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EFFECT OF *IN SITU* WATER HARVESTING TECHNIQUES ON SOIL AND NUTRIENT LOSSES IN SEMI-ARID NORTHERN ETHIOPIA

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ABSTRACT

Land degradation, mainly due to soil erosion and nutrient losses, is a global problem for sustainable agriculture. Farmlands in the Ethiopian highlands are susceptible to water erosion because of steep slopes and extensive cultivation. A field experiment was conducted in the Gule sub-watershed in northern Ethiopia to assess the efficacy of *in situ* water harvesting techniques in reducing soil and nutrient losses. The research was carried out on a sandy clay loam soil under semi-arid conditions. Soil erosion and nutrient losses were monitored during the rainy season (June to September) in 2013 and 2014. Five treatments with tied ridges, wheat-straw mulch and effective microorganisms, alone or in combination, and an untreated control were tested. Combined tied ridges and straw mulch, with and without effective microorganisms, significantly reduced average soil loss over the two rainy seasons by 82 and 90% respectively compared with the control. Tied ridges alone reduced average soil loss by 60%. Straw mulch with and without effective microorganisms decreased average soil loss by 81 and 85% respectively. Combined tied ridges and straw mulch significantly decreased average total nitrogen and total phosphorus losses by 82 and 83% respectively. Average nutrient losses were also significantly decreased by tied ridges (59% for nitrogen, 52% for phosphorus) and straw mulch (63% for nitrogen, 68% for phosphorus). Our results indicated that *in situ* water harvesting techniques can effectively reduce soil and nutrient losses from farmland and were more efficient when the techniques were combined. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS: water harvesting techniques; tied ridges; straw mulch; soil loss; nutrient loss

INTRODUCTION

Land degradation is considered as the main global problem preventing future sustainable agricultural production (Zougmoré *et al.*, 2009). Accordingly, soil erosion is a serious problem due to its severe impacts on agricultural productivity, ecosystem services and environmental balances (Panagos *et al.*, 2015). Soil loss from farmland is aggravated by inappropriate soil management and tillage practices and the absence of erosion control measures (Cerdà *et al.*, 2009; Rodrigo Comino *et al.*, 2015; Prosdocimi *et al.*, 2016a).

Farmlands in the Ethiopian highlands are often located on steep slopes and are extensively cultivated; therefore, they are highly susceptible to water erosion in the rainy seasons (Damene *et al.*, 2013; Taddese, 2001; Teshome *et al.*, 2013). Moreover, a farmer's decision to invest on sustainable land management practices is highly constrained by existing land quality, land fragmentation and land tenure systems (Teshome *et al.*, 2016). Soil loss in the Ethiopian highlands is reported to be around 1·9 billion $Mg\,y^{-1}$ and 80% of the loss comes from cultivated areas (FAO, 1986). Land degradation, mainly by water erosion, is a primary cause of low and declining soil productivity in Ethiopia (Araya *et al.*, 2011). Water erosion causes the removal of soil from farmland, which results in the loss of valuable plant nutrients with the eroded soil (Kraaijvanger & Veldkamp, 2015; Taddese, 2001).

Land degradation in the Tigray region of northern Ethiopia became so critical that it hampered agricultural productivity, so the government and others endeavoured to rehabilitate the land by using soil and water conservation measures (Nyssen *et al.*, 2015; Vancampenhout *et al.*, 2006; Walraevens *et al.*, 2015), mainly stone bunds and area exclosures (Descheemaeker *et al.*, 2006; Desta *et al.*, 2005; Nyssen *et al.*, 2007). According to Desta *et al.* (2005), stone bunds reduced annual soil losses from sheet and rill erosion by 68%. Runoff, however, spilt over these structures because *in situ* water harvesting techniques (WHTs) were rarely used in the agricultural fields (Gebreegziabher *et al.*, 2009). A new paradigm of soil conservation and land rehabilitation by *in situ* soil and water management is therefore needed (Nyssen *et al.*, 2009).

In situ WHTs enhance the collection of rainwater on the surface where it falls and store it in the soil layer (Helmreich & Horn, 2009). The most widely used *in situ* WHTs are tied ridges, mulching, conservation tillage and various furrow systems (Biazin *et al.*, 2012).

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Some studies in Tigray and other parts of Ethiopia have focused on the role of conservation agriculture (e.g. contour furrows, conservation tillage, *terwah* and *derdero*) in reducing soil loss from farmland (Araya *et al.*, 2011; Gebreegziabher *et al.*, 2009; McHugh *et al.*, 2007). The effect of different soil management practices on soil erosion has also been studied in other parts of the world (Adekalu *et al.*, 2007; Fernández & Vega, 2016; Mekonnen *et al.*, 2015; Mwango *et al.*, 2015; Prosdocimi *et al.*, 2016b). *In situ* WHTs have been applied in a variety of climates and landscapes, mainly to improve on-site soil–water regimes and to reduce soil and nutrient losses in runoff (Adimassu *et al.*, 2014; Al-Seekh & Mohammad, 2009; Okeyo *et al.*, 2014).

The effects of combining different measures of soil management, such as crop-residue mulching with organic amendments (Baptista *et al.*, 2015), runoff barriers with nutrient management (Zougmoré *et al.*, 2009) and tillage with mulching (Donjadee & Tingsanchali, 2016; Jin *et al.*, 2008), on soil and/or associated nutrient losses have been studied. Other researchers also investigated the effect of combined use of rice-straw compost with phosphogypsum (Mahmoud & Abd El-Kader, 2015) and crushed maize-straw residue with urea (Tejada & Benítez, 2014) on improving soil chemical and biological properties. Little information, however, is available on the effect of combining *in situ* WHTs such as tied ridges and straw mulch on the reduction of soil and nutrient losses from farmland. Combining different *in situ* WHTs helps to reduce runoff, soil and associated nutrient losses (Baptista *et al.*, 2015). Integrating WHTs with nutrient management can also help to ensure higher and more sustainable agricultural productivity (Miriti *et al.*, 2007). For example, the application of biofertilizers such as effective microorganisms (EMs) to the soil enhances the physical properties of the soil such as infiltration rate and water-holding capacity (Ismail, 2013).

Therefore, the aims of this study were (i) to assess the effect of *in situ* WHTs on soil and nutrient losses and maize yield and (ii) to evaluate the efficacy of combining *in situ* WHTs (straw mulch, tied ridges and EMs) for controlling soil erosion.

MATERIALS AND METHODS

Description of the Study Area

The study was conducted at a farmer-training centre in the Gule sub-watershed of the upper Geba catchment in northern Ethiopia (13°52′49″N, 39°28′59″E; Figure 1). The sub-watershed has a rugged topography with mountains and flat valley floors and with altitudes ranging between 2008 and 2408 m a.s.l. It has a semi-arid climate, with two major seasons: a rainy and a dry season. The rainy season is often from June to September, and the dry season is from October to May (Nyssen *et al.*, 2010). Rainfall

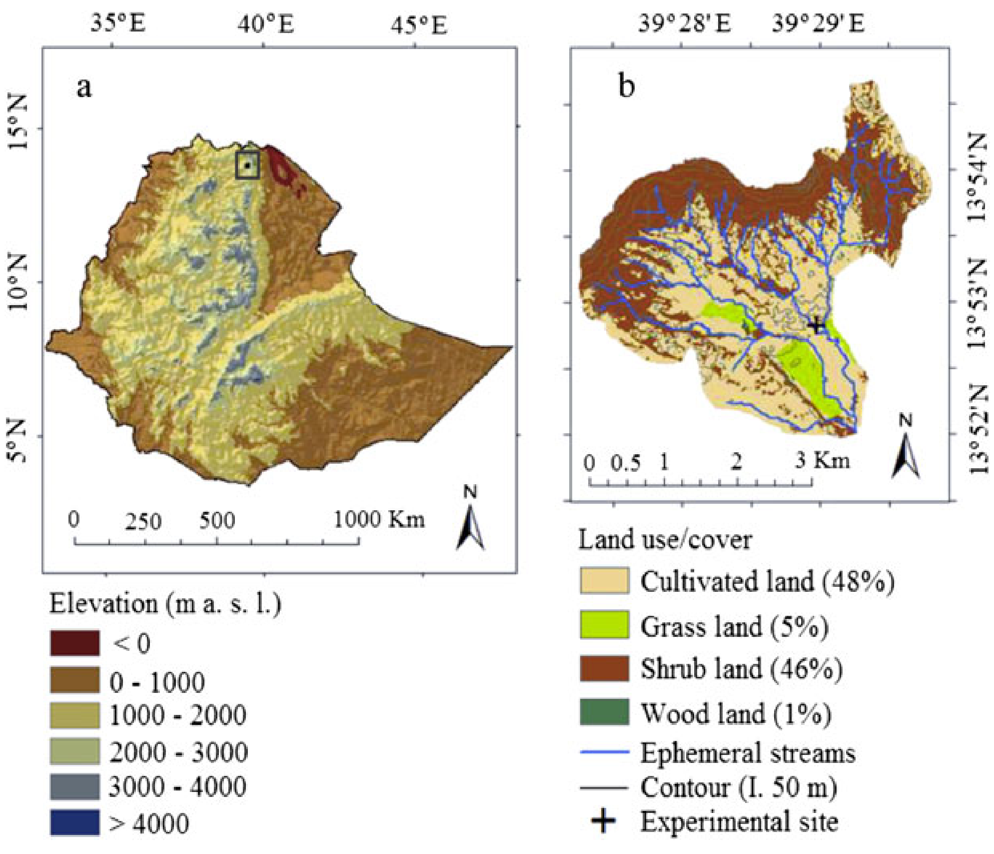

Figure 1. Location of the study area. (a) Topography of Ethiopia. (b) Land use of the Gule sub-watershed and location of the experimental site. [Colour figure can be viewed at wileyonlinelibrary.com]

measurements of three successive years (2013–2015) using a meteorological station that was installed for the purpose of this study showed an average annual rainfall of 465 mm. The temperature is relatively constant throughout the year. Average daily temperature ranges between 15 and 25 °C, with a mean of 20 °C. The study area was selected based on a set of criteria established during a stakeholders' workshop for selecting WHTs (Grum *et al.*, 2016). The experimental site was on the flat valley floor of the sub-watershed at a mean altitude of 2050 m a.s.l. The site had a total area of 1750 m^2, and slopes ranged between 1·8 and 3·4%. The experiment was conducted on a Eutric Cambisol soil type (IUSS Working Group WRB, 2015) with a sandy clay loam texture.

Experimental Design

The experiment was carried out for two successive rainy seasons (June to September) in 2013 and 2014. The experiment had a completely randomized block design consisting of five treatments and a control. The treatments were selected by stakeholders in a participatory WHT selection workshop (Grum *et al.*, 2016). Each treatment had three replicates with plot size of 3 × 15 m, for a total of 18 plots (Figure 2). The treatments and the application of measures are described in Table I.

The experimental field was ploughed twice by oxen-driven *maresha* a month and a week before sowing. The experimental plots were then established by hand. Each plot was isolated by earth bunds 50 cm wide and 40 cm high to prevent the flow of water from neighbouring plots and to provide access to the plots during inspection.

A basal fertilizer was applied to the entire field (all plots) at rates of 64 kg ha^{-1} nitrogen (N) and 46 kg ha^{-1} phosphorus (P) in the form of inorganic fertilizers (urea and diammonium phosphate). These rates of fertilization are blanket recommendations and commonly applied rates in the region (Araya & Stroosnijder, 2010). Wheat-straw mulch was applied for T2–T5 at a rate of 15 Mg ha^{-1}. Wheat straw (*Triticum aestivum L.*), typically used for feedstocks, consists of cellulose (35%), hemicellulose (25%) and lignin (19%; Windeatt *et al.*, 2014). Wheat straw contains 0·6% N (Nicholson *et al.*, 1997; Smil, 1999) and 0·1% P (Smil, 1999). The nutrient inputs from the straw mulch for T2–T5 were thus 90 kg N ha^{-1} and 15 kg P ha^{-1}.

The crop used in the experiment was maize (*Zea mays L.*). Maize seeds were planted in each plot in rows with 30 cm between plants and 60 cm between rows in plots without tied ridges and 70 cm between rows in plots with ridges. Tied ridges for T1, T3 and T5 were established after maize had fully germinated and emerged. The ridges were 20 cm high, 3 m long and 1·9 m apart and were tied in the middle. Each plot with tied ridges therefore had seven tied ridges in the rows (Figure 2). All plots were manually hoed, and weeds were removed 1 and 2 months after planting. Dry wheat-straw mulch was spread onto the soil surface in T2–T5 at a rate of 15 Mg ha^{-1} after the maize had fully germinated and emerged. A diluted solution (1:500) of activated EMs (EMRO, Okinawa, Japan) was also sprayed onto the soil

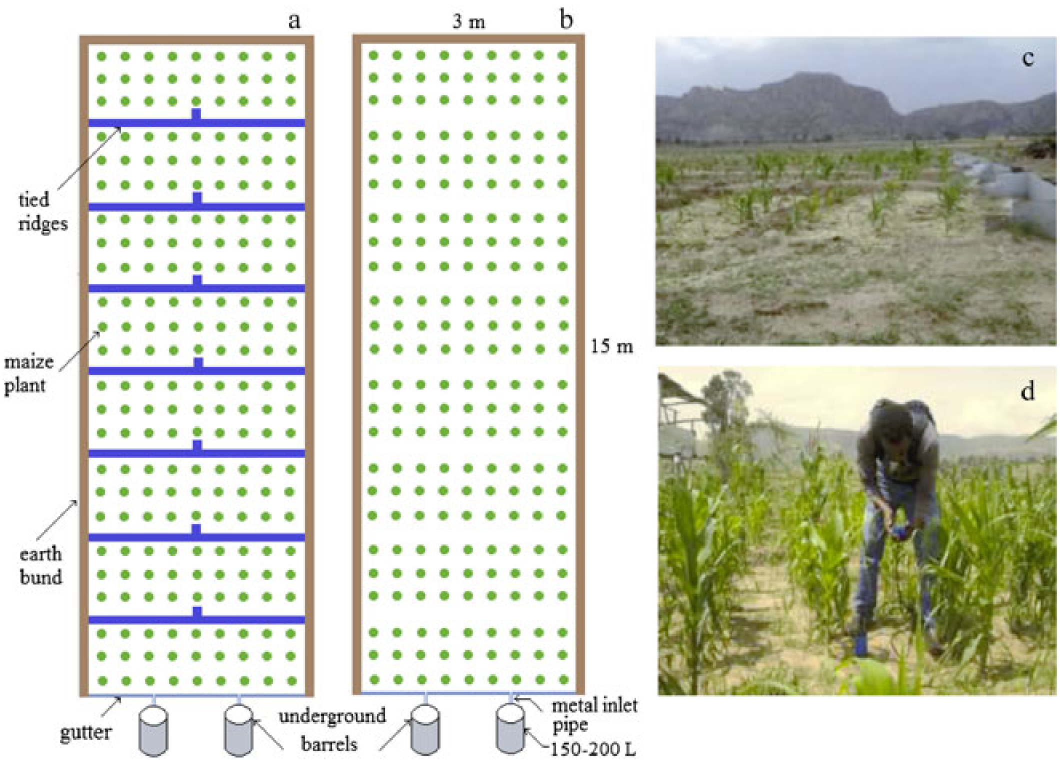

Figure 2. Layout of the experimental runoff plots. (a) Experiment plots with tied ridges (T1, T3 and T5). (b) Experiment plots without tied ridges (T0, T2 and T4). (c) Photograph of the field layout with treatments. (d) Soil-moisture measurement by using Trime-PICO64 soil-moisture sensor. [Colour figure can be viewed at wileyonlinelibrary.com]

Table I. Description of the treatments in the field experiment

Treatment	Description
T0 (control)	Basal fertilization[a]
T1	Basal fertilization + tied ridges
T2	Basal fertilization + straw mulch (15 Mg ha^{-1})
T3	Basal fertilization + straw mulch (15 Mg ha^{-1}) and tied ridges
T4	Basal fertilization + straw mulch (15 Mg ha^{-1}) and 4 L ha^{-1} of EMs
T5	Basal fertilization + straw mulch (15 Mg ha^{-1}), tied ridges and 4 L ha^{-1} of EMs

[a]Basal fertilization: 100 kg ha^{-1} urea (46% N) and 100 kg ha^{-1} diammonium phosphate (18% N, 46% P) applied to the entire field experiment. EMs, effective microorganisms.

surface in T4 and T5. The EMs consisted of a selected group of microorganisms, predominantly lactic acid bacteria, yeast and phototrophic bacteria. The activated EMs were prepared 1 week before sowing at a ratio of 2:96:2 of molasses, rainwater and inactivated EMs respectively. The EMs were applied twice, at sowing and mid of the growing season (early August), at a rate of 4 L ha^{-1}.

Eroded soil exported with the runoff after each rain was collected in 300–400 L of subsurface barrels buried at the end of each plot. The exported soil with runoff was channelled from the plots by a corrugated iron gutter placed directly above the barrels and was then directed into the barrels by a metal inlet pipe (Figure 2).

Data Collection and Measurements

Composite soil samples were collected to a depth of 20 cm before the beginning of the rainy season in 2013 and 2014 for characterizing the physical and chemical properties (Table II). Soil samples were also collected by using ergonomic hand auger (Eijkelkamp, Giesbeek, the Netherlands) from three sampling points in each plot at the end of the experimental period to depths of 20 and 40 cm for the analysis of pH, soil organic carbon content and nutrient (N and P) contents.

Soil texture was determined by the hydrometer method, bulk density by the core method (Blake & Hartge, 1986) and pH by potentiometry. Soil organic carbon content was analysed by the Walkley Black method (Nelson & Sommers, 1982), total N (TN) content by the Kjeldahl method (Jackson, 1958), total P (TP) and available P content by the Olsen method (Olsen & Sommers, 1982).

Rainfall was measured by using tipping-bucket data-logging RG3-M HOBO (precision: 0·2 mm/tip) rain gauge (Onset, Bourne, MA, USA) installed at the site. Soil-moisture content (SMC) was monitored daily by using a Trime-PICO64 (time-domain reflectometer or TDR method) soil-moisture sensor (Eijkelkamp, Giesbeek, the Netherlands) to a depth of 15 cm at six sampling points in each plot in 2013 and 2014.

Table II. Selected initial soil properties at the experimental site

Properties	Mean ± SD
Soil texture	—
0·063–2 mm, sand (%)	64·6 ± 4·7
0·002–0·063 mm, silt (%)	12·6 ± 3·5
<0·002 mm, clay (%)	22·8 ± 1·9
Bulk density (g cm^{-3})	1·6 ± 0·0
pH (H_2O)	6·8 ± 0·2
Soil organic carbon (g kg^{-1})	4·7 ± 1·9
Total nitrogen (mg kg^{-1})	4·4 ± 2·0
Available phosphorus (mg kg^{-1})	8·2 ± 2·1

Runoff volume per plot was measured after each rainfall event. An aliquot of 1 L was collected from each barrel after thoroughly stirring the collected runoff. The aliquot was used to analyse sediment concentration, soil and nutrient losses in the eroded soil in 2013 and 2014. Each water sample was first filtered through a Whatman Grade 42 filter paper by gravity, and the sediment residue on the filter paper was then dried at room temperature. The dried residue was weighed to determine the sediment concentration in the runoff and the total amount of eroded soil per plot. The loss of nutrients (N and P) was determined from only five of the runoff events distributed over each experimental year due to the expense of the analyses.

Data Analysis

Statistical analysis was performed by using SPSS 22 (IBM Corporation, New York, USA). Normally distributed data were analysed by using a least squares one-way analysis of variance. The data that were not normally distributed were analysed by using non-parametric tests for statistical differences. Significant difference between treatments for a measured variable was tested by using the pairwise Mann–Whitney *U*-test. All statistical tests were considered significant at a probability value of 0·05 ($p < 0{\cdot}05$).

The fraction of exported nutrients in eroded soils per runoff event for each treatment was calculated by:

$$\text{Fraction of nutrient loss } (\%) = \frac{\text{Nutrient loss in eroded soil}}{\text{Nutrient input}} \times 100 \quad (1)$$

Soil/nutrient loss reduction per runoff event of a treatment relative to the control was calculated by:

$$R\ (\%) = \frac{O_c - O_t}{O_c} \times 100 \quad (2)$$

Where: R is the reduction in soil/nutrient loss by a treatment relative to the control (%), O_c is the measured soil (kg ha^{-1})

Table III. Average runoff and soil, total N and total P losses per event over two seasons (2013 and 2014)

Treatment	Runoff (mm) Median (min, max) ($n = 84$)	Soil loss (kg ha^{-1}) Median (min, max) ($n = 84$)	Seasonal soil loss (Mg ha^{-1})^{a} Median (min, max) ($n = 3$)	Total N loss (g ha^{-1}) Median (min, max) ($n = 30$)	Total P loss (g ha^{-1}) Median (min, max) ($n = 30$)
T0	4·7 (0·3, 11·2)^{d}	90·6 (2·3, 865·1)^{c}	4·3 (3·6, 4·7)^{d}	364·1 (36·2, 1731·3)^{c}	259·2 (14·2, 746·9)^{c}
T1	2·0 (0·2, 9·2)^{c}	36·4 (2·0, 529·8)^{b}	2·1 (1·7, 2·2)^{c}	134·3 (8·4, 996·2)^{b}	96·7 (3·1, 393·1)^{b}
T2	0·9 (0·2, 8·9)^{b}	16·8 (0·7, 373·6)^{a}	1·0 (0·5, 1·3)^{ab}	154·7 (5·3, 977·9)^{b}	95·1 (1·8, 313·0)^{b}
T3	0·6 (0·1, 8·8)^{a}	8·3 (0·5, 306·4)^{a}	0·8 (0·7, 0·9)^{a}	42·6 (1·3, 1019·5)^{a}	20·0 (1·0, 301·2)^{a}
T4	1·0 (0·2, 8·8)^{b}	10·9 (0·8, 437·5)^{a}	1·3 (1·2, 1·4)^{b}	208·9 (1·9, 1230·8)^{b}	104·6 (0·9, 399·6)^{b}
T5	0·9 (0·1, 8·6)^{b}	11·7 (0·4, 388·1)^{a}	0·8 (0·8, 1·4)^{ab}	98·8 (0·8, 613·2)^{ab}	62·8 (0·3, 451·4)^{ab}

Different letters show significant (Mann–Whitney *U*-test, $p < 0·05$) difference between treatments, a < b < c < d.
[a]Seasonal soil loss was computed from runoff events in 2014. T0, control; T1, tied ridges; T2, straw mulch; T3, tied ridges + straw mulch; T4, straw mulch + EMs; T5, tied ridges + straw mulch + EMs.

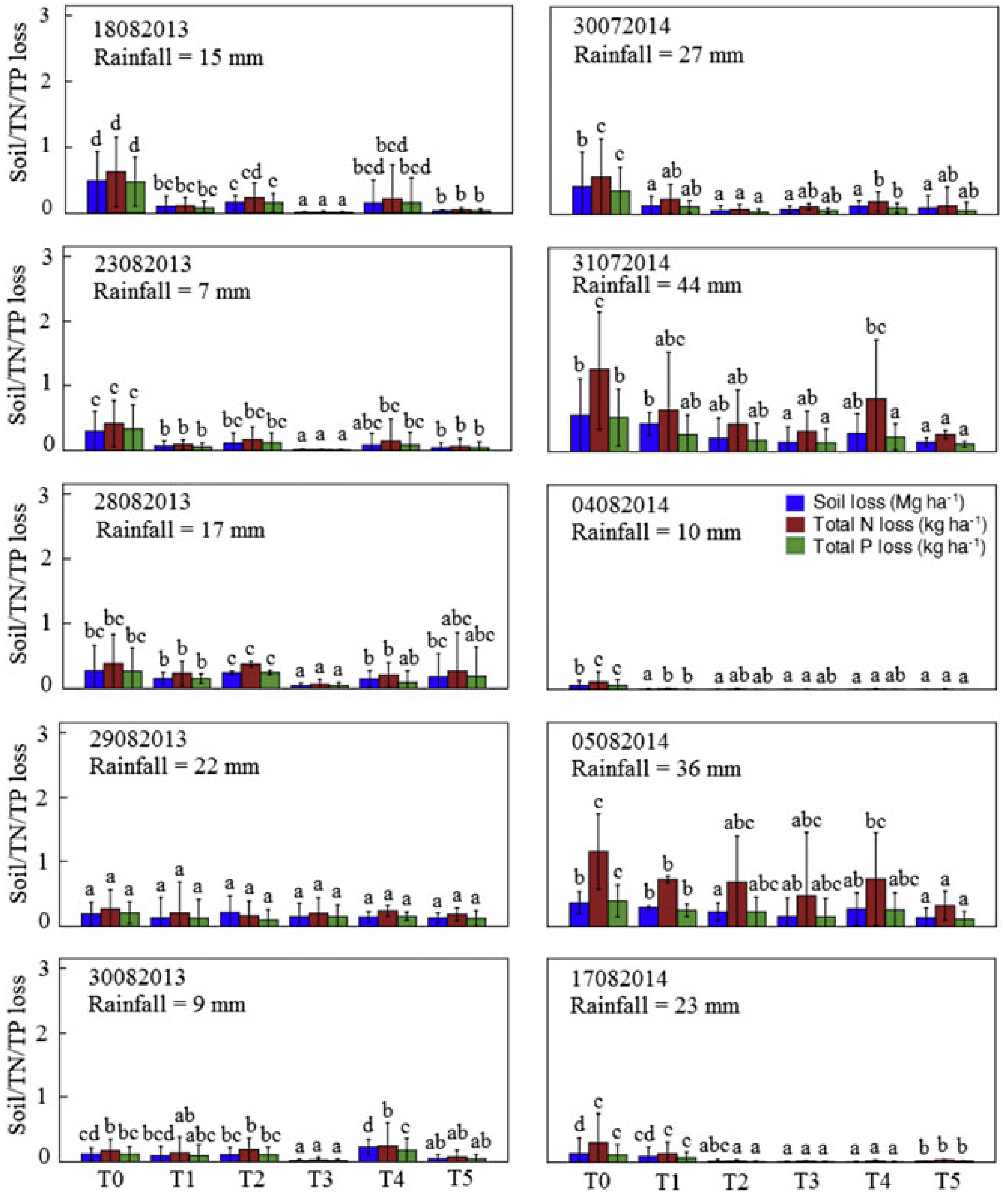

Figure 3. Soil, total N and total P losses per event for different treatments ($n = 3$). Different letters show significant (Mann–Whitney *U*-test, $p < 0·05$) difference between treatments, a < b < c < d. Error bars are standard deviations. T0, control; T1, tied ridges; T2, straw mulch; T3, tied ridges + straw mulch; T4, straw mulch + EMs; T5, tied ridges + straw mulch + EMs. [Colour figure can be viewed at wileyonlinelibrary.com]

or nutrient (g ha^{-1}) loss in the control, and O_t is the measured soil (kg ha^{-1}) or nutrient (g ha^{-1}) loss in a treatment.

Principal component analysis (PCA) was carried out to identify the factors affecting the soil and nutrient losses by using averaged data per treatment and the control for 2013 and 2014 ($n = 36$). The PCA tested seven variables: runoff, soil loss, TN loss, TP loss, SMC, bulk density and plot slope. Correlations between variables were analysed by using Spearman's rank correlation at a significance level of 0·01 ($p < 0·01$). Regression analyses were performed between soil loss and runoff and between nutrient loss and soil loss. The regression analyses were carried out separately for the control (T0) and the *in situ* WHTs (T1–T5).

RESULTS

Effect of the Treatments on Soil and Associated Nutrient Losses

The effects of treatments on runoff, soil and nutrients losses are summarized in Table III.

Runoff was significantly lower in T1–T5 than in T0. Median runoff was lowest and highest in T3 (0·6 mm) and T0 (4·7 mm) respectively.

Soil loss per event was significantly lower in all WHTs than the control. Median soil loss was highest in T0 at 90·6 kg ha^{-1} and lowest in T3 at 8·3 kg ha^{-1}. Median soil loss was significantly higher (36·4 kg ha^{-1}) in T1 than in T2–T5. Median soil loss per event for the various treatments was in the order of T0 > T1 > T2 = T3 = T4 = T5. Seasonal soil loss was also significantly higher in the control than the WHTs and was significantly lower in T2–T5 than in T0 and T1.

The WHTs had significant effects on TN and TP losses in the sediments. The TN and TP losses were the highest in the control, with medians of 364·1 and 259·2 g ha^{-1} respectively. Nutrient losses were significantly lower in all WHTs than in the control. Nutrient losses were lowest in T3 but did not differ significantly from the losses in T5. Nutrient losses in the sediments were generally higher for N than for P. Nutrient losses were generally higher in the treatments with EMs (T4 and T5) than in the corresponding treatments without EMs (T2 and T3). The event-based statistical analysis (Figure 3) showed no significant differences in nutrient losses between the treatments with and without EMs.

T3 (90%) and T1 (60%) decreased soil losses the most and least respectively (Table IV). The efficiencies of reductions in nutrient losses for the treatments ranged between 56 and 84% for TN and between 52 and 86% for TP. T3 decreased the loss of both TN and TP the most by 84 and 86% respectively, and T1 and T4 decreased the loss of both TP and TN the least by 52 and 56% respectively.

The fractions of nutrients exported with eroded soil compared with inputs (basal fertilization and straw mulch) during the growing season in 2014 were low in T2–T5 (Table V). The fractions, however, were significantly higher in T1 (tied ridges) and T0. In T0, 14·3 and 9·3% of the N and P inputs respectively were exported with the eroded soil. The fractions of N and P exported with the eroded soil for

Table IV. Efficiencies of reduction in runoff, and soil, total N and total P losses compared with control over two seasons (2013 and 2014)

Treatment	Runoff reduction (%) Median (min, max) ($n = 84$)	Soil loss reduction (%) Median (min, max) ($n = 84$)	Total N loss reduction (%) Median (min, max) ($n = 30$)	Total P loss reduction (%) Median (min, max) ($n = 30$)
T0	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)
T1	49 (−29, 93)	60 (−32, 94)	59 (−30, 95)	52 (−14, 96)
T2	80 (−17, 96)	85 (−53, 98)	70 (−55, 98)	73 (−45, 98)
T3	85 (0, 99)	90 (−24, 99)	84 (−49, 100)	86 (−11, 100)
T4	77 (−19, 96)	81 (−50, 99)	56 (−21, 99)	63 (−45, 99)
T5	79 (−32, 98)	82 (−32, 99)	80 (2, 98)	80 (3, 98)

T0, control; T1, tied ridges; T2, straw mulch; T3, tied ridges + straw mulch; T4, straw mulch + EMs; T5, tied ridges + straw mulch + EMs.

Table V. Nutrient inputs (N and P) and fractions of exported nutrients in eroded soils [median (min, max)] relative to the inputs in 2014 ($n = 3$)

Treatment	Nutrient inputs		Fractions of N and P losses	
	Total N (kg ha^{-1})	Total P (kg ha^{-1})	Total N (%)	Total P (%)
T0	64	46	14·3 (13·7, 16·1)^{d}	9·3 (7·5, 9·9)^{d}
T1	64	46	5·8 (4·0, 8·1)^{c}	3·6 (2·9, 4·5)^{c}
T2	154	61	1·4 (0·7, 1·7)^{a}	1·5 (0·7,1·6)^{a}
T3	154	61	1·1 (1·1, 1·4)^{a}	1·3 (1·2, 1·3)^{a}
T4	154	61	1·9 (1·8, 2·1)^{b}	1·9 (1·7, 2·2)^{b}
T5	154	61	1·2 (0·9, 1·6)^{a}	1·1 (1·0, 1·7)^{a}

Different letters show significance (Mann–Whitney *U*-test, $p < 0·05$) difference between treatments, a < b < c < d. T0, control; T1, tied ridges; T2, straw mulch; T3, tied ridges + straw mulch; T4, straw mulch + EMs; T5, tied ridges + straw mulch + EMs.

T1 were 5·8 and 3·6% respectively. The fractions of exported nutrients were significantly lower in T1–T5 than in T0. The fractions of exported nutrients were significantly higher in T4 than in the other treatments even though T2–T5 received the same inputs.

Effect of the Treatments on Sediment and Nutrient Concentrations

Sediment concentrations were significantly ($p < 0.05$) lower in T2–T5 than in T0 (Table VI). Sediment concentration in T1 did not differ significantly from those in the other treatments (T2–T5) or T0. The concentrations varied little among T1–T5 but were highest and lowest in T0 and T4 at 2·39 and 1·20 g L^{-1} respectively. Sediment concentrations in the runoff for all treatments were higher at the beginning of the rainy season and decreased towards the end (Figure 4).

Nutrient concentrations in the sediments were generally less variable among the treatments than the sediment concentrations (Table VI). P concentrations were significantly lower than in the control only in T1 and T5. The treatments did not significantly affect the N concentrations in the sediments. N concentrations were generally higher than P concentrations in the sediments.

Effects of the Treatments on Maize Grain Yield and Biomass

The treatments had significant ($p < 0.05$) effects on maize grain yield and biomass but not on plant height (Table VII). Grain yield was significantly higher in T2 and T4 than in T0. The yields were highest and lowest in T4 and T0 at 3·13 and 2·55 Mg ha^{-1} respectively. T2 and T4 increased maize grain yield by 20 and 23% respectively, compared with the control. Grain yield was not significantly higher in T1, T3 and T5 than in T0. Biomass was also significantly higher in T2 and T4 than in T0. Biomass in T2 and T4 was 13·64 and 13·13 Mg ha^{-1} respectively. Biomass was lowest in the control at 10·70 Mg ha^{-1} but was not significantly higher in T1, T3 or T5. Plant height did not differ significantly among the treatments. The plants were smallest and tallest in T3 and T5 at 154·4 and 166·5 cm respectively. In the treatments with tied ridges, there were signs of aeration stresses in the early stages of plant growth in late July 2013 and early August 2014. In these periods, the intensity of rainfall was relatively higher than the other periods.

Table VI. Average sediment, total N and total P concentrations over two seasons (2013 and 2014)

Treatment	Sediment concentration (g L^{-1}) Median (min, max) (n = 84)	Total N concentration (g kg^{-1}) Median (min, max) (n = 30)	Total P concentration (g kg^{-1}) Median (min, max) (n = 30)
T0	2·39 (0·10, 30·40)[b]	1·53 (1·03, 3·27)[a]	1·01 (0·76, 1·22)[b]
T1	1·74 (0·16, 22·07)[ab]	1·56 (0·36, 2·79)[a]	0·91 (0·25, 1·18)[a]
T2	1·45 (0·10, 25·36)[a]	1·63 (0·21, 3·79)[a]	0·95 (0·06, 1·37)[ab]
T3	1·34 (0·10, 39·86)[a]	1·67 (0·73, 3·51)[a]	0·94 (0·64, 1·42)[ab]
T4	1·20 (0·17, 23·63)[a]	1·65 (0·41, 3·15)[a]	0·95 (0·05, 1·24)[ab]
T5	1·26 (0·16, 27·72)[a]	1·52 (0·89, 3·26)[a]	0·86 (0·19, 1·18)[a]

Different letters show significant (Mann–Whitney *U*-test, $p < 0.05$) differences between treatments, a < b. T0, control; T1, tied ridges; T2, straw mulch; T3, tied ridges + straw mulch; T4, straw mulch + EMs; T5, tied ridges + straw mulch + EMs.

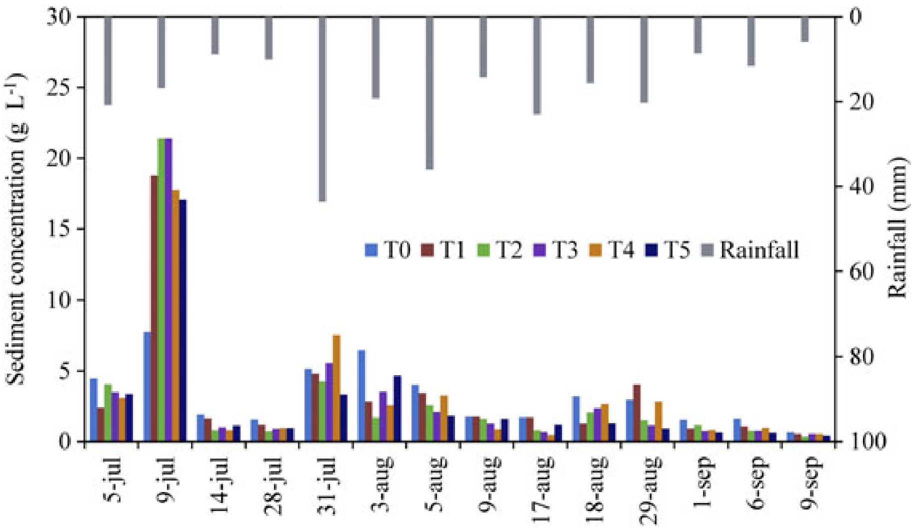

Figure 4. Sediment concentrations in runoff for different treatments and rainfall events in 2014. T0, control; T1, tied ridges; T2, straw mulch; T3, tied ridges + straw mulch; T4, straw mulch + EMs; T5, tied ridges + straw mulch + EMs. [Colour figure can be viewed at wileyonlinelibrary.com]

Table VII. Maize grain yield, biomass and plant height (Mean ± SD) over 2 years in 2013 and 2014 ($n = 6$)

Treatment	Grain yield ($Mg\ ha^{-1}$)	Biomass ($Mg\ ha^{-1}$)	Plant height (cm)
T0	$2{\cdot}55 \pm 0{\cdot}31^{a}$	$10{\cdot}70 \pm 1{\cdot}50^{a}$	$159{\cdot}2 \pm 8{\cdot}1^{a}$
T1	$2{\cdot}79 \pm 0{\cdot}41^{abc}$	$11{\cdot}44 \pm 1{\cdot}45^{ab}$	$156{\cdot}1 \pm 13{\cdot}0^{a}$
T2	$3{\cdot}06 \pm 0{\cdot}40^{bc}$	$13{\cdot}64 \pm 1{\cdot}30^{c}$	$158{\cdot}3 \pm 11{\cdot}7^{a}$
T3	$2{\cdot}61 \pm 0{\cdot}35^{ab}$	$12{\cdot}58 \pm 1{\cdot}76^{abc}$	$154{\cdot}4 \pm 7{\cdot}2^{a}$
T4	$3{\cdot}13 \pm 0{\cdot}49^{c}$	$13{\cdot}13 \pm 1{\cdot}79^{bc}$	$155{\cdot}2 \pm 9{\cdot}9^{a}$
T5	$2{\cdot}65 \pm 0{\cdot}46^{ab}$	$12{\cdot}42 \pm 2{\cdot}08^{abc}$	$166{\cdot}5 \pm 13{\cdot}2^{a}$

Different letters show significance ($p < 0{\cdot}05$) difference between treatments, a < b < c.
T0, control; T1, tied ridges; T2, straw mulch; T3, tied ridges + straw mulch; T4, straw mulch + EMs; T5, tied ridges + straw mulch + EMs.

Relationships Among Runoff, Soil Loss, Nutrient Loss, SMC, Slope and Bulk Density

The PCA identified two components that together explained 69·5% of the variance of the data (Figure 5). The variance was mainly described by PC1, which accounted for 52·2% of the total variation and was strongly associated with runoff, soil loss and N and P losses, with factor loadings of 0·94, 0·93, 0·88 and 0·97 respectively. The high and positive factor loadings of the variables in PC1 were also complemented by strong and significant correlations ($p < 0{\cdot}01$) between these variables (Table VIII). PC2 explained 17·3% of the total variance and was correlated strongly with SMC and moderately with slope, with factor loadings of 0·90 and −0·47 respectively.

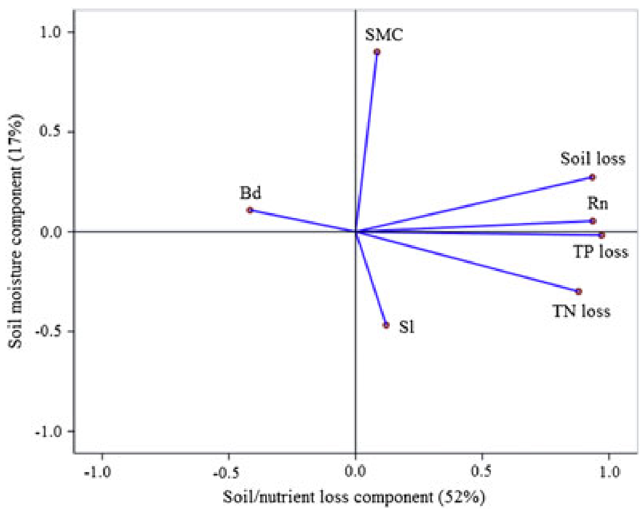

Figure 5. Principal component analysis of runoff (Rn), soil-moisture content (SMC), soil loss, total N (TN) loss, total P (TP) loss, slope (Sl) and bulk density (Bd), based on average seasonal data ($n = 36$) in 2013 and 2014. [Colour figure can be viewed at wileyonlinelibrary.com]

The correlation analysis between runoff and soil loss per event identified a significant ($p < 0{\cdot}01$) logarithmic relationship between the two variables (Table VIII). Fifty-two per cent of the variation in soil loss in T0 was explained by the runoff. The explanatory capability improved slightly for the *in situ* WHTs (T1–T5), where runoff accounted for 63% of the variability in soil loss.

Nutrient losses were positively and significantly ($p < 0{\cdot}01$) correlated with soil losses in both the control and the *in situ* WHTs. Soil loss accounted for 71 and 96% of the variation in the losses of N and P for T0 respectively, and 74 and 84% for T1–T5 respectively.

DISCUSSION

Soil and Nutrient Losses

The application of the *in situ* WHTs significantly decreased the loss of soil compared with T0. Straw mulch (with or without tied ridges) was efficient in reducing soil loss from cultivated land. The positive effect of crop residue mulching on soil loss in cultivated lands has also been documented in other ecosystems in the world (Adekalu *et al.*, 2007; Fernández & Vega, 2016; Gholami *et al.*, 2013; Mwango *et al.*, 2015; Prosdocimi *et al.*, 2016b; Sadeghi *et al.*, 2015a). The good performance of the straw mulch for decreasing soil loss was associated with its good performance in decreasing runoff and sediment concentration compared with the control. This result was also confirmed by other researchers (Gholami *et al.*, 2013; Sadeghi *et al.*, 2015a; Sadeghi *et al.*, 2015b; Prosdocimi *et al.*, 2016b).

Our study did not analyse the costs and social acceptance of straw mulch in the study area. Some researchers have tested the effect of different mulching rates on soil erosion in agricultural fields (Donjadee & Tingsanchali, 2016; Jordán *et al.*, 2010; Lal, 1998). Further research, however, is necessary to determine an optimum rate of mulch application in terms of cost effectiveness and soil erosion control (Cerdà *et al.*, 2016; Jordán *et al.*, 2010).

The efficiency of the decrease in soil loss for the tied ridges alone (T1) was mainly associated with runoff reduction, because the sediment concentration for the tied ridges

Table VIII. Regression equations for estimating soil ($kg\ ha^{-1}$), total N ($g\ ha^{-1}$) and total P ($g\ ha^{-1}$) losses in the control (T0) and *in situ* WHTs (T1–T5)

Control (T0)	*In situ* WHTs (T1–T5)
Log soil loss = 1.25 × log runoff + 1.17 ($r^2 = 0{\cdot}52$, $n = 84$, $p < 0{\cdot}01$)	Log soil loss = 1.33 × log runoff + 1.18 ($r^2 = 0{\cdot}63$, $n = 420$, $p < 0{\cdot}01$)
Nitrogen loss = 1.70 × soil loss + 30.72 ($r^2 = 0{\cdot}71$, $n = 30$, $p < 0{\cdot}01$)	Nitrogen loss = 1.90 × soil loss − 12.11 ($r^2 = 0{\cdot}74$, $n = 150$, $p < 0{\cdot}01$)
Phosphorus loss = 0.89 × soil loss + 25.57 ($r^2 = 0{\cdot}96$, $n = 30$, $p < 0{\cdot}01$)	Phosphorus loss = 0.82 × soil loss + 6.34 ($r^2 = 0{\cdot}84$, $n = 150$, $p < 0{\cdot}01$)

T0, control; T1, tied ridges; T2, straw mulch; T3, tied ridges + straw mulch; T4, straw mulch + EMs; T5, tied ridges + straw mulch + EMs.

was not significantly lower than for the control and the other treatments (T2–T5).

T3 and T5 registered the lowest seasonal soil loss ($0{\cdot}8\,Mg\,ha^{-1}$) in 2014. T0 had the highest seasonal soil loss ($4{\cdot}3\,Mg\,ha^{-1}$). The seasonal soil losses for T1, T2 and T4 were 2·1, 1·0 and $1{\cdot}3\,Mg\,ha^{-1}$ respectively. This result is similar to a study in northern Ethiopia by McHugh *et al.* (2007), who reported soil loss from cultivated land on flat (<3%) plains of $<2\,Mg\,ha^{-1}$. The rate of seasonal soil loss in the control, however, was lower in our study than in other plot-level studies in northern Ethiopia (Araya *et al.*, 2011; Girmay *et al.*, 2009; Nyssen *et al.*, 2008). The lower rate of soil loss in our study was probably associated with the sandy clay loam soil texture and differences in crop cover and to a lower slope gradient and slightly lower seasonal rainfall.

The lower sediment concentrations in T2–T5 were associated with the application of straw mulch in these treatments, emphasizing the role of mulch in decreasing the effects of raindrop splashes on soil surfaces (Cerdà *et al.*, 2016; Okeyo *et al.*, 2014) and hence slowing the detachment of soil particles. Sediment concentrations tended to decrease towards the end of the rainy season irrespective of treatment. Our results corroborated those of other studies in northern Ethiopia and other regions (Araya *et al.*, 2011; Gebreegziabher *et al.*, 2009; Sirjani & Mahmoodabadi, 2014). The decrease in sediment concentrations in runoff late in the rainy season is due to the increase in crop cover, which dissipates the energy of raindrops and decreases the velocity of water on the soil surface (Gebreegziabher *et al.*, 2009).

The higher efficiency of decreasing nutrient losses by the *in situ* WHTs (T1–T5) compared with T0 was mainly associated with the reduction of runoff and soil losses. The treatments had no significant effect on TN concentrations in the sediments. The differences in the nutrient losses in the *in situ* WHTs were mainly associated with the amounts of runoff and soil losses in the treatments, consistent with other findings (Ali *et al.*, 2007; Baptista *et al.*, 2015; Zougmoré *et al.*, 2009), where nutrient losses were primarily a function of the amounts of runoff and soil loss. Although nutrient losses were generally higher in the treatments with EMs than the corresponding treatments without EMs, the effect of EMs was however inconclusive because the differences were not significant either for medians (Table III) or per event (Figure 3).

The fractions of exported nutrients in the eroded soils compared with the nutrient inputs were significantly higher in T0 and T1 than in T2–T5 (Table V), likely due to the lower nutrient inputs in T0 and T1. The straw mulch application might have increased the nutrient contents in T2–T5. The slightly higher and significant fraction of nutrient exports in T4 than T2 may be an indication of the release (mineralization) of nutrients from straw mulch due to the microbial activity of the EMs. N and P may not be immediately released by the decomposition of the organic matter in wheat-straw mulch due to its high C : N ratio (Bertoldi *et al.*, 1983), but the application of straw mulch can maintain carbon and N stocks in the soil (Abbasi *et al.*, 2015; Smil, 1999). The availability of soil nutrients, contributed by the straw mulch, would help in the long term to maintain soil quality by minimizing the fraction of nutrient exports in eroded soils.

Several researches demonstrated the dependency of soil erosion rates at various plot-scale experiments (e.g. Le Bissonnais *et al.*, 1998; Moreno-de las Heras *et al.*, 2010; Parsons *et al.*, 2006; Sadeghi *et al.*, 2015b). A field experiment by Parsons *et al.* (2006) revealed the decrease of soil erosion rate with increasing plot length. Moreno-de las Heras *et al.* (2010) confirmed the decrease of soil erosion rate with plot length in less degraded lands. On the contrary, the rate of soil loss substantially increased with increasing plot length for highly degraded lands. These findings confirm the variation of soil erosion rates with the scale of plot experiments. Therefore, the soil erosion rates from this study might slightly differ from field conditions because of the size of the plots and the setup of the experiment.

Maize Grain Yield and Biomass

Maize grain yield and biomass were significantly higher in the treatments with straw mulch (with and without EMs) compared with the control. The effect of the mulch on yield may have been due to an increase in soil moisture and decrease in evaporation in the plots by the mulch during dry periods. The release of N from mulch decomposition may also have contributed to the higher grain yield and plant biomass in the treatments with mulch. The use of EMs with the mulch, however, did not significantly increase yield. The lack of effect of the EMs on yield may have been due to the slow release of nutrients from the mulch because of its high C : N ratio (Bertoldi *et al.*, 1983). Some studies, however, reported an increase in grain yield by using good organic amendments (e.g. compost and farmyard manure) with EMs (Hu & Qi, 2013; Hussain *et al.*, 1999; Javaid & Bajwa, 2011). Hussain *et al.* (1999) reported an increase in wheat and rice grain yields by using farmyard manure with EMs. In another study, the long-term application of EMs with compost increased wheat grain yield (Hu & Qi, 2013). Further research is required to ascertain the benefits of EM application with different organic materials for increasing the release of nutrients to the soil and thus for increasing maize yield.

Tied ridges alone or combined with straw did not significantly increase grain yield or plant biomass compared with the control, perhaps because excess water in the root zone with the tied ridges from successive and intensive rains caused aeration stress. Similar symptoms of aeration stress were reported in another study in northern Ethiopia in barley fields during seasons with high rainfall (Araya & Stroosnijder, 2010). Maize is vulnerable to aeration stress during the early stages of growth (Mason *et al.*, 1987). Nutrient deficiency due to restricted nutrient uptake is the primary reason of inhibited plant growth in waterlogged soils (Steffens *et al.*, 2005). Anaerobic soil conditions caused by waterlogging also enhance the release of N_2 to the atmosphere (Eickenscheidt *et al.*, 2014). Grain yield might thus be improved if tied ridges are avoided during the early stages of plant growth. The time of application of tied ridges merits further study for the improvement of grain yield in northern Ethiopia.

Factors Influencing Soil and Nutrient Losses

The PCA indicated that runoff, soil loss and nutrient (N and P) losses were closely associated with each other, demonstrated by high factor loadings in the PCs (Figure 5) and the strong correlations (Table VIII). Event-based logarithmic soil loss was positively correlated with logarithmic runoff. Soil loss is primarily governed by runoff (Ali *et al.*, 2007), which allows the estimation of soil loss per event by using measured runoff. A similar logarithmic relationship was established by Girmay *et al.* (2009), in which runoff volume alone accounted for 76% of the variability in annual soil loss.

The positive and direct correlation between the nutrient and soil losses suggested that nutrient losses from farmland could be easily estimated by using data for soil loss. Similar associations were reported between soil and nutrient losses from micro-dam catchments in northern Ethiopia (Haregeweyn *et al.*, 2008). This underlines that any measure taken to decrease soil loss will also proportionally decrease N and P losses (Jie *et al.*, 2013).

CONCLUSIONS

In situ WHTs are useful for reducing soil erosion and nutrient losses from farmland. The combined use of tied ridges and straw mulch was the best *in situ* WHT for reducing soil loss from farmland with coarse-textured soils and gentle slopes. All *in situ* WHTs significantly reduced soil loss and associated nutrient losses. Straw mulch (with or without EMs) significantly increased maize grain yield and biomass, substantiating the role of straw mulch in improving *in situ* water harvesting for combating soil-moisture deficiency during dry periods. The use of straw mulch as an *in situ* WHT would further help in the long term to mitigate nutrient losses from the soil due to the release of nutrients from the straw. Further research, however, is required to identify the stage of plant growth when tied ridges should be installed for improving maize yield in northern Ethiopia.

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