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Deposition of eroded soil on terraced croplands in Minchet catchment, Ethiopian Highlands

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ABSTRACT

In the Ethiopian Highlands, soil and water conservation practices are of utmost importance to conserve eroded soil and combat soil loss. This study provides detailed results on on-site sediment deposition and net soil loss in terraced croplands in a catchment in the sub-humid Ethiopian Highlands. Sediment deposition was measured on horse bean and maize fields during the crop growing seasons of 2014 and 2015. Measurements took place on observation plots on terraced cropland with varying spacing between terraces and varying slope gradients. Net soil loss, in this case the amount leaving the terraced cropland, was calculated by modelling the Universal Soil Loss Equation (USLE) for the whole observation field and subtracting the measured sediment deposition. The study result showed about 8–11 t ha^{-1} sediment was deposited in the deposition zone of the terraced cropland, with greater sediment deposition on terraces with narrow spacing and steeper slope gradients. Sediment deposition was highest in July and August, and relatively low in September. Annual soil loss ranged from 32 to 37 t ha^{-1} in the terraced cropland of the study area. From the total soil loss in the crop growing season, about 54–74% sediment was deposited on the deposition zone of terraced crop fields. Implementation of soil and water conservation with narrow spacing, especially on the steep slopes of the sub-humid Ethiopian Highlands or other similar area, are thus highly recommended as they enable conservation of the eroded soil in the cropland.

1. Introduction

In Ethiopia, land degradation has been on the rise since the 1950s due to rapidly increasing human and livestock pressure (Hurni, Tato, & Zeleke, 2005). Human pressure coupled with strong precipitation events and a hilly landscape have led to serious on-site soil erosion and related problems in the Ethiopian Highlands (Nyssen, Poesen, & Deckers, 2009; Nyssen, Poesen, Moeyersons, Haile, & Deckers, 2008; Vanmaercke, Zenebe, Poesen, Nyssen, Verstraeten & Deckers, 2010). Loss of topsoil in some parts of the Ethiopian Highlands can reach up to 265 t ha^{-1} yr^{-1} (Gelagay & Minale, 2016), leading to a high loss of soil quality including soil organic carbon (Teferi, Bewket, & Simane, 2016). A study covering all of the Ethiopian Highlands (490,000 km^2) estimated the cost of nutrient replacement through inorganic fertilizer to be €364 to €412 million per year (Tesfahunegn & Vlek, 2013). Accordingly, since the 1970s the Ethiopian government has been engaged in a massive implementation of Soil and Water Conservation (SWC) technologies to combat soil erosion (Hurni, 1988; Nyssen et al., 2008), with an expected higher on-site deposition of the eroded soil in the conserved lands.

Our focus in this paper is soil erosion caused by water, which can be considerably reduced by SWC technologies that shorten slope length and slope gradient (Herweg & Ludi, 1999; Mekonnen, Keesstra, Stroosnijder, Baartman, & Maroulis, 2015). The most commonly used SWC technologies in the croplands of northern Ethiopia are *fanya juu*, stone bunds, and soil bunds (Teshome, Rolker, & Graaff, 2013; Haregeweyn et al., 2015). *Fanya juu* in Swahili means "throw and uphill" (Herweg & Ludi, 1999) and is a type of structural SWC technology made by excavating the trench below the riser and throwing the soil up towards the riser (Hurni, Chadhokar, Daniel, Gete, Grunder & Martin Kassaye, 2016). Soil

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bunds are constructed by digging trenches and throwing the soil downward to the riser of the bund (Yakob, Gebremicheal, Aklilu, & Melaku, 2015). Stone bunds require the availability of stone rather than soil for construction, and are common in stony areas such as Tigray Highlands, Northern Ethiopia (Nyssen et al., 2007). Rainfall in the Ethiopian Highlands is monsoonal and concentrated from July to September (Conway, 2005). Consequently, the main focus of SWC technologies in the Ethiopian Highlands has been to trap sediment, safely drain run-off, and reduce on-site soil erosion by reducing slope length and gradient (Brhane & Mekonen, 2009; Hurni et al., 2005; Haregeweyn, Berhe, Tsunekawa, Tsubo, & Meshesha, 2012).

In the mid-1980s Minchet catchment in the northern Ethiopian Highlands was treated with SWC technologies such as graded *fanya juu* and waterways for drainage (Hurni et al., 2016), under the supervision of the Soil Conservation Research Programme (SCRP) (Bosshart, 1997). Mengistu, Bewket, and Lal (2015) showed that following application of SWC technologies, soil quality in the catchment had improved, including the level of phosphorus and soil organic carbon in the cropland. In addition, Alemu, Amare, Yitaferu, Selassie, Wolfgramm, and Hurni (2013) assessed the land suitability for crops such as teff, maize, wheat, and barley, finding that 50% of the catchment was transformed from "less suitable" in 1984 to "highly suitable" in 2010 for wheat and maize. The study demonstrated that implementation of SWC technologies improved soil depth and reduction in slope steepness in Minchet catchment, improving crop production (Adgo, Teshome, & Mati, 2013; Amare, Terefe, G. Selassie, Yitaferu, Wolfgramm & Hurni, 2013). However, even though SWC technologies reduced soil erosion (Herweg & Ludi, 1999), large amounts of sediment yield were observed at many catchment outlets (Setegn, Dargahi, Srinivasan, & Melesse, 2010). It is therefore important to assess sediment deposition and soil loss on the cropland itself, to ascertain the actual effect of SWC technologies there. Measuring sediment yield in catchment outlets may show the cumulative sediment yield from all land uses as well as other erosion sources such as riverbank or gully erosion.

A study on the effectiveness of 3–21-year-old stone bunds on on-site sediment deposition in the semi-arid highlands of Ethiopia found that more sediment deposition occurs on stone bunds with longer spacing than on those with short spacing (Gebremichael, Nyssen, Poesen, Deckers, Haile & oeyersons, 2005; Nyssen et al., 2008). However, the methods and observations used in that study are not transferable to the sub-humid and humid highlands of Ethiopia with their different soils, climate, and SWC technologies. Another study in the sub-humid Ethiopian Highlands measured sediment deposited in trenches below a newly constructed *fanya juu* in a controlled experiment (Fisseha, Gebrekidan, Kibret, Yitaferu, & Bedadi, 2011). In Minchet catchment, the graded trenches below the *fanya juu* were either destroyed by farmers or silted up after a few rainy seasons (Herweg & Ludi, 1999); this meant the trench was no longer functional and the area became a soil-loss zone (Amare et al., 2013). As a result, studies in the sub-humid Ethiopian Highlands have not yet been able to observe on-site sediment deposition on the existing farming system of conserved croplands, and soil loss and net soil loss from conserved cropland have not been addressed.

The main objectives of the present study were: first, to assess on-site sediment deposition due to soil erosion by water under the real field conditions on the terraced croplands; second, to measure the on-site sediment deposition in respect to precipitation; and third, to model soil loss using USLE and to determine net soil loss for the study period on terraced croplands.

2. Materials and methods

2.1. Description of the study area

The study was conducted in the terraced croplands of Minchet catchment in the northern Ethiopian Highlands, at 37°31′E 10°40′N (Fig. 1). The total area of the catchment is 107 ha, of which about 81 ha is cropland (Alemu et al., 2013). Like other areas of the Ethiopian Highlands, Minchet catchment is characterized by a high population density and a farming system that requires intensive tillage, which exposes the land to high soil erosion (Zeleke & Hurni, 2001). The major soil types in Minchet catchment are Alisol, Nitosol, Combisol, and Regosole (Zeleke, 2000). Common crop types in the study area include teff, wheat, maize, barley, and horse bean (Alemu et al., 2013). The mean annual rainfall is 1690 mm yr^{-1}, which is unimodal, starts in May and lasts until October (Bayabil, Tebebu, Stoof, & Steenhuis, 2016).

Minchet catchment, established in 1984, is a catchment of the SCRP. In 1986 the catchment was fully treated with graded *fanya juu,* waterways, check-dams, reforestation, and protection of degraded grazing plots for rehabilitation (Bosshart, 1997). In a graded *fanya juu,* the bunds and trench below have a lateral gradient of about 1–5% and are thus connected to the constructed waterways (Hurni et al., 2016), allowing run-off to drain to the river (Hurni et al., 2005). The bund components of these graded *fanya juu* were well maintained, developing into outward-sloping terraces over the years, while the trench filled up or was destroyed within a few years of its implementation. However, a few farmers removed some of the *fanya juu* with short spacing, as these reduce the crop production area. Due to high precipitation in the study area, the farmers also integrated their traditional ditches to drain the excess surface water to the waterways. These traditional ditches, which have been integrated with the other SWC technologies in the study area, are very important to control run-off and water logging.

2.2. Selection of measurement sites and observation plot setup

The measurement sites in the terraced cropland of the catchment are located between 2430 and 2460 m a.s.l. Crop fields in the terraced croplands, confined by an upper and a lower terrace, were selected as observation fields for sediment deposition measurements and soil loss modelling. The terraced croplands were purposely selected for this study, because on non-terraced croplands with only traditional ditch and contour ploughing, deposition of eroded soil is very irregular. Therefore, it is not possible to measure deposition of eroded soil on non-terraced croplands in a systematic manner. The observation plots were thus selected from terraced cropland based on crop type and topography (slope gradient and slope length). Space between the planted crops was required throughout the crop growing period, which allows measurement of sediment deposition in the deposition zone. Therefore, the chosen fields had to be cultivated with row crops such as maize and horse bean. In 2014, the observation field were covered with horse bean. Crop rotation meant that different observation fields had to be chosen for 2015, as the farmers in the study area plant teff and wheat after horse bean. Accordingly, in 2015 the observation fields were selected from the available maize fields following the same procedure.

To see the effects of slope gradient and spacing between terraces on sediment deposition, the six selected observation fields were of two spacing classes, 8–13 m and 14–25 m, and three gradient categories, 4 – 8%, 8 – 13%, and 13 – 17% (Table 1). To obtain representative data of on-site sediment deposition from the selected observation fields, three replications of the observation plots were placed in the deposition zone of the observation field

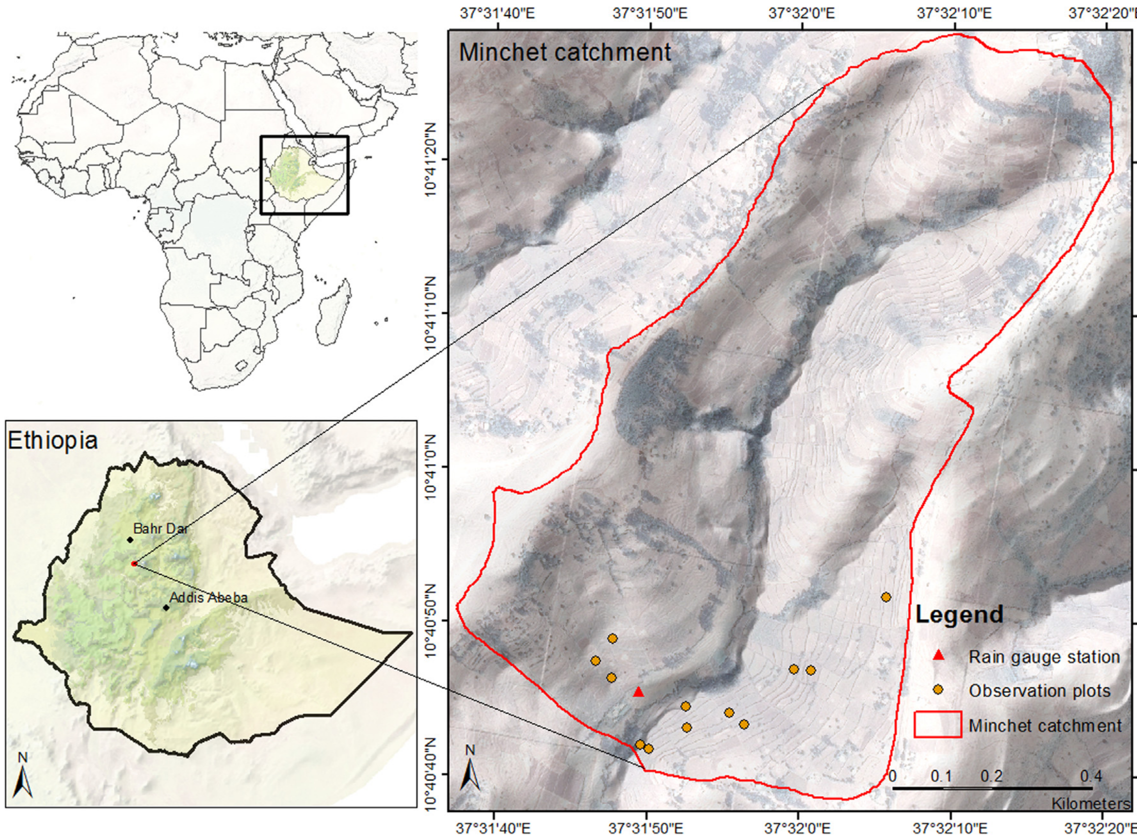

Fig. 1. Location map of the study area, Minchet catchment in northern Ethiopian Highlands.

Table 1
Spacing between terraces, slope gradient, and area of observation plot.

Slope gradient	Area of observation plot with spacing of 8 – 13 m	Area of observation plot with spacing of 14 – 25 m
4–8%	2 m × 2 m	2 m × 3 m
8–13%	2 m × 2 m	2 m × 3 m
13–17%	2 m × 2 m	2 m × 3 m

(Fig. 2). The dimension of the deposition zone was identified with the local knowledge of field experts and through field observation. Depending on the spacing between the terraces, the width was 2 m to 3 m (shorter terrace spacing results in a shorter width of deposition zone) above the terrace riser. Accordingly, the area of the observation plots was 2 mx2 m for the spacing of 8 m to 13 m, and 2 mx3 m (2 m length and 3 m width) for the spacing of 14 m to 25 m (Table 1). This study focused on measuring the sediment stay after precipitation events on the deposition zone of terraced fields. The measurements were done under real field conditions; therefore boundaries of the observation plots were purposely left open and marked by pegs.

2.3. Measurement of sediment deposition

On-site sediment deposition due to soil erosion by water in the cropland conserved with SWC technologies was measured in the observation plots. The measurements were conducted after harrowing and planting during the cropping season of 2014 (horse

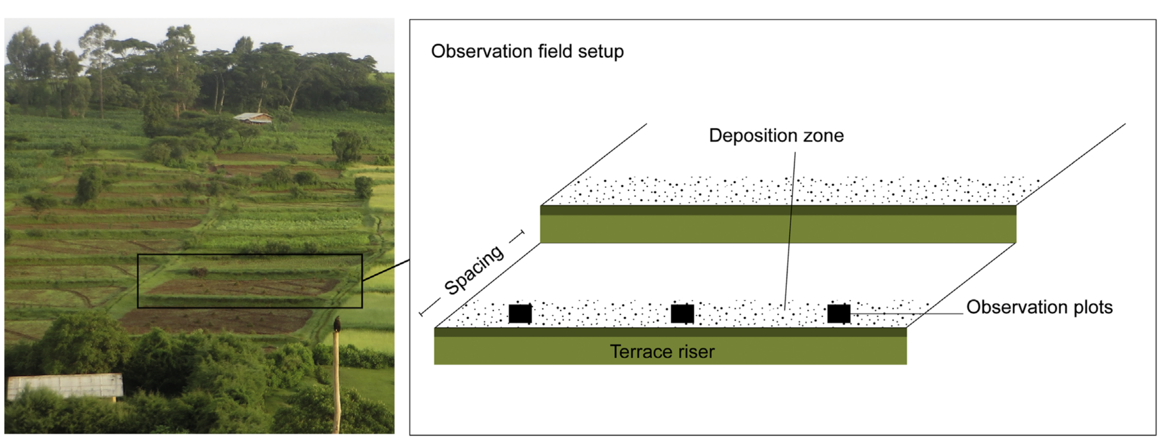

Fig. 2. Observation field (of which we had six in both 2014 and 2015) and observation plots. In the diagram, the rectangle between the two terrace risers is the observation field. The deposition zone is at the bottom of the observation field with a width of 2–3 m; the three designated replications of observation plots are placed in the deposition zone. The distance between two terraces – from the top of the terrace riser to the bottom of the next terrace riser – is referred to as spacing.

Table 2
Cropping calendar of horse bean (2014) and maize (2015) in Minchet catchment. Source: Field experts in Minchet catchment.

Crop type	Field preparation	Planting	Harrowing	Harvesting
Horse bean	April to July	5–10 July	no	November to December
Maize	January to May	15 May–10 June	1–30 June	November to December

bean) and 2015 (maize) (Table 2). In 2014, the plantation year of horse bean, the measurement period lasted from 10 July to 30 September. Under the cropping calendar in the study area (Table 2), maize was planted in May 2015 and harvested between November and December. Harrowing activities in the maize plots until the end of June meant that we could only start the measurements on 1 July, stopping on 30 September when sediment deposition had nearly ceased. Sediment deposition from previous years was already mixed with the original soil during tillage activities, which is why this study focused on sediment deposition after harrowing and planting. During and after rainfall events, the run-off transported the sediment to the deposition zone where both sediment and run-off accumulated. Within four hours of the rainfall events, the accumulated run-off had usually infiltrated or evaporated, and the new sediment loosely deposited on the top of original soil could be easily observed and measured, while the original soil remained untouched and had an aggregated soil structure. Nevertheless, specific care was given to collect only the newly deposited sediment of each measurement day. Data were collected once every 24 h, usually between 8 am and noon. In case of continuous precipitation, when the accumulated run-off could not infiltrate or evaporate, the sediment was collected the following day. The sediment was collected in plastic bags from each observation plot using a spoon; the plastic bags had a capacity of up to 4 kg of wet sediment, and one or more plastic bags (depending on the amount of sediment deposited) were required on each measurement day. After the wet sediment was collected in plastic bags, the wet weight was weighed and recorded, and 100 g from each plot was oven dried to calculate the total dry weight of the sediment deposition.

The dry weight of sediment was measured in kilograms (kg) from each observation plot, and then extrapolated from kg per m^2 to tonnes per hectare (t ha^{-1}). First, the area of the deposition zone (Ad) per hectare was calculated as follows:

$$Ad = L*Wd*N \tag{1}$$

In Eq. (1), Ad is the area of the deposition zone in square metres per hectare (m^2 ha^{-1}), L is length of terraces in one hectare, Wd is average width of deposition zone (in m), and N is number of terraces per hectare. We assume L to be 100 m (even though 2–3 narrow waterways per hectare can cross the consequent terraces that could reduce the length of the terraces to about 98 m, but we assume this can be compensated by the greater-than-average widening of the deposition area in a few extreme precipitation events). Wd was 2 m for the observation fields with a spacing of 8–13 m, and 3 m for the observation fields with a spacing of 14–25 m. N was calculated as 100 m (width of one hectare) divided by the spacing (m) between the terraces (Fig. 2), which was measured for each observation field (Table 4).

Subsequently, sediment deposition per hectare was calculated from the area of the deposition zone and sediment deposited in the observation plots. Thus, total sediment deposition per hectare in the deposition zone was calculated as follows:

$$Sed = Sp*Ad \tag{2}$$

In Eq. (2), Sed is Sediment deposition in tonnes per hectare (t ha^{-1}), Sp is Sediment deposition in the observation plot in tonnes per square metre (t m^{-2}), and Ad is Area of the deposition zone in square metres per hectare (m^2 ha^{-1}) (see Eq. (1)).

The sediment deposited in the 6 observation fields was statistically tested using a Kruskal-Wallis Test that fits non-parametric data (Field, 2009); the test was applied to see whether the amount of sediment deposition in the 6 observation plots was significantly different or not.

2.4. Soil loss and net soil loss

Soil loss due to water erosion in crop fields of the observation plot was estimated using the Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978). The USLE was adapted for Ethiopia (Hurni, 1985; Kaltenrieder, 2007). Previous studies revealed that USLE has some limitations related to the definition of the slope length (the area that contributes to the run-off) and run-on from upslope (Pistocchi, Cassani, & Zani, 2002). However, no run-on from upland slopes was observed in the study site. Because of the high levels of rainfall in the study area, farmers control the run-off by integrating traditional ditches into the terraced croplands. This allows the run-off to flow through the ditches to the waterways, which were implemented as part of the SWC technologies in the study area. Therefore, the limitations of USLE mentioned by Pistocchi et al. (2002) were not a problem in the present study, and soil loss in the observation field was calculated following the equation of USLE updated from (Wischmeier & Smith, 1978):

$$A = R*K*LS*C*P \tag{3}$$

In Eq. (3), A is Soil loss in tonnes per hectare per year (t $ha^{-1}yr^{-1}$), R is Rainfall erosivity factor (MJ mm h^{-1}), K is Soil erodibility factor, LS is Topography factor, C is Cover and management factor, and p is Supporting practices factor.

Rainfall erosivity (R) factor: the R factor (MJ mm h^{-1}) quantifies the impact of precipitation as one of the driving forces of soil

Table 3
Calculated soil loss with updated and previous C and P factor of USLE and measured soil loss in the SCRP test plots of Minchet catchment.

Year	Test plot number	Crop cover	Annual soil loss (t ha^{-1}) with updated C and P factor[a]	Annual soil loss (t ha^{-1}) with C and P factor from Hurni (1985)[b]	Measured annual soil loss (t ha^{-1})
2000	1	horse bean	103	43	101
2003	2	maize	40	15	29
2004	4	maize	99	37	137
2012	1	horse bean	94	39	91
Coefficient of determination R^2			*0.83*	*0.68*	

Note: K factor from Zeleke (2000); R factor from WLRC (2016); LS factor from Hurni (1985).
C: Cover and management (C) factor; P: Supporting practices (P) factor; and t ha^{-1}: tonne per hectare.

[a] updated P factor for contour ploughing and traditional ditch 0.81; updated C factor 0.3 for maize and 0.4 for horse bean.
[b] P factor for contour ploughing 0.9; C factor 0.1 for maize and 0.15 for horse bean.

Table 4
Sediment deposition in the observation plot and net soil loss in the observation fields of Minchet catchment in 2014/15.

Year	OP[1]	OP[1]size (m)	OF[2] Slope (%)	OF[2] spacing (m)	OF[2] Terrace length (m)	Sed[3] (t ha^{-1})	Sed[3] (%)	Net soil loss[4] (t ha^{-1})	Soil loss[5] (t ha^{-1})	Annual soil loss (t ha^{-1})
2014	p1	2 × 3	5	20	21	5	70	2	7	13
	p2	2 × 3	12	16	27	6[a]	26	18	24	45
	p3	2 × 3	17	15	31	7[a]	18	30	36	68
	Average (p1-3)					6	38	16	22	42
	p4	2 × 2	5	12	16	8	112	−1	7	13
	p5	2 × 2	12	8	16	10[b]	56	8	19	35
	p6	2 × 2	16	8	16	12[b]	43	16	27	51
	Average (p4-6)					10	70	8	18	33
	Average 2014					8	54	12	20	38
2015	p1	2 × 3	7	22	50	9	86	1	10	19
	p2	2 × 3	11	18	40	9	54	8	17	33
	p3	2 × 3	16	20	40	10	34	19	29	55
	Average(p1-3)					9	58	10	19	35
	p4	2 × 2	5	13	23	10	133	−2	7	14
	p5	2 × 2	11	13	30	13[c]	80	3	16	29
	p6	2 × 2	16	8	40	15[c]	62	9	24	44
	Average (p4–6)					12	92	3	15	29
	Average 2015					11	75	6	17	32

[1]OP: Observation plot, [2]OF: Observation field, [3]Sed: Sediment deposition per study period, [4]soil loss that leaves the cropland, [5]Soil loss per study period, t ha^{-1}: tonne per hectare, and m: metre; and [a, b, c]: significantly different value with $p < 0.05$ according to the Kruskal-Wallis test.
Note: K value from Zeleke (2000); R value from WLRC (2016); LS factor and P factor for contour ploughing from Hurni (1985); P factor for drainage ditch 0.9, total P factor 0.81. C factor: 0.3 for maize and 0.4 for horse bean.

erosion by water (Nyssen et al., 2005). The R factor was determined from the sum of storm kinetic energy (E, in MJ ha $^{-1}$) and maximum 30-min rainfall intensity (I30, in mm h^{-1}) (Yin, Xie, Nearing, & Wang, 2007); accordingly, the R factor was determined from summation of the EI30 index (Water and Land Resource Centre [WLRC], 2016). The precipitation was measured with the digital HOBO rain gauge located within 1 km^2 of the study site (Fig. 1). The digital HOBO rain gauge was installed in 2013 and monitored by researchers from the Centre for Development and Environment (CDE) at the University of Bern, and the Water and Land Resource Centre (WLRC) in Addis Abeba, Ethiopia (WLRC 2016). Accordingly, the R factor was determined using the EI30 index for the precipitation data measured in the study area in 2014 and 2015 (WLRC, 2016). In order to model soil loss per year and soil loss during the study period, the R factor was determined per study period and per year for both 2014 and 2015.

Soil erodibility (K) factor: the K factor determined for the study area by Zeleke (2000) was used to calculate soil loss at the study site.

Topography (LS) factor: the dimensionless LS factor was adapted to Ethiopia (Hurni, 1985) and calculated using slope length (L, in m) and gradient (S, in %).

Cover and management (C) factor: in Ethiopia, the dimensionless C factor was recommended at 0.1 for maize and 0.15 for other pulses including horse bean (Hurni, 1985). This differs from Kaltenrieder (2007), who recommended the C factor of 0.05 for maize and 0.5 for horse bean and validated the USLE for the SCRP research sites including Minchet catchment. However, we observed soil loss modelled with USLE using these C factors in the observation fields, and soil loss was less than sediment deposition for most of the observation fields, which was unrealistic on normal (natural) processes of soil erosion and sediment deposition. Thus, we had to recheck the C factor of maize and horse bean, using the soil loss data that had been measured over a period of 28 years in the SCRP test plot. However, from the available data of SCRP test plots in Minchet catchment, only 2000, 2003, 2004, and 2012 were with a crop cover of maize or horse bean (WLRC, 2016). Nonetheless, we found the measurements from these four years adequate to update the C and P factors, and obtained a reasonable result of modelled soil erosion in the observation fields. Calibrating the C factor for maize and horse bean, we arrived at 0.3 and 0.4 respectively. The soil loss of the SCRP test plot for the selected year was thus calculated with a C factor of 0.3 and 0.4, having the closest result to the measured soil loss of the test plot with the R^2 value of 0.83 (Table 3).

Supporting practices (P) factor: the P factor for supporting practices was proposed to be 0.9 for contour ploughing (Hurni, 1985). The traditional ditches drain excess surface flow and are used to control run-off and reduce soil erosion, almost like contour ploughing. Therefore, the P factor for traditional ditches as supporting practice was set at 0.9, and for plots without a traditional ditch it was set at 1. Where both traditional ditches and contour ploughing occurred, the P factor was set at 0.81 (0.9 × 0.9).

The annual soil loss was calculated for 2014 and 2015 using the USLE and parameters as defined above. Soil loss during the cropping season was calculated following the same procedure as for annual soil loss, with the exception that the R factor only represented precipitation during the cropping season. Net soil loss during the cropping season was then calculated as soil loss during the cropping season minus sediment deposition during the cropping season in t ha^{-1}.

3. Result and discussion

3.1. On-site sediment deposition in the terraced croplands

This study measured on-site sediment deposition due to water erosion on terraced croplands during the growing period of horse bean and maize in 2014/15 (Table 2). Because on-site sediment deposition due to water erosion occurs in the crop growing season in the study area, we assume that only a small amount of sediment deposition occurred in rainfall events before and after the observation period.

In the cropping season, average sediment deposition in the observation plots was 8–11 t ha^{-1} (Table 4) after planting and harrowing of horse bean and maize in 2014/15 (Table 2). In 2014, average sediment deposition in the observation plots with above 13 m and below 13 m spacing between terraces was about 6 t ha^{-1} and 10 t ha^{-1} respectively; similarly, in 2015: 9 t ha^{-1} and 12 t

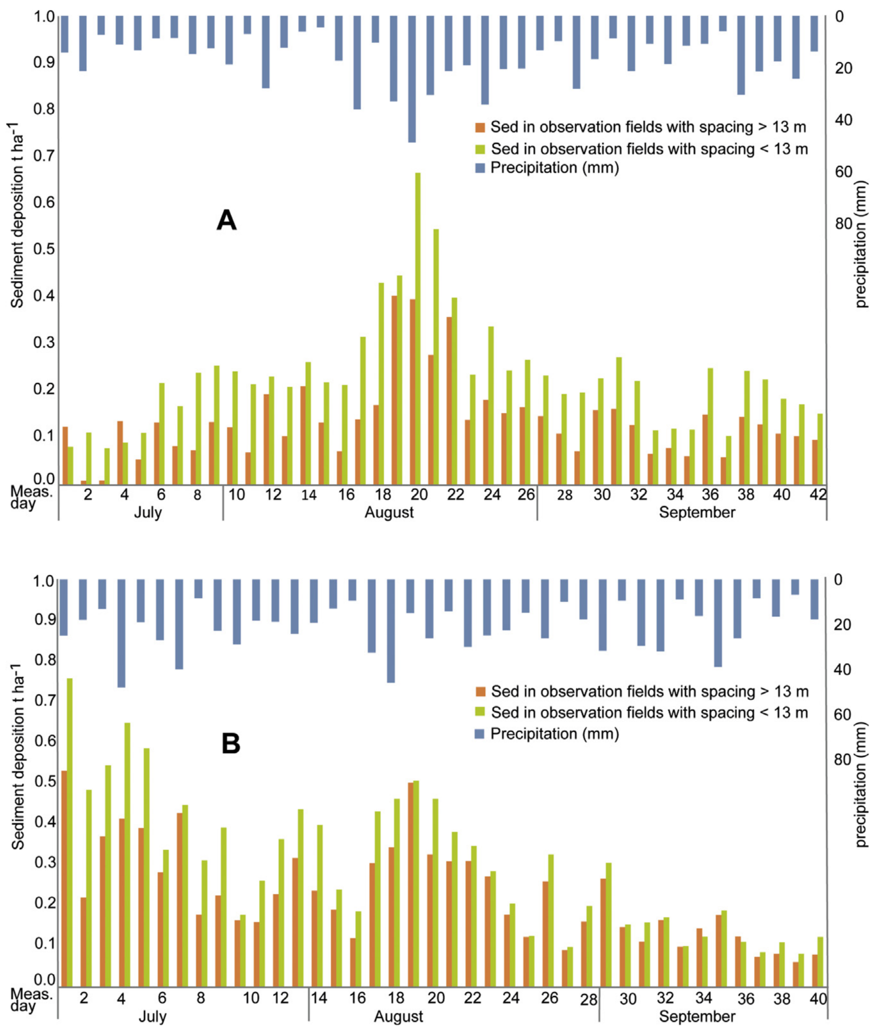

Fig. 3. Average sediment deposition in t ha^{-1} and precipitation in mm in respect to measurement days in Minchet catchment for 2014 (A) and 2015 (B). The x-axis shows the number of measurement days and months from July to September; the y-axis to the left shows sediment deposition (t ha^{-1}); the y-axis to the right shows precipitation (mm) by means of blue bars; the red and green bars depict sediment deposition (Sed) in the observation plots with spacing between terraces of above 13 m and below 13 m respectively.

ha^{-1}. Relatively low sediment deposition was observed on plots with a spacing of more than 13 m compared to those of less than 13 m spacing (Table 4, Fig. 3 [A and B]). Similarly, fields with more terraces (i.e. narrow spacing between terraces) showed more sediment deposition than those with fewer terraces (wider spacing between terraces).

The Kruskal-Wallis test showed that the sediment deposition in at least one of the six observation plot was significantly different ($p \le 0.00$) for both 2014 and 2015; with subsequent tests we then verified that the sediment deposition in p1 was smaller than p2 and p3 ($p \le 0.03$); in p4 it was smaller than in p5 and p6 in 2014 ($p \le 0.00$); and in 2015, p5 and p6 showed significantly higher sediment deposition ($p \le 0.03$) (Table 4). This is because narrow spacing between terraces means more terraces per hectare, and the total area of the sediment deposition zone from each terrace results in more sediment deposition in t ha^{-1} in the study area. This result contradicts an earlier study on sediment deposition in croplands with stone bunds in the semi-arid highlands of Ethiopia (Gebremichael et al., 2005). This could be due to the area of terraced field possibly being directly related to sediment deposition in the semi-arid area, the assumption being that all run-off from the terraced field drains to the deposition zone and then either evaporates, infiltrates, or following the water flow direction, overflows to the next bund below. As a result, more sediment stays in the deposition zone. In Minchet catchment, part of the run-off directly flowed to the waterways through the traditional ditches before reaching the deposition zone: the terrace was graded and the run-off collected in the deposition zone drained to the waterway. This may have affected the result of on-site sediment deposition in Minchet catchment.

While increasing the number of terraces (or narrow spacing between terraces) was found to reduce soil loss and improve on-site soil conservation, creating terraces with short spacing is not always favoured by farmers. This is because increasing the number of terraces reduces the crop production area of each field (Herweg & Ludi, 1999). However, it is possible to cultivate the terrace risers, e.g. with grass that can be used as fodder. A study on economic profitability of the terraces in Minchet catchment by Teshome et al. (2013) found that grass covered terraces were profitable, as the grass was a source of fodder.

On-site sediment deposition increases with slope gradient, which is true for both below and above 13 m spacing, with the exception of the similar results observed on the observation plots of p1 to p3 in 2015 (Table 4). Technically this can be justified as the spacing between terraces can be narrow in croplands, with a steeper slope gradient resulting in more terraces per hectare. The more terraces per hectare, the greater the sediment deposition area per hectare and sediment deposition per hectare. Moreover,

Table 5
Monthly precipitation and sediment deposition from July to September 2014/15.

Year	Month	Precipitation (mm)	Sediment deposition (t ha^{-1})
2014	July[a]	314	1.1
	August	367	4.4
	September	262	2.4
	Total	943	8
2015	July	312	5
	August	322	4
	September	242	2
	Total	876	11

[a] Sediment deposition is only from 11 to 31 July; t ha^{-1}: tonne per hectare; and mm: millimetres.

steeper slope gradients result in more soil loss than gentle gradients, resulting in more eroded soil available for deposition above the terrace risers of steeper slopes. This result is in line with a previous study in the semi-arid parts of the Ethiopian Highlands, where sediment deposition also increased with increasing slope gradients (Gebremichael et al., 2005; Nyssen et al., 2008).

Sediment deposition at the beginning of the cropping season was higher in 2015 than in 2014 (Table 5). However, this may be due to the differing plantation dates of the two crops (Table 2), which led to different starting dates of data collection. Less sediment deposition was measured in July 2014 (Table 4), as data collection started later (10 July, rather than 1 July as in 2015) due to field preparation and plantation activities on the horse bean fields (Table 2). Taking into account these variations in planting time and start of data collection, total sediment deposition in 2014 and 2015 may not be significantly different. We can assume that because of the soil disturbance in July and high run-off in August, soil loss in Minchet catchment could be almost the same in July and August. This agreed with Setegn et al. (2010) who found the catchment's mean monthly sediment yield in July and August to be almost in the same range.

In both 2014 and 2015 monthly precipitation from July to September ranged from 261 to 366 mm (Table 5). This is only a slight difference, and yet there was more sediment deposition in July and August than in September. This higher result for July and August can be explained as follows: while in 2015 the maize field had better crop cover in July and August than the horse bean crop had in 2014, the soil was disturbed by harrowing until July, and was therefore easily detached and transported by run-off or deposited above the terrace. Less sediment deposition was measured in September, possibly as a result of less soil erosion due to soil compaction and soil aggregation by plant roots and vegetation cover. In general, sediment deposition in both maize and horse bean fields may not be significantly different.

3.2. On-site sediment deposition and precipitation

On-site sediment deposition for each measurement day shows a higher result on the observation plots with narrow spacing (less than 13 m spacing between terraces) than on wider spacing (more than 13 m spacing between terraces) (Fig. 3 [A and B]). In 2014, due to the missing measurements at the start of July, less sediment deposition is shown, but this increases at the end of July and mid-August in both years (Fig. 3 A). Levels of both sediment deposition and precipitation showed similar tendencies of increasing and decreasing on most of the observation days with a few exceptions (Fig. 3 [A and B]). This could be because excess run-off flowed through the drainage ditches and joined the waterways. The run-off drained in this way from the cropland carried suspended sediment and may have affected the sediment trapping efficiency of the terraces. On the other hand, in semi-arid areas of Ethiopia such as Tigray, the conservation structures have been constructed to accumulate both water and soil in the deposition zone (Nyssen et al., 2009); accordingly, we assume precipitation and on-site sediment deposition might show a high correlation. This is in line with previous studies, which have shown that the effect of SWC technologies on run-off rate has been higher in semi-arid areas but lower in the humid Ethiopian Highlands (Hurni et al., 2005). Moreover, Haregeweyn et al. (2015) noted that the relative efficiency of SWC was higher in the drylands than in the sub-humid and humid areas of Ethiopia.

3.3. Net soil loss on the terraced cropland

The present study applied the USLE to calculate the amount of net soil loss on the observation field (Fig. 2) of terraced cropland, using the method presented in Section 2.4. The C and P factors of the USLE were updated for this study, because the USLE input factors 0.1 for maize and 0.15 for horse bean suggested by Hurni (1985) differed from the C factor of 0.5 for horse bean and 0.05 for maize suggested later by Kaltenrieder (2007). As a result, the updated C factor after Hurni (1985) and Kaltenrieder (2007) was 0.3 and 0.4 for maize and horse bean respectively, with an R^2 value of 0.83 (Table 2). In addition to the previous P factor (0.9) for contour ploughing recommended by Hurni (1985), the traditional ditch is also considered as a supporting practice with a P factor of 0.9, as it is very important to control run-off in the croplands of the study area. The total P factor for contour ploughing and drainage ditches was thus 0.81. Therefore, the updated C factor for horse bean and maize, and the combined P factor for contour ploughing and drainage ditches, gives results that correspond better with measured soil loss in the SCRP test plot in Minchet catchment.

Using the USLE, average soil loss by water ranges from 31 to 37 t $ha^{-1}yr^{-1}$ (Table 4) in the terraced crop field where the observation plots are located. Soil loss increases as slope gradients increase, which is in line with a previous study in the Ethiopian Highlands where soil loss was found to increase with the slope by up to 25% (Defersha, Quraishi, & Melesse, 2011). In 2014/15, soil loss in the observation period ranged from 17 to 22 t ha^{-1} (Table 4). From the total soil loss in the observation plots in the observation period, about 54–74% was deposited in the deposition zone of the terraced crop field. This increases soil depth, contributing to the improvement of soil quality in the study area (Mengistu et al., 2015). The improvement in soil quality and reduction in slope gradient leads to improvement in land suitability for crop production in the study area (Alemu et al., 2013). Moreover, the SWC in the study area helped to develop a terraced landscape. This reduced slope length as well as slope gradient, both of which could reduce soil loss.

The amount of net soil loss that leaves the observation field in the cropping season 2014 and 2015 ranges from 6 to 12 t ha^{-1}, and the net soil loss is slightly higher in 2014. In 2014, the crop cover was horse bean and the C factor for horse bean is slightly higher than for maize, possibly contributing to more soil loss. Although a substantial amount of sediment deposited in the terraced plots, such net soil losses especially in the terraced cropland with wider spacing are still above the tolerable level. According to Hurni (1983), areas between 2000 and 2500 m a.s.l. should not have more erosion than 6 t ha y^{-1}, corresponding to the soil formation rate in this agro-ecological zone. Thus, reducing spacing by increasing the number terraces even in the terraced croplands can reduce net soil loss below the tolerable level of the study area.

The negative results of net soil loss in the observation field of p4 could indicate some limitation of USLE for less than 13 m slope length and gentle slope gradients (Table 4), because this shows sediment deposition is higher than soil loss. Furthermore, run-on from the upper farm plots to the next lower field is not common in the study area, as the traditional drainage ditches and the terraces control the run-off; then deposition may not be higher than erosion. Perhaps the LS factor for short slope length and gentle slope gradient might affect the result of soil loss. The USLE has been recommended to calculate annual soil loss (Wischmeier & Smith, 1978), and most of the previous studies use USLE for annual erosion (Brhane & Mekonen, 2009; Nyssen, Poesen, & Haile, Moeyersons, Deckers & Hurni, 2009). Nevertheless, the overall estimation of soil loss in the cropping season was quite reasonable, except in the plots with short slope length and gentle slope gradient. This might indicate that further research is needed to calculate the LS factor for short slope length and gradient.

4. Conclusion

This study clearly showed deposition of eroded soil by water on terraced croplands in Minchet catchment in the sub-humid Ethiopian Highlands. Such deposition is mainly above the riser slope of the terrace, on the deposition zone of the terraced field. During the crop growing seasons of 2014 and 2015, it was observed that about 54–74% of soil loss was deposited on the terraced cropland, a highly promising result of SWC technologies to combat soil erosion and boost soil quality in area. However, net soil loss above the tolerable level of the study area was observed especially on terraced fields with wider spacing between terraces.

The wider spacing between terraces results in fewer terraces and smaller deposition areas per hectare. The widely-spaced terraces thus have less deposition in t per ha than those with narrow spacing. More on-site sediment deposition was seen on the observation plots with narrower spacing and steeper slope gradient than in those with wider spacing and gentle slope gradient. Thus, more soil can be sustainably conserved in the cropland in two ways. One, by increasing the number of terraces, especially through steeper slope gradient and wider spacing. Two, by making the terrace productive by planting e.g. fodder grass to compensate occupying crop production area.

Methodologically, studying on-site sediment deposition without influencing the natural process of soil erosion and deposition was quite challenging. This study did so with minimum influence. The USLE-based assessment of soil loss using the updated C factor for maize and horse bean crops, and including the traditional ditches and contour ploughing as P factors, gives a result closer to the measured soil loss in Minchet catchment. However, the USLE needs to be further developed for use in the sub-humid Ethiopian Highlands, particularly the LS factors for fields with short slope length and gentle slope gradient. Moreover, another challenge was measuring the area of the sediment deposition zone: the equation for the area of the deposition zone could be further developed in relation to spacing between the terraces, slope gradient, and precipitation for areas of terraced croplands. The findings of our study show that SWC technologies conserve a substantial amount of the eroded soil in the terraced croplands, which can contribute to enhancing sustainable land management in the Ethiopian Highlands. However, a good deal of eroded soil is still leaving the terraced cropland. Thus, continued improvement of SWC technologies to reduce net soil loss even further and to improve on-site sediment deposition capacity are recommended.

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