^a
	NT	3.4 ± 1.2^a	0.15 ± 0.1^a	$<0.01^a$	0.04 ± 0.0^a	0.9 ± 0.8^b	0.52 ± 0.6^{ab}	0.002 ± 0.0^b	0.04 ± 0.1^a
	BT	3.8 ± 1.2^a	0.05 ± 0.0^a	$<0.01^a$	0.02 ± 0.0^a	9.3 ± 6.5^a	0.35 ± 0.1^b	0.002 ± 0.0^b	0.06 ± 0.0^a
	CT + Bio	2.9 ± 1.9^b	0.09 ± 0.1^a	$<0.01^a$	0.01 ± 0.0^a	8.1 ± 5.8^a	1.22 ± 1.1^a	0.011 ± 0.0^a	0.25 ± 0.3^a
Total	CT		3.72 ± 2.9^a	0.04 ± 0.02^a	1.18 ± 0.4^a		68.10 ± 19^a	0.81 ± 0.3^a	11.23 ± 8^a
	NT		5.73 ± 3.1^a	0.04 ± 0.16^a	1.59 ± 0.9^a		51.25 ± 25^a	0.50 ± 0.3^{ab}	9.52 ± 6^a
	BT		1.93 ± 1.1^b	0.02 ± 0.01^a	0.73 ± 0.2^a		29.58 ± 20^b	0.32 ± 0.1^b	5.29 ± 4^b
	CT + Bio		3.17 ± 1.7^a	0.03 ± 0.01^a	0.94 ± 0.6^a		58.23 ± 17^a	0.69 ± 0.4^a	13.07 ± 11^a

Key: CT - conventional tillage; NT - no-till; BT - *Berken* plough; and CT + Bio - conventional tillage with maize intercropped with tap rooted pigeon pea. Different superscripts for a particular nutrient across a month depict a significant difference between treatments at $p < 0.05$ within the same year.

average net benefit from 2016 and 2017 was negative except for the BT treatment (138 USD ha^{-1}) (Table 7). The negative net benefit was mainly related to the high labor cost related to plowing, weeding, planting, and fertilizer application.

4. Discussion

4.1. Effect of Berken plow and pigeon pea intercropping on hydrological responses

The positive effect of the *Berken* plow on soil penetration throughout the soil profile (Fig. 5) resulted in an improvement of the rate of infiltration (Fig. 6), reduction in runoff and soil loss (Table 4). The available storage for rainfall in the soil simulated using the SCS-CN method showed a significant increase in storage under BT and CT + Bio treatment compared to those under CT and NT (Fig. 8, Table 5). These results suggest that the pore space increased under the BT treatment, possibly creating continuity in pore space between the cultivated surface and the subsurface layer of the soil. The *Berken* plow forms U-shaped furrows, increasing infiltration, root growth (ISD, 2015) whilst the use of the *Maresha* plow forms V-shaped furrows, leaving a non-plowed strip of land between adjacent passes, results in higher runoff and loss of soil organic carbon (Temesgen et al., 2007; Gebreegziabher et al., 2009; Araya et al., 2015). Additionally, tillage with the *Berken* implement (BT) was deeper and therefore created a greater reservoir resulting in greater soil moisture in the soil profile than treatments conventionally tilled or not tilled (Fig. 7). Penetration resistance at 40 and 60 cm increased throughout the season for all treatments. Results suggested that despite increasing the pore space at the onset of the season by the *Berken* plow the sediment-rich infiltrating water silts up the pores in the soil during the rainy season.

The reduction in runoff when farmers used the *Berken* plow corresponded well to the observed positive effects of the plow on tillage depth, penetration resistance, increase in storage and infiltration rates. Additionally, the presence of invisible barriers along the contour, in the Berken plowed system, retards the movement of generated runoff water. The effect of the BT treatment on storage varied as a result of plot location within the watershed and soil profile characteristics. As plot 2, is located at the bottom part of the watershed (Fig. 1), the soil profile becomes saturated as the rainy season progresses, resulting in a significant decrease in available storage compared to the other plots. Similarly, plot 4 has a limited storage potential due to its limited soil depth of 0.8 m. The effect of the intercropped tap-rooted pigeon pea in CT + Bio treatment on storage was less pronounced compared to the *Berken plow.* In plots 1, 4, and 5, results suggest that the pigeon pea roots were able to penetrate the hardpan and increase infiltration of the rainfall water, resulting in a significant runoff reduction compared to the NT and CT treatments. Results suggest that for larger rainfall events the biological and mechanical treatments would behave similarly to the CT and NT treatments. However, longer term ploughing with the *Berken* plough could move the restrictive plough layer downwards over time. Longer trials are needed to understands whether the positive effects on soil water retention will remain over time.

Sediment concentrations and hence associated nutrient removal were greatest at the onset of the rainy season and decreased throughout the rainy season for all treatments (Table 6). Higher runoff volumes and soil loss were observed at the onset of the season. This is related to the increase in crop cover, dissipating the raindrop energy, and decreasing the rainwater velocity as the season progresses. Similarly, Tilahun et al. (2015) and Bayabil et al. (2017) pointed out that at the beginning of the rainy phase transport limiting capacity was higher while source limiting was seen at the end of the rainy phase. Contour and deep plowing in the BT treatment increase the storage of rainfall in the soils and thereby retards the amount of runoff and the transportation of soil material. Furthermore, the intercropping with pigeon pea in the CT + Bio treatment resulted in a thicker canopy cover reducing rainfall energy and

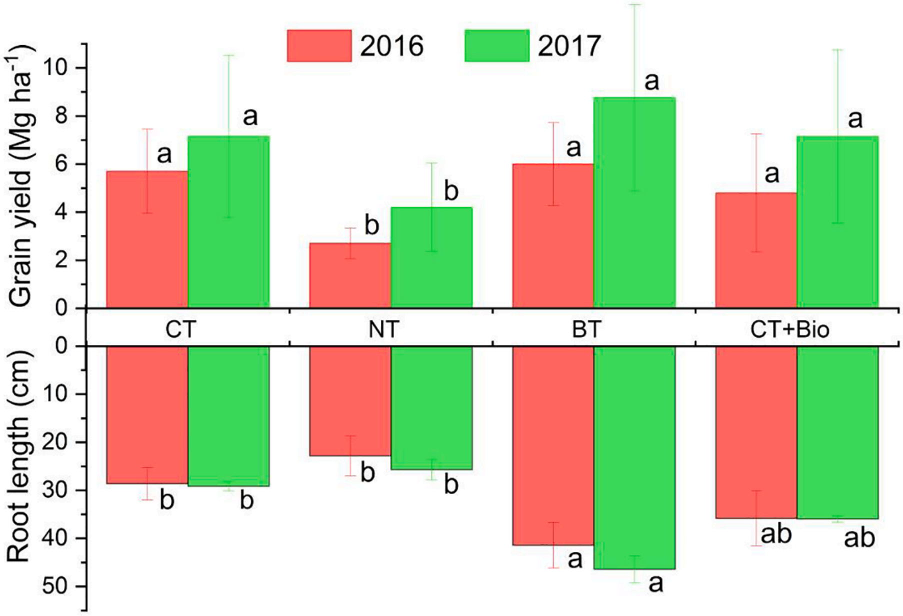

Fig. 9. Average and standard error of maize grain yield (Mg ha^{-1}) and rooting depth (cm) for both years across the various treatments (n = 15 for each treatment and year). (CT - conventional tillage; NT - no-till; BT - *Berken* plow; and CT + Bio conventional tillage with maize intercropped with tap-rooted pigeon pea). The bars with different letters represent a significant difference in grain yield or rooting depth between the treatments within a year ($p < 0.05$).

therefore soil loss (Tables 5 and 7).

As a result, total soil loss and associated nutrient removal were lowest in the BT followed by the CT + Bio treatment. Total soil loss for all treatments except CT for 2017 did not exceed the normal soil loss tolerance limit (40 Mg ha^{-1} yr^{-1}) for Ethiopian conditions (Ayele et al., 2016) and (Araya et al., 2016). Results on measured sediment-associated nutrients removal in 2017 are in line with the findings of Ayele et al., (2015) at the watershed scale who estimated a loss of 78 kg TN ha^{-1} yr^{-1} and 1.93 kg PO_4^{3-} ha^{-1} yr^{-1}. The average nutrient depletion in the topsoil for 2017 was significantly greater than those obtained in 2016 as a result of the significant greater rainfall in the 2017 rain season. Trends in both years suggest that the reduction in soil loss in both the BT and CT + Bio treatments resulted in the preservation of sediment-associated nutrients in the topsoil.

4.2. *Effect of Berken plow and pigeon pea intercropping on maize production and economic benefits for smallholder farmers*

While zero tillage is promoted as part of conservation agriculture, the results of this study suggest that no-tillage on soils with a restrictive hard pan could further decline the already low yields obtained in the CT treatment by 40%. A ten-year experiment Videnović et al., (2011) showed that the long term effect of no-till decreases the maize grain yield from 5 Mg ha^{-1} in 1999 to 1.8 Mg ha^{-1} in 2008.

Average maize yields obtained in this study under the BT (7.4 Mg ha^{-1}), CT + Bio (6.0 Mg ha^{-1}), and CT (6.4 Mg ha^{-1}) were greater compared to the national averages of 3.5 Mg ha^{-1} reported by Logan & Yeshtila (2018), 2.2 Mg ha^{-1} by van Ittersum et al. (2016); ten Berge et al. (2019). However, the potential increases in maize yield in 2017, following the BT and CT + Bio treatment, suggest that the use of *Berken* plow and the intercropping with pigeon pea could provide several benefits to the mixed-crop livestock system of smallholder farmers and contribute to closing the estimated yield gap of 5–9 Mg ha^{-1} (van Ittersum et al., 2016).

The increase in soil moisture below 20 cm and deeper root zone (Fig. 7) in both treatments suggests that maize was able to access soil moisture at deeper soil horizons compared to the CT and NT treatments. Furthermore, the ability of pigeon pea to penetrate the hardpan in the CT + Bio treatment, likely facilitate soil moisture availability for maize through its mycorrhizal network (Singh et al., 2019). The increase in soil moisture has likely postitively affected grain yield under variable rainfall patterns (Magombeyi et al., 2018). Furthermore, given the low nitrogen content in the soil and nitrogen remaining one of the most important attributes in the resource-related yield gap (Silva et al., 2019; ten Berge et al., 2019), intercropping of maize with an N-fixing deep taprooted plant like pigeon pea could further support sustainable intensification of rainfed maize.

Overall, results showed that without mechanization and labor reducing implements, rainfed maize cultivation does not break even necessarily. In traditional maize systems, labor associated with conventional tillage, is often carried out by men and provided by the household, and very demanding as fields are often tilled 5 times or more. However, as this is family labor, it often is not included into profitability analysis of rainfed maize systems. Reduction in labor costs for the BT

Table 7
Estimated costs, revenue and net benefit per treatment across 2016 and 2017 (USD ha^{-1}).

Treatment	Costs ($ ha^{-1})			Revenue ($ ha^{-1})*			Net benefit ($ ha^{-1})
	Seed + fertilizer	Tool	Labor	Total nutrient loss	Grain yield	Straw	
CT	591	3	1,339	2	1,327	427	−181
NT	591	–	1,510	1	878	313	−911
BT	591	10	1,373	1	1,526	587	138
CT + Bio	600	3	1,460	2	1,336	413	−316

*Estimated cost to replace N, P and K were calculated using respective fertilizer costs of urea, DAP and blended fertilizer.

treatment together with the higher maize yield and residual biomass resulted in a positive net benefit compared to the other treatments. Investing in a *Berken* plow is a relatively low-cost option for smallholder farmers with an investment cost of 10 USD which is 7 USD higher than the *Maresha* plow. The estimated net benefit suggests that investment in a *Berken* plow is an economically viable solution for smallholder farmers to safeguard their degrading fields under a changing climate. However, there is a need to increase farmer's awareness on the existence of the plow.

The benefits of combining the *Berken* plow with intercropping pigeon pea is likely to further benefit the mixed-crop livestock smallholder systems where livestock production contributes to 80% of the farm income. The higher residual biomass, obtained in the BT and CT + Bio treatment, together with the pigeon pea yield, provides additional nutritious feed opportunities for smallholder mixed crop-livestock systems. With increasing pressure on pasture as a result of agricultural intensification and population growth, continuous supply of high quality and nutritious feed has been a challenge (ILRI, 2009; SAC, 2015). Furthermore, the reduction in N, P and K losses following both interventions further support sustainable agricultural intensification. Van Beek et al. (2016) estimated that the current yearly depletion rate due to erosion in the Ethiopian highlands is 0.2% of the soil total N stock. Reducing macronutrient losses together with increasing soil organic matter and N availability through N-fixation (Smith et al., 2016) could reduce the inorganic fertilizer requirement of urea and DAP in the long term, further increasing the profitability and sustainability of smallholder maize-livestock systems.

5. Conclusion

Latest research has shown that sub-Saharan Africa would be able to meet its growing maize demand by 2050 without the need to increase agricultural land. However, this would require significant efforts in closing the current existing yield gaps by tackling the challenges of land degradation, dry spells as a result of higher rainfall variability, low fertilizer use efficiencies as well as labor constraint amongst others. In areas such as the north-central highlands of Ethiopia, this translates into addressing the low productivity of the highly degraded uplands where a hardpan prevails because of repeated cross plowing. This study demonstrated that using the locally adapted *Berken* plow and intercropping of maize with pigeon pea for two years in a row could reduce erosion processes, increase root zone soil moisture, and maize production. However, longer term trials are needed to validate the findings of the *Berken* plow and verify that repeated use of the plow does not translate into a new hard pan formation at about 30 cm depth.

Based on the economic analysis, the low cost Berken plow provided an economically feasible solution to smallholder farmers to combat soil degradation, whilst sustainably improving rainfed production of maize and supporting the mixed crop-livestock system. Following this study, over 1000 farmers invested in a *Berken* plow after a farmers exchange event organized by the Innovation Laboratory for Small Scale Irrigation (ILSSI) project and extension agents. In areas with increasing variability of rainfall, scaling of these tested solutions could provide a buffer during dry spells making the mixed crop-livestock systems more resilient in degraded areas under a changing climate.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2021.115523.

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