Assessing Sediment Enrichment Ratio in Mai-Negus Catchment, Northern Ethiopia

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Abstract

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Soil degradation is a threat to sustainable development in Ethiopia. However, degradation indicators, such as sediment enrichment ratio (SER), are not adequately documented in literature. This study aims to investigate the SER of different erosion-status sites (aggrading, stable, eroded) in various landforms in Mai-Negus catchment, northern Ethiopia. The erosion-status sites in the landforms were identified using field indicators, and soil samples were collected for analysis of selected soil parameters. In this study, due to the ratio of aggrading to eroded or stable sites at catchment and landform levels, the SER of soil nutrients and fine soil particles was > 1. But due to the ratio of aggrading to eroded sites in the landforms the average SER of the soils were higher (1.42–7.22) as compared to the ratios of aggrading to stable sites (1.10–3.66). The SER significantly ($P \leq 0.05$) differed among the landforms, which indicated differences in the effect of erosion. The relationships between the SER of fine soil particles and soil nutrients were strong. Thus, priority for introducing appropriate anti-erosion measures should be given to sources of high SER sites such as the mountainous and central ridge landforms in the catchment using the limited resources available.

Keywords: degradation; erosion-status sites; landform

Soil erosion is a serious form of land degradation and is threatening agriculture in many parts of the world such as Ethiopia (UNEP & UNESCO 1980; Eswaran *et al*. 2001). Land degradation due to erosion in the Tigray region of Ethiopia can be tracked even from space (Vlek *et al.* 2010). The impact of erosion is high in the region with the average soil loss of more than 49 t/ha per year (Tamene 2005). This value exceeds the average soil loss of 42 t/ha per year for Ethiopia as a whole (Hurni 1993). Soil loss through water erosion is almost always accompanied by losses of essential soil nutrients. This is because the erosion process is selective in that the fine soil particles, which are relatively richer in soil nutrients, are more susceptible to erosion (Ellison 1950; Hashim *et al.* 1998). Reports also show that as compared to rates in Sub-Saharan Africa, Ethiopia belongs to the countries exhibiting the highest soil nutrient outflow rates of 60 kg/ha (30 kg/ha nitrogen and 15–20 kg/ha phosphorus), while inflows from fertilizers are very low (< 10 kg/ha) (e.g. Stoorvogel & Smaling 1990; UNDP 2002). In the long term, soil nutrient losses by erosion adversely affect soil productivity of the source areas while increase of nutrients in deposition areas is expected (Ellison 1950; Hashim *et al.* 1998).

Enrichment ratios can describe degradation of the source soils and enrichments in the deposition sites (Haregeweyn *et al.* 2008). An enrichment ratio, which is defined as the ratio of values in the sediment to the source soil, is often used as an index of soil productivity (Quansah *et al.* 1997; Hashim *et al.* 1998; Haregeweyn *et al*. 2008). Despite such utility, the nutrient enrichment ratio as a means of assessing degradation from landforms in a catchment considering different erosion status-sites has not received researchers' attention yet. However, such a study is pertinent to the development of site-specific strategies targeting the source sites.

Characterizing sediment enrichment ratios in a landscape unit such as landforms is critical for predicting rates of degradation processes (Schimel *et al.* 1991), and for understanding how systems in a catchment work (Kosmas *et al.* 2000). Knowledge on spatial variability of erosion-deposition processes in a landform through enrichment ratio is also necessary to locate homogeneous sites that need careful management for sustainable development (Schimel *et al.* 1991). Despite of these facts, soil degradation indicators such as sediment enrichment ratio are not sufficiently documented at landform level. Research is thus needed on such issue to properly identify landscape units that are prone to erosion in a catchment. The aim of this study is to assess sediment enrichment ratio of selected soil properties using the aggrading, stable, and eroded erosion-status sites in the landforms of Mai-Negus catchment, northern Ethiopia.

MATERIAL AND METHODS

Study area description. This study was conducted in Mai-Negus catchment in the Tigray region, northern Ethiopia (Figure 1). The catchment has an area of 1240 ha and is situated at altitudes ranging 2060–2650 m a.s.l. Mean annual temperature attains to 22°C and precipitation to 700 mm. The land is predominantly arable, with teff (*Eragrostis tef*) being the major crop along with different-sized areas of pasture, bushes, and shrubs. The major rock types are lava pyroclastics and meta-volcanics. Soils are mainly Leptosols on very steep positions, Cambisols on middle to steep slopes, and Vertisols on flat areas.

Terrain assessment approach. In this study, field reconnaissance surveys were carried out to gain an overall image of the catchment characteristics (Table 1). Data were collected from June to December 2009. The landforms in the catchment (Figure 1) were developed in ArcGIS software using field survey-based data in combination with information from the topographic map. Considering elevation, slope, geology, and geomorphologic character (surface flows, alluvial and colluvial deposition), the catchment topography can be classified into six main landforms (Figure 1), namely: valley (19% of the catchment area), plateau (8%), rolling hills (9%), central ridge (27%), escarpments (29%), and mountainous (6%).

The reservoir was considered a separate landform. Sediment deposition in the reservoir was used to determine the enrichment ratio at the catchment level. Erosion-deposition sites in the other landforms of the catchment were identified using field indicators. During the field survey, based on observation of geomorphological indicators, three erosion-status sites – deposition/aggrading, stable, and eroded – were identified within the landforms.

Erosion-status site selection and soil sampling points. Erosion-status sites (aggrading, stable, and eroded) and the corresponding soil sampling points (Figure 1) were selected in four steps. A reconnaissance survey (Table 1) was followed by informal discussions with farmers to gain insight in land-use history as well as land- and crop-management practices. Subsequently, erosion-status sites were selected

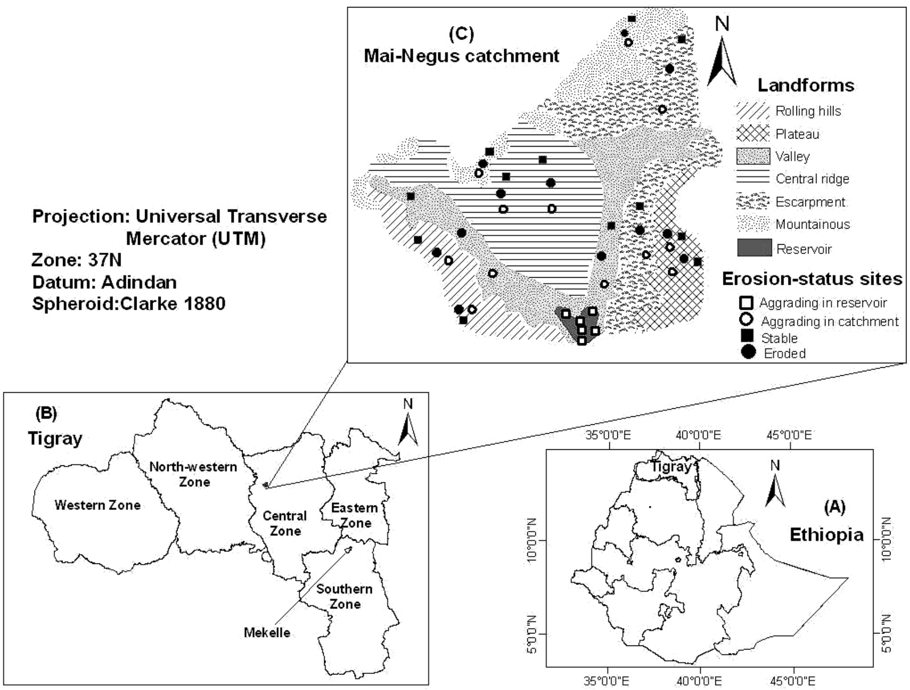

Figure 1. Study area: Ethiopia (A), Tigray (B); Mai-Negus catchment with soil sampling points for aggrading (deposition), stable, and eroded sites (C)

Table 1. Biophysical description of landforms in the study catchment

Landform	Area[e] (%)	Land-use cover[a] (%)				Lithology[b] (%)			Slope[c] (degrees)	Elevation[d] (m)
		arable	grazing	bush and wood[f]	others[g]	BM	LP	ST		
Rolling hills	10.0	80	10	4	6	100	n.a.	n.a.	3–16	2150–2240
Mountainous	14.5	36	34	26	4	35	65	n.a.	4–79	2350–2650
Central ridge	25.5	70	13	5	12	5	95	n.a.	3–25	2230–2450
Valley	19.9	65	31	2	2	77	23	n.a.	0–6	2070–2100
Plateau	9.8	47	16	30	7	58	42	9	3–10	2500–2550
Escarpment	19.1	47	31	14	5	84	7	n.a.	3–30	2270–2540
Reservoir	1.2	n.a.	n.a.	n.a.	n.a.	100	n.a.	n.a.	0	2060–2080

BM – basic metavolcanics; LP – lava pyroclastics; ST – sandstone; n.a. – not applicable; [a]the proportion of land cover derived from Landsat image of November 2007 overlaid on the landform map; [b]landform map data projection on the geological map (Ethiopia Geological Survey 1996); [c]developed from digital elevation model (DEM); [d]derived from DEM; [e]total catchment area – 1240 ha; [f]including closed area, plantations, natural vegetation; [g]Including settlements, rock outcrops, marginalized areas, etc

using soil morphology indicators such as thickness of alluvial/colluvial deposits and degree of truncation of the top soil horizon (52 soil profile) and erosion indicators (rills, gullies, sheet wash, roots and stones exposure, depositions). In the stable sites, slopes are flat to gentle with little evidence of soil truncation or deposition, indicating that soil loss and gain is more or less balanced. The eroded sites were assessed based on a combination of erosion indicators and features associated with soil profile thickness. Areas that received sediment from upper slopes and erosion channels were indicated as aggrading sites. Finally, the soil/sediment sampling points in the erosion-status sites were located and geo-referenced. Five to eight composite samples were collected from sampling grid areas ranging from 150 to 300 m^2 for each sampling point in each erosion-status site. Each erosion-status site had two sampling points at the soil depth of 0–20 cm. A sub-sample of 500 g was taken from each pooled composite sample and air-dried and sieved to pass through a 2-mm sieve. A total of 36 soil samples (6 landforms × 3 erosion status-sites in each landfrom × 2 sampling points), and 6 sediment samples from the reservoir resulted in a grand total of 42 samples intended for analysis.

The distribution of the sampling points selected in the reservoir considered sediment depth, flow source, outflow and its duration in the case of water presence in the reservoir. Six pits were dug down to the depths of 1.0–2.5 m and three composite samples were collected from the entire depth of each pit. The samples collected from each pit were pooled, mixed thoroughly, and a sub-sample of 500 g was taken for analysis.

Soil/sediment analysis. Soil/sediment samples texture was determined using the Bouyoucos hydrometer method (Gee & Bauder 1986), organic carbon was analyzed by the Walkley-Black method (Bremmer & Mulvaney 1982), available phosphorus by the Olsen method (Olsen & Sommers 1982), and total nitrogen and total phosphorus by the Kjeldahl Digestion method (Anderson & Ingram 1993). Cation exchange capacity was determined by ammonium acetate extraction buffered at pH 7 (Rhoades 1982). Exchangeable bases (calcium, magnesium, potassium) were analyzed after extraction using 1M ammonium acetate at pH 7.0. Iron and zinc were determined by the method described in Baruah and Barthakur (1999).

Sediment enrichment ratio calculation. The sediment enrichment ratio (SER) is the concentration in the sediment over the concentration in the soil of the eroded/stable sites (Hashim *et al.* 1998; Lemunyon & Daniel 2002). The SER of the reservoir (aggrading site) was calculated with respect to the mean values of the eroded as well as stable sites in the landforms. Similarly, the SER at catchment level was calculated as the ratio of the mean value of all aggrading sites in the landforms excluding the reservoir to the mean of the eroded sites in the landforms. The same approach was used to calculate the SER with respect to the mean values of the stable sites in the landforms.

Data analysis. Data were subjected to One-Way Analysis of Variance (ANOVA) using SPSS software (Version 18.0, 2011). Normality and homogeneity assumptions were checked. Means were calculated using the Least Significant Difference and tested by all-pairwise comparisons at the probability $P \leq 0.05$.

Descriptive statistics, correlation and regression analysis were also used.

RESULTS AND DISCUSSION

Sediment enrichment ratio of soil nutrients and textures. The SER of aggrading (in the reservoir; Ar) to eroded soils, Ar to stable soils, aggrading (at catchment level; Ac) to eroded soils, Ac to stable soils, and stable soils to eroded soils for most parameters was > 1 except for sand (Tables 2 and 3). The higher SER were observed for Ar to eroded sites followed by Ac to eroded sites. The higher SER for OC (organic carbon), TN (total nitrogen), and Pav (available phosphorus), for the ratios of Ar and Ac to eroded soils, may be associated with the transportation of inorganic fertilizers (N and P) and organic matter (all nutrients) to aggrading sites by erosion. The raised SER may be also explained by addition of birds and livestock dung to the soil of the aggrading sites such as the reservoir where the water has been used for drinking for 8–10 months. Several researchers have reported that aggrading sites contain higher amounts of organic carbon and plant nutrients than the soil from which these were eroded (e.g. Monke *et al.* 1977; Zheng *et al.* 2005; Haregeweyn *et al.* 2008; Amegashie 2009). However, previous studies have not reported SER results from stable sites and landform level.

The SER of aggrading to stable site soils showed significant differences ($P \leq 0.05$) among some landforms (Table 3). The reservoir showed significantly higher values than the other landforms. However, the ratios of aggrading to stable site soils in the mountainous and central ridge landforms were not significantly different, possibly due to similarities in the content of source soils. The lower ratio of aggrading to stable sites for some soil parameters in the mountainous and central ridge may be attributed to the low nutrient stocks in the original soils. In contrast, the higher ratios in the reservoir and valley showed that deposition was higher than erosion. In general, the SER of aggrading to stable soils were lower than those of the aggrading to eroded sites (Table 3).

The SER of aggrading to eroded sites for the soil parameters showed significant differences among most of the landforms (Table 3). This implies that the effect of erosion on the source soils and on the deposition patterns varies significantly across the landforms. The overall trend showed that the highest ratios were in the reservoir followed by the valley, mountainous, and central ridge landforms. The reason for this is the reservoir represents the largest sediment sink over the entire catchment. Similarly, the valley receives sediments and runoff routing from the upper landforms. The SER values generally indicated that erosion-deposition processes are less severe in the rolling hills, plateau, and escarpments. Such a variability may be attributed to differences concerning terrain characteristics, land cover, management practices (personal observation).

The SER for aggrading to stable sites for all the soil attributes ranged 1.10–3.66, except for sand (Table 3). The average ratio for aggrading to eroded sites ranged from 1.42 for silt in the plateau to 7.22 for TN in the reservoir (Table 3). However, higher enrichment ratios than in this study have been reported, ranging 2–4 for OC, 1.1–5.0 for TN, 1–6 for P, and 1.3–13 for K

Table 2. Catchment level mean enrichment ratio of soil properties

Parameter	Sand	Silt	Clay	ExK	ExCa	ExMg	CEC	OC	TN	Pav	TP	Fe	Zn
Ac[a]:stable[b]	0.64	1.12	1.46	1.15	1.18	1.17	1.14	1.19	1.30	1.32	1.55	1.15	1.13
Ac:eroded[c]	0.51	1.67	1.55	2.59	2.01	2.29	2.23	2.59	2.24	2.55	2.49	1.90	2.15
Stable:eroded	0.80	1.49	1.09	1.62	1.70	1.95	1.96	2.18	1.73	1.93	1.61	1.65	1.91
Ar[d]:stable	0.32	1.65	1.55	1.65	1.52	1.51	1.37	3.66	3.34	1.99	2.03	1.86	1.62
Ar:eroded	0.28	2.81	2.98	2.67	2.59	2.85	3.70	6.99	7.22	3.83	3.75	3.06	3.09
Mean	0.51	1.75	1.73	1.94	1.80	1.95	2.08	3.32	3.17	2.32	2.29	1.92	1.98
SD	0.22	0.63	0.73	0.66	0.53	0.66	1.01	2.23	2.39	0.95	0.90	0.70	0.728

Ac and Ar – aggrading in the catchment and reservoir, respectively; ExK – exchangeable potassium; ExCa – exchangeable calcium; ExMg – exchangeable magnesium; CEC – cation exchange capacity; OC – organic carbon; TN – total nitrogen; Pav – available phosphorus; TP – total phosphorus; SD – standard deviation; [a]mean of all aggrading sites in the landforms excluding reservoir; [b]mean of all stable sites in the landforms; [c]mean of all eroded sites in the landforms; [d]mean of all aggrading samples in the reservoir

Table 3. Enrichment ratio for soil properties in the landforms of the study catchment

Landform	Sand	Silt	Clay	ExK	ExCa	ExMg	CEC	OC	TN	Pav	TP	Fe	Zn
Aggrading to stable sites													
Rolling hills	0.66^{b}	1.08^{c}	1.19^{bc}	1.14^{b}	1.04^{c}	1.12^{b}	1.08^{d}	1.12^{bc}	1.26^{c}	1.12^{d}	1.22^{c}	1.11^{c}	1.06^{c}
Mountainous area	0.89^{a}	1.24^{b}	1.03^{d}	1.23^{ab}	1.19^{bc}	1.18^{b}	1.03^{d}	1.09^{c}	1.16^{c}	1.24^{cd}	1.36^{c}	1.03^{c}	1.02^{c}
Central ridge	0.97^{a}	1.13^{b}	1.09^{d}	1.22^{ab}	1.27^{c}	1.09^{b}	1.06^{d}	1.07^{c}	1.19^{c}	1.31^{cd}	1.35^{c}	1.02^{c}	1.06^{c}
Valley	0.33^{c}	1.12^{b}	1.27^{b}	1.32^{ab}	1.36^{b}	1.26^{b}	1.26^{b}	1.31^{b}	1.48^{b}	1.62^{b}	1.69^{b}	1.36^{b}	1.33^{b}
Plateau	0.51b^{c}	1.09^{c}	1.16^{cd}	1.16^{b}	1.29^{b}	1.17^{b}	1.17^{c}	1.18^{bc}	1.29^{c}	1.33^{c}	1.40^{c}	1.14^{b}	1.11^{c}
Escarpment	0.37^{c}	1.06^{c}	1.22^{bc}	1.19^{b}	1.20^{bc}	1.21^{b}	1.11^{cd}	1.15^{bc}	1.32^{c}	1.26^{cd}	1.31^{c}	1.12^{b}	1.14^{c}
Reservoir	0.32^{c}	1.65^{a}	1.55^{a}	1.65^{a}	1.52^{a}	1.51^{a}	1.37^{a}	3.66^{a}	3.34^{a}	1.99^{a}	2.03^{a}	1.86^{a}	1.62^{a}
LSD (0.05)	0.21	0.13	0.09	0.23	0.17	0.21	0.08	0.21	0.15	0.20	0.23	0.18	0.13
Aggrading to eroded sites													
Rolling hills	0.62^{c}	1.55^{d}	1.47^{f}	1.58^{c}	1.98^{c}	2.00^{d}	1.94^{d}	2.28^{d}	1.93^{d}	2.22^{e}	2.38^{ed}	1.79^{cd}	2.02^{d}
Mountainous area	0.72^{b}	1.74^{c}	2.27^{c}	2.08^{b}	2.36^{b}	2.41^{c}	2.35^{c}	2.58^{c}	2.27^{c}	2.42^{d}	2.59^{cd}	1.93^{c}	2.21^{c}
Central ridge	0.85^{a}	1.71^{c}	1.99^{d}	2.10^{b}	2.27^{b}	2.46^{c}	2.32^{c}	2.62^{c}	2.36^{c}	2.78^{c}	2.63^{c}	2.02^{b}	2.32^{c}
Valley	0.26^{f}	2.37^{b}	2.60^{b}	2.13^{b}	2.52^{a}	2.68^{b}	2.75^{b}	3.01^{b}	2.83^{b}	3.28^{b}	2.90^{b}	2.33^{a}	2.86^{b}
Plateau	0.45^{d}	1.42^{d}	1.53^{ef}	1.62^{c}	1.85^{c}	2.07^{d}	1.98^{d}	2.41^{d}	1.85^{d}	2.14^{e}	2.23^{e}	1.64^{d}	1.78^{e}
Escarpment	0.31^{e}	1.51^{d}	1.65^{e}	1.75^{c}	1.82^{c}	2.14^{d}	2.06^{d}	2.33^{d}	2.08^{cd}	2.25^{e}	2.31^{e}	1.69^{d}	1.89^{ed}
Reservoir	0.28^{f}	2.81^{a}	2.98^{a}	2.67^{a}	2.59^{a}	2.85^{a}	3.70^{a}	6.99^{a}	7.22^{a}	3.83^{a}	3.75^{a}	3.06^{a}	3.09^{a}
LSD (0.05)	0.05	0.14	0.14	0.21	0.16	0.20	0.24	0.13	0.25	0.12	0.23	0.15	0.19

ExK – exchangeable potassium; ExCa – exchangeable calcium; ExMg – exchangeable magnesium; CEC – cation exchange capacity; OC – organic carbon; TN – total nitrogen; Pav – available phosphorus; TP – total phosphorus, LSD – Least Significant Difference; means within column with different letters are significantly different at $P \leq 0.05$

(Marston 1989), 3.86–12.61 for clay, 1.60–4.84 for silt, and 1.25–5.94 for Ca (Amegashie 2009).

The reservoir showed the highest SER for CEC (cation exchange capacity), OC, TN, Pav, TP (total phosphorus), Fe, Zn, silt, and clay. This study also generalized that these soil parameters were significantly higher in the other aggrading sites. This is consistent with the finding by Ellison (1950) and Hashim *et al.* (1998), who reported a higher SER of fine soil particles and soil nutrients. In the present study, however, the inclusion of SER of aggrading to stable sites across different landforms showed that the extent of soil nutrients enrichment was higher at the aggrading sites than in the stable soils. The stable sites with least runoff maintaining the balance between erosion and deposition are expected to show little change in soil nutrients and fine soil particles as compared to the aggrading sites. The results of this study on SER thus confirmed the selective mobilization of clay and silt to aggrading sites by erosion from the source sites. In line to this, previous studies reported that aggrading sites have higher concentrations of

Table 4. Pearson's correlation coefficients between the enrichment ratios of aggrading to eroded sites of selected soil parameters in the landforms

Parameter	Sand	Silt	Clay	ExK	ExCa	ExMg	CEC	OC	TN	Pav	TP	Fe	Zn	SSY
Sand	1	–0.54*	–0.38	–0.13	–0.16	–0.35	–0.49	–0.51	–0.50	–0.47	–0.44	–0.32	–0.44	0.02
Silt	–0.54*	1	0.94**	0.83**	0.89**	0.95**	0.98**	0.97**	0.96**	0.98**	0.95**	0.90**	0.92**	0.54*
Clay	–0.38	0.94**	1	0.94**	0.93**	0.91**	0.95**	0.92**	0.90**	0.93**	0.89**	0.91**	0.82**	0.72**

ExK – exchangeable potassium; ExCa – exchangeable calcium; ExMg – exchangeable magnesium; CEC – cation exchange capacity; OC – organic carbon; TN – total nitrogen; Pav – available phosphorus; TP – total phosphorus; SSY – specific sediment yield; *correlation is significant at the 0.05 level (2-tailed); **correlation is significant at the 0.01 level (2-tailed)

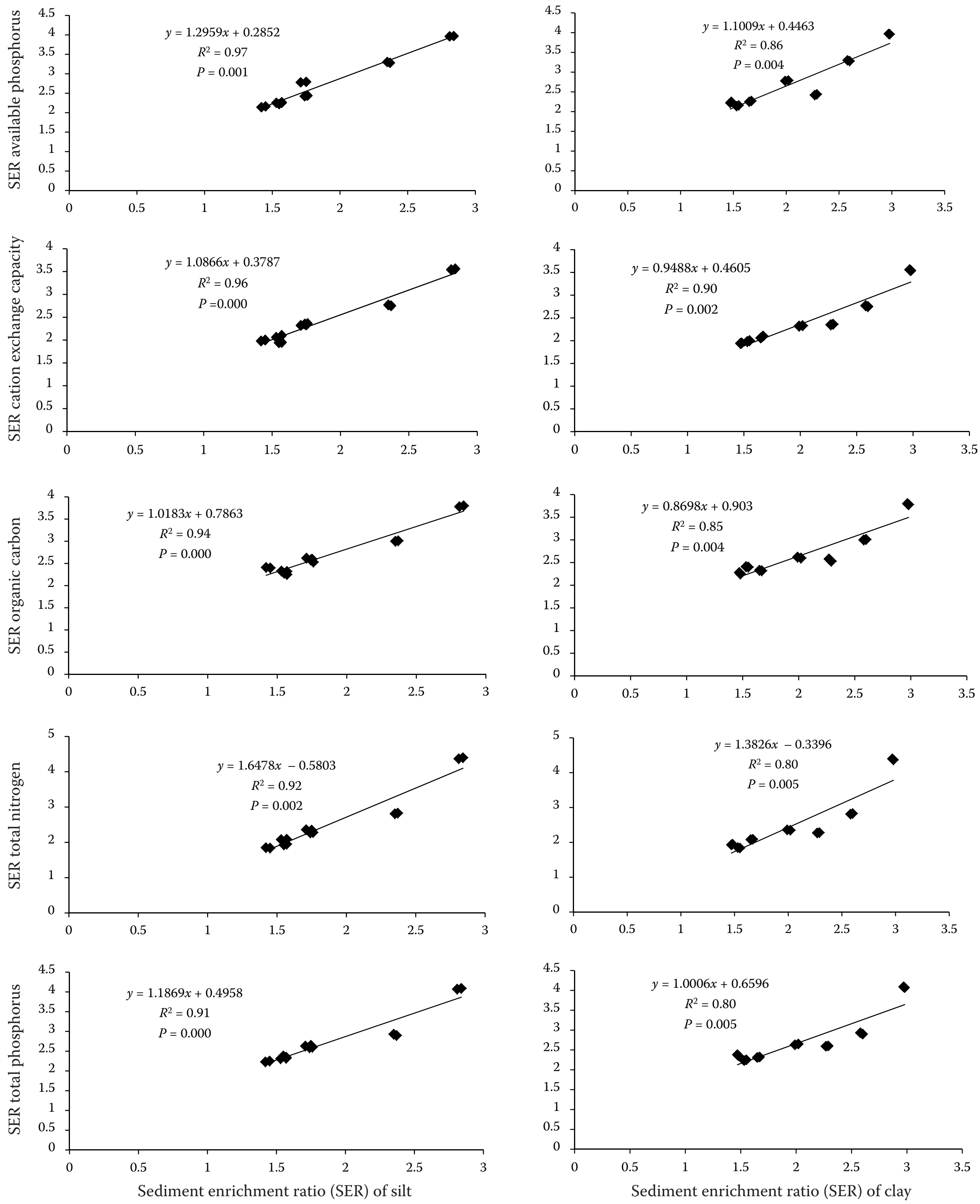

Figure 2. Scatter plot and best fitting regression lines between sediment enrichment ratio (SER) of the fine soil particles and soil nutrients in the landforms; R^2 – coefficient of determination

soil nutrients than the original soils, as the soils are transported to aggrading sites mainly attached to fine soil particles dissolved in runoff (e.g., Ellison 1950; Monke *et al.* 1977; Marston 1989; Hashim *et al.* 1998; Zheng *et al.* 2005; Amegashie 2009). Thus, our results may contribute to identification of high enrichment ratio sources in order to introduce immediate targeted anti-erosion measures.

Relationships between enrichment ratios of soil textures and soil nutrients. The highest Pearson's correlation coefficients were observed between the SER of silt and CEC (r = 0.98) and silt and Pav (r = 0.98) (Table 4). The TN in the aggrading sites could mainly be of organic origin as SER of TN strongly correlated with OC (r = 0.92, P = 0.001). This is consistent with the finding of Nye and Stephen (1962), who stated that carbon is an important reserve for TN. The correlation coefficients between the SER of clay and soil nutrients also showed strong relationships, the highest value being with CEC (r = 0.95) and the lowest with Zn (r = 0.82). Nonsignificant (P > 0.05) but weakly negative correlations between the SER of sand and soil nutrients were also observed (Table 4).

The five soil nutrients (Pav, CEC, OC, TN, and TP) with higher SER were selected to conduct a regression analysis with the fine soil particles (Figure 2). The variance of 97% for Pav, 96% for CEC, 94% for OC, 92% for TN, and 91% for TP can be best explained by the variability in SER of silt in the landforms. These variances are higher than those for clay for the same soil nutrients, implying that silt can better account for the variability of nutrient enrichment ratios in the study catchment.

CONCLUSION

The present study showed that the sediment enrichment ratio (SER) of the soil nutrients and fine soil particles exceeded 1.0. However, the ratio of aggrading to eroded soils ranged 1.42–7.22, being higher than that of aggrading to stable soils (1.10–3.66). The SER also significantly differed ($P \leq 0.05$) among most landforms. This variability could be the result of erosion as some landforms are more susceptible to erosion. The highest SER for the soil parameters were observed in the reservoir. Since the source of sediment for the reservoir is the entire catchment, this is not helpful for identifying the most erosion-prone landform in the catchment. The assessment of SER across different landforms in the catchment should contribute to taking priority measures in the source sites. Integrated interventions should be introduced to sources of highier SER sites such as the mountainous and central ridge landforms. Such technologies should be aimed to retaining soil in place just after detachment by raindrops and before transporting from the source areas by runoff.

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References

Amegashie B.K. (2009): Assessment of catchment erosion, sedimentation and nutrient export into small reservoirs from their catchments in the upper east region of Ghana. [MSc. Thesis.] Kwame Nkrumah University of Science and Technology, Kumasi.

Anderson J.M., Ingram J.S.I. (1993): Tropical Soil Biology and Fertility. A Handbook of Methods. CAB International, Wallingford.

Baruah T.C., Barthakur H.P. (1999): A Text Book of Soil Analysis. Vikas Publishing House Pvt. Ltd., New Delhi.

Bremmer J.M., Mulvaney C.S. (1982). Nitrogen total. In: Page A.L. (ed.): Method of Soil Analysis. Part 2. Chemical and Microbiological Properties. Agronomy Monography No. 9, America Society of Agronomy, Madison, 595–624.

Ellison W.D. (1950): Fertility erosion. The Land, **9**: 487.

Eswaran H., Lal R., Reich P.F. (2001): Land degradation: an overview. In: Bridges E.M., Hannam I.D., Oldeman L.R., Penning De Vries F.W.T., Scherr J.S., Sombatpanit S. (eds): Response to Land Degradation. Science Publisher, Inc., Enfield, 20–35.

Ethiopian Geological Survey (1996): Ethiopia 1:250 000 Geological Map. Axum Sheet. Geological Survey of Etiopia, Addis Ababa.

Gee G.W., Bauder J.W. (1986): Particle-size analysis. In: Klute A. (Ed.): Methods of Soil Analysis. Part 1. 2nd Ed. America Society of Agronomy, Soil Science Society of America, Madison, 383–411.

Haregeweyn N., Poesen J., Deckers J., Nyssen J., Haile M., Govers G., Verstraeten G., Moeyersons J. (2008): Sediment-bound nutrient export from micro-dam catchments in northern Ethiopia. Land Degradation & Development, **19**: 136–152.

Hashim G.M., Coughlan K.J., Syers J.K. (1998): On site nutrient depletion: an effect and a cause of soil erosion. In: Penning De Vries F.W.T., Agus F., Kerr J. (eds): Soil Erosion at Multiple Scales: Principles and Methods for Assessing Causes and Impacts. CAB International, Town, 207–221.

Hurni H. (1993): Land degradation, famine, and land resource scenarios in Ethiopia. In: Pimentel D. (ed.): World Soil Erosion and Conservation, Cambridge University Press, Cambridge, 27–62.

Kosmas C., Gerontidis S., Marathianou M. (2000): The effect of land use change on soils and vegetation over various lithological formations on Lesvos (Greece). Catena, **40**: 51–68.

Lemunyon J.L., Daniel T.C. (2002): Quantifying phosphorus losses from the agricultural system. Journal of Soil Water Conservation, **57**: 399–401.

Marston R.A. (1989): Particulate and dissolved losses of nitrogen and phosphorus from forest and agricultural soils. Progress in Physical Geography, **13**: 234–259.

Monke E.J., Marelli H.J., Meyer L.D., De Jong J.F. (1977): Runof, erosion, and nutrient movement from interrill areas. America Society of Agricultural Engineering, **20**: 58–61.

Nye P.H., Stephens D. (1962): Soil fertility. In: Wills J.G. (ed.): Agriculture and Land Use in Ghana. Oxford University Press, London, 127–143.

Olsen S.R., Sommers L.E. (1982): Phosphorus. In: Page A.L. (ed.): Method of Soil Analysis. Part 2. Chemical and Microbiological Properties. Agronomy Monography No. 9, America Society of Agronomy, Madison, 403–430.

Quansah C., Ampontuah E.O., Tetteh F.M.K., Amankwal A.S., Safo E.Y., Kyeibaffour N. (1997): Fertility erosion under variable mulching rates. In: Santanna R., Quansah C., Asiamah R.D. (eds.): Proc. Workshop on Erosion Induced Loss in Soil Productivity. FAO Regional Office for Africa, Accra, 103–119.

Rhoades J.D. (1982): Cation exchange capacity. In: Page A.L., Miller R.H., Keeney D.R. (eds.): Methods of Soil Analysis. Part 2. Agronomy Monography No. 9, America Society of Agronomy, Madison, 149–157.

Schimel D.S., Kittel T.G.F., Knapp A.K., Seastedt T.R., Parton W.J., Brown V.B. (1991): Physiological interactions along resource gradients in tallgrass prairie. Ecology, **72**: 672–684.

SPSS (2011): Statistical Package for Social Sciences. Release 18.0, SPSS Inc., Chicago.

Stoorvogel J.J., Smaling E.M.A. (1990): Assessment of soil nutrient depletion in Sub-Saharan Africa, 1983–2000. [Report 28.] The Winand Staring Centre, Wageningen.

Tamene L. (2005): Reservoir siltation in the drylands of northern Ethiopia: causes, source areas and management options. [Ph.D. Thesis.] University Bonn.

UNDP (2002): Technical Note on the Environment. United Nations Development Programme, DCGE, Addis Abeba.

UNEP and UNESCO (1980): Provision Map of Present Land Degradation Rate and Present State of Soil. FAO, Rome.

Vlek P.L.G., Le Q.B., Tamene L. (2010): Assessment of land degradation, its possible causes and threat to food security in Sub-Saharan Africa. In: Lal R., Stewart B.A. (eds): Advances in Soil Sciences, Food Fecurity and Soil Quality. CRC Press, Boca Raton, 57–86.

Zheng F., He X., Gao X., Zhang C-E., Tang K. (2005): Effects of erosion patterns on nutrient loss following deforestation on the Loess Plateau of China. Agriculture, Ecosystems & Environment, **108**: 85–97.

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