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ORIGINAL ARTICLE

Quantifying annual soil and nutrient lost by rill erosion in continuously used semiarid farmlands, North Ethiopia

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Abstract The loss of soil from land surfaces by erosion is widespread and reduces the productivity of agricultural lands. Concurrently, due to increasing human population, agricultural land expansion and exploitation, soil erosion and nutrient loss are the major environmental problems in Ethiopia. This study was conducted to estimate annual losses of soil, soil nutrients and carbon due to rill erosion. The entire watershed was classified into 12 land mapping units (LMUs). Consequently, the cropland was delineated to estimate soil and nutrient losses. Dimensions of the rills were measured at different parts of the landscape, and rill volume of rill erosions was assessed in the field. Disturbed representative composite soil samples were taken from each LMU to estimate the main soil nutrients, and each soil nutrient was estimated using different methods. The result revealed that the amount of soil lost through rill erosion was found to be 3.17 t ha^{-1} $year^{-1}$. The average annual nutrient loss by the rill erosion was 41.4 kg ha^{-1} soil organic matter content, 2.4 kg ha^{-1} total N, 0.02 kg ha^{-1} available P and 0.3 kg ha^{-1} exchangeable K. The annual estimated cost of the soil nutrient lost (total N and available P) due to rill erosion was found to be 1341 USD. This cost would be used to replace the total N and available P nutrients lost through the addition of mineral fertilizers. Water erosion in the form of rill erosion was severely affecting soil fertility management and crop production in the study watershed. Hence, effective integrated watershed management interventions and farmland managements could combat soil erosion.

Keywords Rill erosion · Land mapping units · Soil loss · Nutrient loss

Introduction

Land degradation particularly through soil erosion is the main challenge to agricultural sustainability in Ethiopia. Loss of soil due to current and historical poor management is the main cause for low crop productivity and inefficient use of cropping inputs. It can also have significant off-farm adverse impacts on the environment (Meadows 2003). Soil erosion is regarded as one of the most critical environmental problems in the world (Meadows 2003; Le Roux et al. 2007, 2008; Wei et al. 2007; Schonbrodt-Stitt et al. 2013; Ma et al. 2014). It mainly occurs in the form of sheet, rill and/or gully erosion (Morgan 2005; Le Roux et al. 2008). Rill erosion mainly occurs as a result of concentrated overland flow of water leading to development of small well-defined channels (Haile and Fetene 2012). These channels act as sediment sources and transport passages leading to soil loss (Wirtz et al. 2012). Although soil erosion is a natural process, it has been accelerated by human impact on the landscape due to continuous agriculture activities, overgrazing, mining and others (Gimenez-Morera et al. 2010; Leh et al. 2013;

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Lieskovský and Kenderessy 2012; Mandal and Sharda 2013; Zhao et al. 2013; Ziadat and Taimeh 2013). Tillage results in the permanent alteration of the soil structure and soil aggregate, leading to increased soil erosion (Ramos-Scharron and Macdonald 2007).

Ethiopian agriculture is a traditional way commonly described with rain-fed mixed farming system (crop cultivation and livestock rearing) managed by smallholder farmers (Mamo 2010). Ethiopia's topography is generally categorized into uplifted central highlands and tapering into peripheral lowlands. The Ethiopian highlands, which are the center of major agricultural and economic activities, have been the victim of soil erosion for many decades. The gradual increment in soil erosion and nutrient depletion in Ethiopia became a serious threat to agricultural productivity (Kebede and Chekol 2009). Moreover, high tillage frequency and other soil management problems have seriously affected soil erosion over 25% of the Ethiopian highlands (Haile et al. 2006). Hurni (1993) has also estimated that average soil loss from Ethiopian croplands is 42 t ha^{-1} $year^{-1}$. This resulted in a loss of 1–2% annual crop production. The expansion and intensification of agricultural cultivation using inappropriate practices leads to exhaustion of soil resources, deterioration of soil quality and eventually to a decline in land productivity (Shivakoti 2005).

In Ethiopia, many land management technologies such as soil and water conservation (SWC) activities have been introduced and implemented over the previous three decades by governmental and non-governmental institutions (Kebede et al. 2010). However, ongoing degradation of cultivated land together with the small plot size is threatening the food security of rural communities (Lema et al. 2016). Despite this degradation, and that rill erosion is likely to be a major contributor to total erosion, there are few data available from the watershed on rill erosion severity on cropland. Thus, the main objectives are to estimate the amounts of soil and soil nutrient lost due to rill erosion on continuously cultivated farmlands.

Methodology

Description of the study area

The study was conducted in Ruba Gered watershed, Werie Leke district, which is located between 14°00′ to 14°03′ N latitude and 38°58′ to 39°00′ E longitude (Fig. 1).

The altitude of the study area ranges from 1811 to 2286 m.a.s.l. The study area has a unimodal rainfall distribution, averaging 800 mm p.a. (Fig. 2a) with the rainy season from June to September. Average precipitation exceeds 250 mm per month in August alone, causing soil erosion and formation of rills in cultivated lands (Fig. 2b).

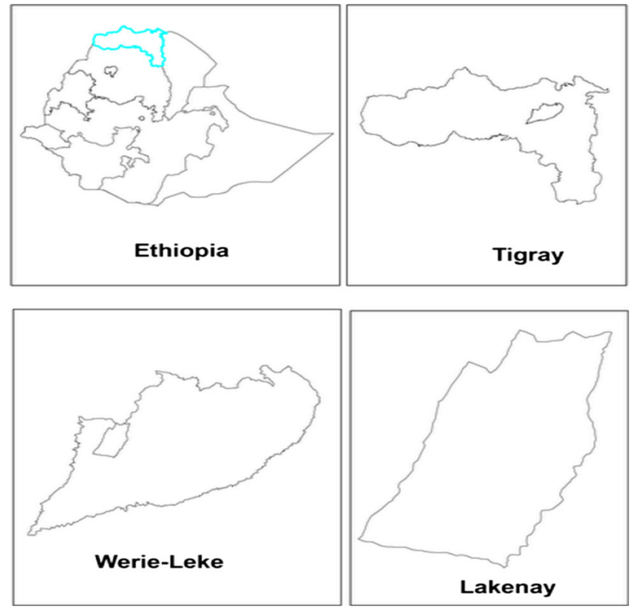

Fig. 1 Location map of the study area

The highest and lowest mean monthly temperature of 23.1 and 17.7 °C was recorded in May and November, respectively. The main soil types of the study watershed are Regosols, Cambisols, Luvisols and Arenosols (BoFED 2003). The total area of the watershed is 768.8 ha of which 406.8 ha is cultivated land. The study watershed is characterized by undulating surface, flatlands and mountains. The surrounding mountains are characterized by gentle to steep slopes covered with scattered bushes. The study watershed has a total population of 1032 in 241 households. The dominant crops produced in the study area are teff, wheat, bean and maize. Free grazing is widely practiced in the area. As a result, the vegetation cover has been degraded for a long period of time.

Map production

Land-use cover and rill erosion maps were produced using GIS software. A digital elevation model (DEM) was used as input data for TNTmips (micro image-X server 2006) to develop a base map of the study watershed. This was based on an automatic procedure with 30 × 30 m resolution using geographical positioning system (GPS) readings of the watershed outlet with a correction factor of ±8 m. Two GPS reading points were taken from each current land use to validate and separate land uses. The GPS readings were used as base points for supervised land-use classification (Lema et al. 2016). Thereafter, true color merged images were formed through combining the visible spectral bands. Finally, the Thematic Mapper (TM) images were used to produce a land-use map. Moreover, a topographic map (1:50,000 scale) of the study watershed was used as a base

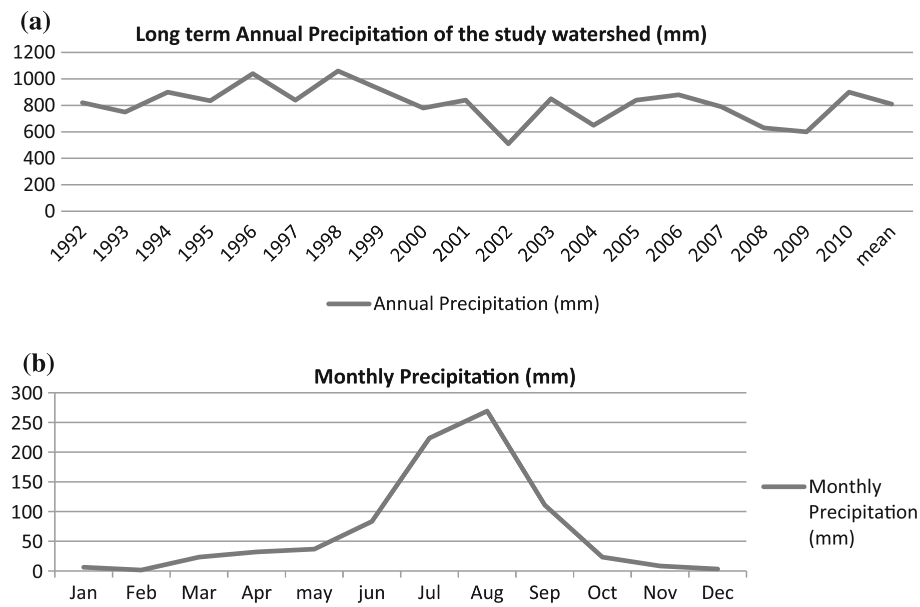

Fig. 2 Long-term annual precipitation (**a**) and monthly rainfall (**b**) of the study area

for aligning the GPS data with satellite imagery classification. Accordingly, cultivated land, grazing land, closure area, bare land, earthen dam and settlement areas were identified. Slope map of the study watershed was produced from DEM with the help of GPS data based on the similarity of the landforms. The soil map was delineated using the GPS readings, the 2007 TM images and TNTmips software. Maps of the Luvisols, Cambisols, Regosols and Arenosols were then produced after on-screen digitization. Land mapping units (LMU) that show similar characteristics to the watershed were identified by overlaying the digitized slope and soil map of the watershed and assuming that other factors were constant (Fig. 5a). After subdividing the watershed into LMUs, soil lost from each LMU was estimated. Similarly, cultivate area of the cultivated land in each LMU was computed by the overlaying process described above.

Quantification of soil lost by rill erosion

To estimate the amount of soil lost through rill erosion from the study watershed, eight rigidly selected transect walks (200 m width) were made along the contour (Fig. 3).

The rigidly selected transects include cultivated lands from the twelve LMUs. The rill erosion was identified with weekly field visits in the months of July and August. Rill dimensions of the croplands obtained with in these eight rigidly selected transects were then measured (Fig. 3).

Rill erosion creates channels of which the dimensions can be measured. Rill erosion dimensions (length, width and depth) were measured to estimate the volume of soil lost. The rills in each LMU were categorized to estimate volume of soil loss per LMU. 243 rills were measured in the eight transects from the twelve LMUs and categorized into each LMU with the help of GPS and Topo-map. The sample area covered 30.7% of the total cultivated land. Each rill was divided into sections, and length, width and depth were measured in the cultivated area using tape meter and ruler. The length of a rill was measured from its starting point (upper part) up to the place where sedimentation occurred. Furthermore, the width and depth were also measured at three different points along the length of each rill (up slope, mid slope and down slope) and then the average was taken. Finally, rill volume, rill density, rill texture, soil loss and actual area damaged were determined after Getachew (2009). Thus, volume of soil loss was estimated using Eq. (1).

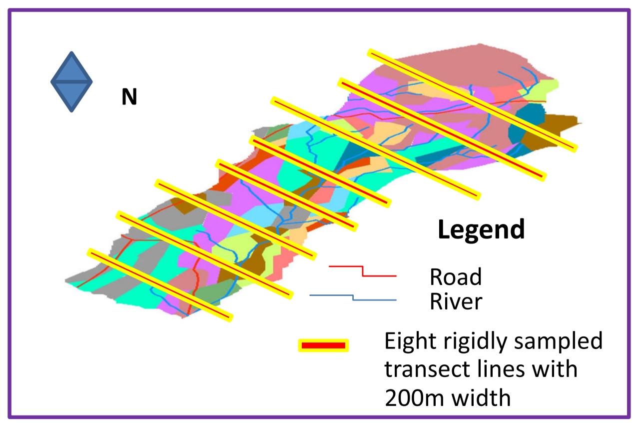

Fig. 3 Rill erosion measurement sampling method

$$\text{Volume of rills}\ (\mathrm{m}^3) = 1.57 \times \text{width} \times \text{depth} \times \text{length} \quad (1)$$

where 1.57 is $\pi/2$

Mass of soil lost was estimated using Eq. (2);

$$\text{Mass of soil loss by rills (t/ha/year)} = \frac{\text{volume of rill } (m^3) \times \text{Bulk density } (\text{t/m}^3)}{\text{Field size (ha)}} \quad (2)$$

$$\text{Damaged area out of total field size } \left(\text{m}^2/\text{ha}\right) = \frac{\text{width of rill (m)} \times \text{length of rill (m)}}{\text{Field size (ha)}} \quad (3)$$

$$\text{Rills density (m/ha)} = \frac{\text{Length of rill (m)}}{\text{Field size (ha)}} \quad (4)$$

Estimation of nutrient lost by rill erosion

The nutrients that were lost by rill erosion were analyzed through soil samples from the rills' side at soil depth equal to rills' depth. To estimate soil nutrient lost through rill erosion, the main soil nutrients were analyzed from the measured rills in the sampled cultivated area. Accordingly, representative disturbed composite soil samples made of five auger points were collected from each LMU (Fig. 4) at 0–20 cm depth. Finally, SOM content, total N, available P and exchangeable K per unit cropland were estimated.

Soil was analyzed for organic carbon using the Walkley and Black method through oxidation of organic carbon with potassium dichromate ($K_2Cr_2O_7$) in sulfuric acid (Walkley and Black 1934). Exchangeable K was estimated using flame photometer method extracted by ammonium acetate (Morgan 1941), and total N was analyzed using Kjeldahl method through titration in sulfuric acid (0.01N H_2SO_4) (Bremmer and Mulvaney 1982). Available P was analyzed using Olsen method for soil samples with pH greater than 7 (Olsen et al. 1954) and using Bray method for soil samples with pH less than 7 (Bray and Kurtz 1945). Soil bulk density was estimated using core method (Jury and Horton 2004). Analysis of the above soil nutrients helped to determine the amount of nutrients available in the

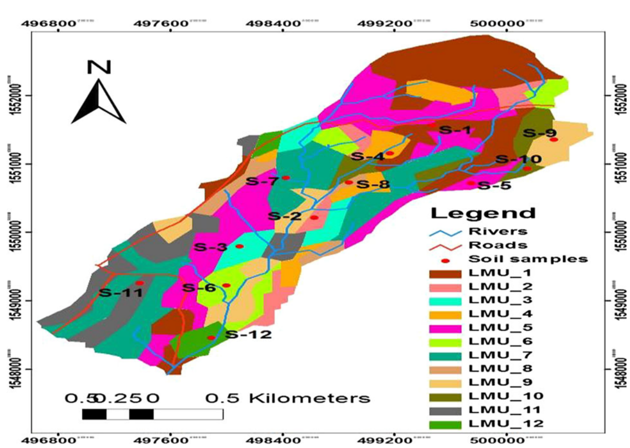

Fig. 4 Soil sampling points

soil lost due to rill erosion. Bulk density was used as a multiplier to determine weight of soil lost (t ha^{-1} $year^{-1}$) from volume of soil lost (m^3 ha^{-1}). Cost of the nutrients lost was computed using the nutrient content of the soil in each LMUs and current cost of mineral fertilizers especially urea and diammonium phosphate. The only sources of nutrients from inorganic fertilizers in the study area were urea and diammonium phosphate.

$$\text{Nutrients loss (kg)} = \text{soil loss (kg/ha/year)} \times \% \text{ of nutrient content of the soil} \times \text{field size (ha)}. \quad (5)$$

$$\text{Cost estimation (\$)} = \frac{\text{nutrient loss (kg)} \times \text{current cost of fertilizer (\$)}}{\text{Content of nutrient in 100 kg of fertilizers (kg)}}. \quad (6)$$

Results and discussion

Map development

The slope of the watershed ranged from 0 to 33%, and slope of the cultivated land is 0 to 15%. The study watershed was categorized into three slope classes as flat or almost flat (0–3%), moderate (3–8%) and moderate to steep slope (8–33%). Moreover, twelve land mapping units were developed depending on their homogeneity (Fig. 5a), and features of each LMU are characterized in Table 1.

Soil loss due to rill erosion

The average soil loss in the study watershed due to rill erosion was found to be 3.17 t ha^{-1} $year^{-1}$ and ranged from 1.46 t ha^{-1} $year^{-1}$ in LMU 8–9.02 t ha^{-1} $year^{-1}$ in LMU 6 (Table 2). The average width, depth and length of rills found were 68, 9 and 892 cm, respectively. The total number of rills was 243 with a total length of 1878.8 m. The average rill density was 17.33 m ha^{-1}, with the highest rill density observed in LMU 6 (40.8 m ha^{-1}) and the lowest was observed in LMU 12 (4.3 m ha^{-1}). The total damaged area of the sampled field due to rill erosion was 1568.48 m^2. The average damaged area of the cultivated land was 12.1 m^2 ha^{-1}, i.e., 2.5% of the total cultivated land, with a range of 3.5 m^2 ha^{-1} in LMU 8–16.9 m^2 ha^{-1} in LMU 11 (Table 2). Different factors such as slope length, slope gradient, soil depth and vegetation covers vary among the land mapping units and affect rill erosion differently. Hence, the cultivated land degradation severity was rated by the rill erosion rates based on the amount of soil lost (Fig. 5b).

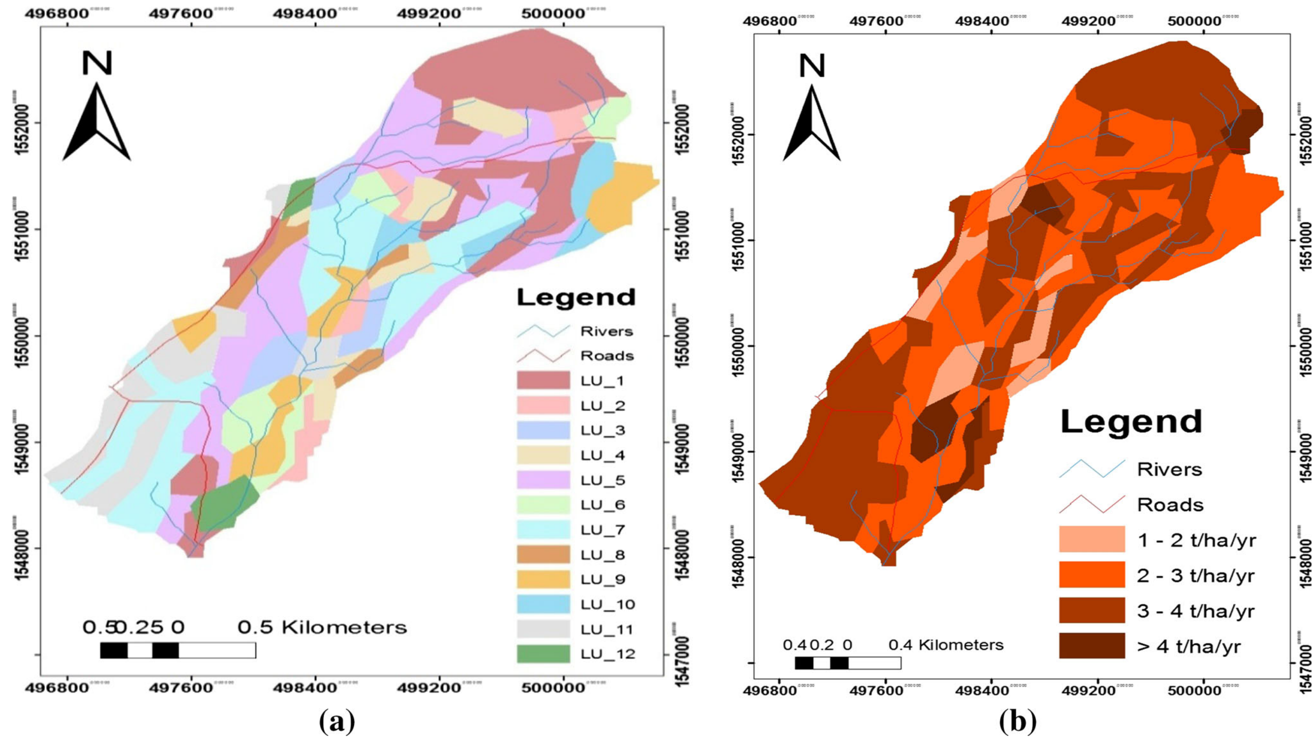

Fig. 5 Land units map (**a**) and rill erosion severity classes (**b**)

Table 1 Major features of land mapping units

Land mapping units	Area (ha)		Soil type	Slope (%)	Landform	Vegetation status and erosion indicator
	Total	Cultivated land				
LMU1	142.3	15.6	L	8–33	Hus	Scattered bushes with high erosion indicators
LMU2	30.5	21.4	C	8–33	Hs	Few vegetation with high erosion indicators
LMU3	32.4	20.6	R	8–33	Hs	With scattered trees with low erosion indicators
LMU4	38.8	15.3	A	8–33	Ss	Scattered trees with some erosion indicators
LMU5	150.6	59.9	L	3–8	Msp	Some scattered trees with some erosion indicators
LMU6	43.9	32.7	C	3–8	Ms	Bare land/no vegetation with very high erosion indicator
LMU7	122.2	97.5	R	3–8	Ms	Scattered bushes with erosion indicators
LMU8	22.8	9.8	A	3–8	Fs	High grass cover with minimal erosion indicator
LMU9	55.3	47.1	C	0–3	P	Few vegetation with erosion indicators
LMU10	33.0	11.8	L	0–3	P	Some fallow practice with minimal erosion indicator
LMU11	77.5	58.9	R	0–3	Gs	Some agroforestry species with erosion high indicators
LMU12	19.5	16.2	A	0–3	Fp	Some scattered trees with some erosion indicators
Total	768.8	406.8				

NB: *L* luvisols, *C* cambisols, *R* regosols arenosols, *Hus* hills and upper slope, *Hs* hills side, *Ss* steep slope, *Msp* middle slope in plateau, *Ms* middle slope, *Fs* foot slope, *P* plateau, *Gs* gentle slope, *Fp* flood plain

All LMUs lost less than 10 t soil ha^{-1} year^{-1} due to rill erosion. Hence, according to FAO's (1998) water erosion rating, all LMUs were classified as no to slight erosion. The highest rill erosion found in LMU 6 might be due to unstable soil aggregates and excessive tillage. According to Herweg (1996), the highest rill size/width of the study watershed was 97.5% (237 rills) and classified as medium, 2% (5 rills) as small and 0.5% (1 rill) classified as large classes. Similarly, 90% (219) of the rill depth were classified as shallow, 9% (21) as medium, 1% (3) as deep classes and no rill was recorded as very deep. The majority of the rills were small and ended within the same fields.

Nutrient lost by the rill erosion

The annual estimated nutrient losses due to rill erosion were 3.92–106.44 kg ha^{-1} of SOM content, 0.86–6.4 kg ha^{-1} total N, 0.01–0.06 kg ha^{-1} available P and 0.09–0.86 kg ha^{-1} exchangeable K (Table 3). The total annual nutrient losses from the total cultivated land were 18,277 kg SOM content, 1137 kg total N, 9 kg available P and 146 kg exchangeable K (Table 3). In agreement to this study, Pimentel et al. (2004) point out that a ton of fertile agricultural topsoil typically contains 1–6 kg of total N, 1–3 kg of available P and 2–30 kg of exchangeable K, whereas a severely eroded soil may have total N level of only 0.1–0.5 kg ton^{-1}. The annual nutrient loss cost due to rill erosion is estimated to be 1341 USD (22,794 ETB). This can replace the nutrients lost (total N and available P nutrients) by adding mineral fertilizers.

The highest organic matter and nutrient loss (SOM content, total N, available P and exchangeable K) per hectare due to rill erosion was observed in LMU 6 while the lowest losses were in LMUs 9, 3, 1 and 8, respectively. This might be due to more exposure of LMU 6 to rill erosion while LMUs 9, 3, 1 and 8 had the lowest corresponding nutrient values (Table 3). Thus, the nutrient loss difference among the LMUs was mainly due to the differences in nutrient content of the soils rather than differences in soil loss rates. The amount of soil loss due to rill erosion is less than some studies done in different parts of Ethiopia. For example, soil loss due to rill erosion in Rekame catchment, Ethiopia was 16.53, 12.07 and 6.12 t ha^{-1} $year^{-1}$ from upper, middle and lower slope, respectively (Getachew 2009). However, Lema et al. (2016) has reported that soil erosion in the study watershed transported important soil nutrients such as SOM content, TN, Av. P and Av.K. As most soil nutrients are accumulated in the topsoil, the eroded topsoil due to sheet and rill erosion holds about three times more soil nutrients per unit weight than are left in the remaining subsoil (Young 1989). The differences in rill density, number of rills and the magnitude of soil loss might be due to land management, topographical factors, soil type and depth and vegetation cover (Woo et al. 1997).

Conclusions

The results have shown that the width, depth and length of rills range from small to large depending on the soil type and slope gradient. However, the majority of the rills have medium width, shallow depth and short length. Though there is a difference in soil loss among LMUs, soil lost due to rill erosion from the cultivated land of the study area was slight to medium compared to other studies. The

Table 2 Summary of measured characteristics of some rills in Ruba Gered watershed

Land units	No. of transects out of 8 randomly selected	No of rills	Rills aver. width (cm)	Rills aver. depth (cm)	Rills aver. length (m)	Field size (ha)	Total volume of soil lost (m^3)	Volume of soil lost (m^3 ha^{-1})	Bulk density (t m^{-3})	Soil loss (t ha^{-1} $year^{-1}$)	Damaged area (m^2)	Damaged area (m^2 ha^{-1})	Rills length (m)	Damaged area out of total (%)	Rills density (m ha^{-1})
LU1	4	38	49.66	8.39	7.58	11.29	25.40	2.25	1.54	3.46	159.58	4.2	288.0	0.142	25.51
LU2	6	16	70.17	8.56	8.94	9.41	22.23	2.36	1.47	3.47	119.20	7.5	143.0	0.127	15.20
LU3	4	11	67.06	6.98	8.27	5.54	7.35	1.33	1.22	1.62	63.90	5.8	91.0	1.235	16.40
LU4	3	11	59.55	6.61	8.64	6.65	8.78	1.32	1.68	2.22	64.40	5.9	95.0	0.097	14.30
LU5	7	58	51.51	8.57	0.96	26.16	53.04	2.03	1.46	2.96	302.80	5.2	55.4	0.143	26.20
LU6	4	42	59.05	11.41	11.55	11.88	67.82	5.71	1.58	9.02	318.30	7.6	485.2	0.268	40.80
LU7	5	32	64.42	8.91	11.18	21.08	42.72	2.03	1.57	3.18	245.40	7.7	357.7	0.116	17.00
LU8	2	6	31.28	7.63	10.75	2.78	2.61	0.94	1.56	1.46	21.00	3.5	64.5	0.075	23.20
LU9	5	13	68.79	11.40	9.99	15.52	21.01	1.35	1.61	2.18	94.50	7.3	129.9	0.061	8.40
LU10	1	5	71.66	9.36	11.40	3.50	6.00	1.71	1.37	2.35	43.60	8.7	57.0	0.058	8.60
LU11	2	7	120.04	10.33	13.64	9.08	23.35	2.57	1.45	3.73	118.40	16.9	95.5	0.108	8.10
LU12	1	4	105.75	11.80	4.15	2.15	3.24	1.51	1.59	2.40	17.40	4.4	16.6	0.045	4.30
Aver.	3.67	243	68.24	9.43	8.92	125.04	283.55	2.09	1.508	3.17	1568.48	7.0	1878.8	2.475	17.33

Table 3 Soil nutrient lost due to rill erosion

Land units	Field size (ha)	Soil loss (kg ha^{-1} year^{-1})	OM (%)	OM loss (kg ha^{-1})	Total OM loss (kg)	Total N (%)	Total N loss (kg ha^{-1})	Total N loss (kg)	Avail. P (%)	Avail. P loss (kg ha^{-1})	Total Avail. P loss (kg)	Exch. K (%)	Exch. K loss (kg ha^{-1})	Exch. K loss (kg)
LU1	15.6	3460	1.79	61.93	966.2	0.05	1.73	26.99	1.17	0.004	0.063	120.37	0.42	6.50
LU2	21.4	3470	1.16	40.25	861.4	0.041	1.42	30.45	5.45	0.019	0.405	55.56	0.19	4.13
LU3	20.6	1620	3.91	63.34	1304.8	0.053	0.86	17.69	7.14	0.012	0.238	125.36	0.20	4.18
LU4	15.3	2220	1.03	22.87	349.8	0.07	1.55	23.78	6.16	0.014	0.209	80.48	0.18	2.73
LU5	59.9	2960	1.47	43.51	2606.4	0.095	2.81	168.44	1.88	0.006	0.333	140.31	0.42	24.88
LU6	32.7	9020	1.18	106.44	3480.5	0.071	6.40	209.42	6.88	0.062	2.029	90.46	0.82	26.68
LU7	97.5	3180	1.92	61.06	5953.0	0.104	3.31	322.45	12.06	0.038	3.739	110.4	0.35	34.23
LU8	9.8	1460	0.92	13.43	131.6	0.099	1.45	14.16	3.88	0.006	0.056	60.54	0.09	0.87
LU9	47.1	2180	0.18	3.92	184.8	0.048	1.05	49.29	5.59	0.012	0.574	100.37	0.22	10.31
LU10	11.8	2350	1.74	40.89	482.5	0.109	2.56	30.23	3.17	0.007	0.088	130.34	0.31	3.61
LU11	58.9	3730	0.83	30.96	1823.5	0.101	3.77	221.89	7.28	0.027	1.599	110.4	0.41	24.25
LU12	16.2	2400	0.34	8.16	132.2	0.057	1.37	22.16	5.38	0.013	0.209	85.47	0.21	3.32
Total	406.8	3170	1.4	**41.40**	18,276.7	0.077	**2.36**	1136.94	5.34	**0.018**	9.060	100.84	**0.32**	145.69

Bold values denote the nutrient lost

differences in soil loss among LMUs were due to the differences in slope gradient, soil length and vegetation cover.

Nutrient lost due to rill erosion was not severe. Nevertheless, as mineral fertilizers are not affordable for smallholder farmers to replace the nutrient lost from their cultivated land, it is essential that management changes are taken to ensure the long-term sustainability of agricultural systems and to avoid irreversible losses.

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