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Assessment and Evaluation of Nutrient Export and Associated Costs from Micro-dam Catchments in Tigray, Northern Ethiopia

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Résumé
Les objectifs de cette étude dans 13 bassins drainant vers des micro-barrages au Tigré (Ethiopie septentrionale) étaient: évaluer la dégradation de la fertilité du sol causée par l'érosion, comprendre la relation entre le sol érodé et le sédiment déposé et identifier les facteurs régissant ce rapport. Le résultat montre un enrichissement élevé en éléments nutritifs et en fractions fines du sédiment, ce qui est dû à la sélectivité des processus d'érosion et d'écoulement; en conséquence, le sédiment déposé est plus fertile que le sol du bassin versant. Par ailleurs, il y a une importante séquestration de carbone organique dans le sédiment. Les taux d'exportation sont élevés en dépit du fait que les sols des bassins sont peu fertiles. Le coût estimé dû à la perte de N et de P seuls s'élève à plus d'un tiers du budget annuel brut du Tigré. Par conséquent, c'est non seulement le taux de dégradation qui doit être analysé, mais cela doit également être accompagné de gestion intégrée de la fertilité du sol.

1. Introduction

Soil erosion is the most serious form of environmental degradation that threatens agriculture in the world. However global efforts to assess degradation by soil erosion often measure degradation in terms of erosion rate rather than by its impact on productivity (Pierce and Lal, 1994). The economic costs of erosion are also rarely documented (Robinson and Blackman, 1987). Haregeweyn et al. (2005) assessed that five out of ten studied reservoirs in northern Ethiopia faced extreme sedimentation problem leading to loss of their useful storage before half the design period. Moreover, soil erosion and sediment delivery processes are also responsible for associated export of sediment bound nutrients.

The objectives of the study were: (1) to assess the nutrient contents in the catchment soils and in the deposited sediment in the reservoirs and then to understand the relationship and identify the factors controlling the relationship; (2) to evaluate the fertility status of the deposited sediment and its potential use for land reclamation; (3) to assess and evaluate rates of nutrient export; and (4) to quantify the costs of land degradation by soil erosion.

2. Materials and methods

This study was conducted in Tigray (northern Ethiopia); where 54 micro dam reservoirs have been built since 1994 for irrigation purpose. Representative samples from soils and reservoir sediment in 13 catchments have been analyzed for major nutrients and soil physical properties. Standard soil test procedures adopted by Ethiopian National Soil Laboratory were used for analyzing nutrients. The sediment-bound nutrient export value for the catchment draining to the reservoirs was calculated by:

$$NE = \frac{SV * \sum_{i=1}^{n} (dBD_i * NC_i)}{10 * n * A * NTE}$$ (after Verstraeten and Poesen, 2002)

where, NE represents the nutrient export in kg ha^{-1} y^{-1}, SV is measured sediment volume (m^3) in the reservoirs, dBD dry bulk density Mg m^{-3}, NC is nutrient content of the sample (mg of nutrient kg^{-1} of soil), NTE is nutrient trap efficiency of the reservoirs, A is catchment area in ha. The cost of erosion-caused soil fertility degradation was estimated based on a 'replacement cost' approach (Bojö, 1996).

Table 1. Average (n =13) catchment sediment yield in Tigray (after Haregeweyn et al., 2005).

SV (m^3)	SM (t)	Age (y)	A (km^2)	TE (%)	SSY(t km^{-2} y^{-1})
33740 ±39775	36691 ±40594	5 ±1	7.8 ±6.46	98 ±5	866 ±506

SV: annual volumetric sediment yield; SM: annual sediment mass yield; A: catchment area; TE: trap efficiency; SSY: specific sediment yield.

3. Results and discussions

3.1 Variability of plant nutrients between reservoirs and catchments

Total Nitrogen (TN): The mean enrichment ratio (ER) is 1.11 with non-significant difference between means (Tables 2, 3 and 4). There is significant positive correlation (r = 0.49) between the catchment soil and deposited sediment (Table 4) and the N in the reservoir is shown to be organic as it is strongly correlated with OC (r = 0.88, Table 5).

Available Phosphorus (P): The P level is significantly higher in reservoirs than in catchments, with mean ER = 1.82 and r = 0.68 (Tables 2, 3 and 4). The high ER is partly due to the selectivity of erosion as shown by the strong correspondence (r =0.73, Table 5) between the silt fraction and the P level in the reservoir. On the other hand, the negative correlation between P and clay fractions (r = -0.67, Table 5) is due to decreased availability of P as a result of high adsorption of phosphate ions between the clay minerals.

Organic carbon (OC): The mean OC in the catchment soils is relatively high with ER = 0.93 but is not significantly different from the reservoir sediment (Tables 2, 3 and 4). Moreover, there is no clear relationship between the catchment and reservoir sediment (Table 4). The relative low C level in the reservoirs can be an indication of rapid decay (humification) as the C:N ratio is 9 ± 2, which encourages microbial activity.

Exchangeable Potassium (K): The K content is significantly higher in the reservoirs than in the catchments with ER = 1.81 (Tables 2, 3 and 4) with highly significant positive correspondence between catchment soils and reservoir sediment (r =0.63, Table 4). The high

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level of K in the sediment can be explained mainly by the selectivity of erosion and transport processes as K and clay fraction of the deposited sediment are strongly correlated (r = 0.72, Table 5).

Exchangeable Calcium (Ca): The mean difference between catchment and sediment is significant with ER = 1.54 (Tables 2 and 3) and they are strongly correlated (r = 0.52, Table 4). The high level of Ca in the reservoirs is a result of the catchments' domination by limestone and shale/marl formations.

Exchangeable Magnesium (Mg): The Mg level in reservoirs is generally higher with ER = 1.5 (Tables 2, 3 and 4) and yet significantly correlated with the catchment Mg level (r = 0.70, Table 4) what could indicate the Mg source is probably from precipitation of dissolved dolomite. Dolomite and limestone are occurring in most catchments.

3.2 Evaluation of nutrients in the deposited sediment in terms of fertility and availability

The individual nutrient level and their interaction with the deposited sediment (Table 2) were evaluated for nutrient status using various indexes: low and marginal for N, P, OM; medium for K; high for Ca and Mg. Moreover the C:N ratio showed humification and K:Mg, Ca:Mg dictated magnesium unavailability problem (Landon, 1984).

Table 2. Average nutrient content in 13 catchments and reservoirs in Tigray.

	n	pH	N^{+}	P^{++}	OC^{+}	K^{+++}	Ca^{+++}	Mg^{+++}	C:N	Ca:Mg	K:Mg
Catchments	14±6	7.78±0.2	0.14±0.03	4.97±2.46	1.53±0.46	273±137	10762±3090	182±116	11±15	59±27	2±1
Reservoirs	8±2	7.76±0.21	0.15±0.04	8.13±2.75	1.31±0.56	429±164	14926±1560	240±138	9±2	97±78	3±2

n: number of samples; +: %; ++: ppm; +++: mg kg^{-1}.

Table 3. Average ER of nutrients and soil texture classes in 13 catchments in Tigray.

N	P	OC	K	Ca	Mg	Clay	Silt	Sand
1.11±0.24	1.82±0.64	0.93±0.43	1.81±1.09	1.54±0.60	1.50±0.79	1.57±0.43	1.07±0.31	0.42±0.35

ER is calculated as the mean concentration in the reservoir sediment divided by the mean concentration in the catchment soils.

Table 4. Paired mean comparison and samples correlations in 13 catchments in Tigray.

Pairs	Mean comparison		Correlation	
	Paired mean difference	df	R	n
pHC & pHR	0.015^{ns}	12	-0.01^{ns}	13
NC & NR	-0.01^{ns}	12	0.49*	13
PC & PR	-3.00**	12	0.68**	13
OCC & OCR	0.22ns	12	0.28^{ns}	13
KC & K_R	-0.40**	12	0.63*	13
CaC & CaR	-21.00**	10	0.52*	11
MgC & MgR	-0.48*	10	0.70*	11

Suffixes C and R: catchment and reservoir; df: degrees of freedom; R: correlation coefficient; n: number of samples, ns: non significant, * and ** significant at 10 and 1 % respectively.

Table 5. Pearson correlations matrix for sediment nutrients and textural classes

	N	P	OC	K	Ca	Mg	Clay	Silt	Sand
pH	-0.11^{ns}	0.11^{ns}	-0.04^{ns}	-0.31^{ns}	0.08^{ns}	0.51^{ns}	-0.15^{ns}	0.32^{ns}	0.43^{ns}
N		0.55*	0.88**	-0.14^{ns}	0.65*	0.55*	-0.35^{ns}	0.22^{ns}	-0.08^{ns}
P			0.49*	-0.43^{ns}	-0.22^{ns}	0.63*	-0.67**	0.73**	0.13^{ns}
OC				-0.08^{ns}	0.33^{ns}	0.60*	-0.32^{ns}	0.12^{ns}	0.17^{ns}

K	0.34^{ns}	-0.012^{ns}	0.72*	-0.32^{ns}	-0.54^{ns}
Ca		-0.03^{ns}	0.30^{ns}	-0.16^{ns}	-0.30^{ns}
Mg			-0.23^{ns}	0.31^{ns}	0.12^{ns}
Clay				-0.66**	-0.50*
Silt					0.12^{ns}

* and ** significant at 10 and 1 % respectively

3.3. Evaluation of nutrient export and its association with specific sediment yield

The average export rates (in kg ha^{-1} y^{-1}) calculated in this study were: 11.56 ± 5.22 for N, 0.063 ± 0.035 for P, 97.11 ± 44.96 for OC, 3.85 ± 2.85 for K, 140.97 ± 62.83 for Ca, 2.11 ± 1.49 for Mg. The export rate for N, P, K and Mg may seem low as compared to similar studies in Belgium by Verstraeten and Poesen (2002). This is due to the low concentration for the corresponding nutrients in the Ethiopian soils. The Ca rate is significantly higher in Ethiopian soils due to carbonate rich geology in the catchments of Tigray. The OC export is relatively high and varies spatially between catchments with mean of 97.11 ± 44.96 kg ha^{-1} y^{-1}. This is equivalent to total annual deposition of 980 tons of OC from 13 catchments (101 km^2) and 6640 tons per year in 64 reservoirs in Tigray constructed since 1970.

Nutrient export rates were correlated with the specific sediment yield for the 13 catchments. There is significant correspondence for all cases with r^2 of 0.95, 0.89, 0.69, 0.64, 0.48 and 0.29 for Ca, N, K, P, OC and Mg respectively. The strong relationship between NE and SSY indicate that (1) erosion is playing a major role for the nutrient stocking in the sediment and (2) there is low spatial variation of fertility status between catchments. It is however important to identify other factors which are responsible for the major spatial variation between catchments especially in the case of Mg.

3.4. Costs of soil erosion-caused land degradation

Table 6 shows that an average of 68.47 Birr ha^{-1} y^{-1} (10.5 Eth Birr = 1 €) is needed to maintain in situ N and P levels. This information could be scaled up to the Ethiopian Highlands (4.48 x 10^5 km^2) and estimated at 3.06 Billion Birr annually. The inclusion of OC and other nutrient losses and the losses in physical soil fertility brings the cost much higher.

Table 6. Erosion costs due to loss of TN and P from 13 catchments of Tigray.

Urea addition		**DAP addition**		**Total Cost***
(Kg ha^{-1} y^{-1})	**Cost (Birr ha^{-1} y^{-1})**	**(kg ha^{-1} y^{-1})**	**(Birr ha^{-1} y^{-1})**	**(Birr ha^{-1} y^{-1})**
25.01 ±11.77	67.54 ±31.78	0.31 ±0.18	0.94 ±0.54	68.47 ±32.17

* 10.5 Eth Birr = 1 € in October 2005.

4. Conclusions

Selective soil erosion results in high nutrient export and relatively high fertility status of deposited sediment. The annual nutrient export rates were maximal mainly for Ca, OC. The strong relationship between NE and SSY can also explain the less pronounced variability of fertility status between catchments. The yearly cost only due to loss of N and P is more than 1/3 of the gross annual budget. However, the magnitude of the problem is yet not recognized by policy makers and beneficiaries. Therefore, it is important not only minimizing the current degradation rate but also it should be accompanied with an integrated soil fertility management practices.

Reference

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