LAND DEGRADATION & DEVELOPMENT

Land Degrad. Develop. **19**: 136–152 (2008)

DOI: 10.1002/ldr.830

SEDIMENT-BOUND NUTRIENT EXPORT FROM MICRO-DAM CATCHMENTS IN NORTHERN ETHIOPIA

N. HAREGEWEYN[1]*, J. POESEN[2], J. DECKERS[3], J. NYSSEN[1,3], M. HAILE[1], G. GOVERS[2],
G. VERSTRAETEN[2] AND J. MOEYERSONS[4]

[1] *Department of Land Resources Management and Environmental Protection, Mekelle University, P.O. Box 231, Mekelle*
[2] *Physical and Regional Geography Research Group, K.U. Leuven, Celestijnenlaan 200 E, B-3001 Heverlee*
[3] *Division Soil Water Management K.U. Leuven, Celestijnenlaan 200 E 3001 Heverlee*
[4] *Agriculture and Forestry Economics, Royal Museum for Central Africa, B-3080 Tervuren*

Received 2 October 2006; Revised 20 February 2007; Accepted 31 May 2007

ABSTRACT

The losses in soil nutrients (nitrogen (N), available phosphorus (P_{av}), organic carbon (OC), potassium (K), calcium (Ca) and magnesium (Mg)) in the catchment and the storage in the reservoir as a result of sediment delivery were assessed in 13 catchments/reservoirs in Tigray, Northern Ethiopia. This specifically dealt with factors controlling the losses, the fertility status of the deposited sediment, the nutrient export (NE) rates and associated costs.

Enrichment ratio (ER) values >1 were observed for the plant nutrients and the finer soil fractions. The high ER is associated with the preferential transport of nutrients bound to finer soil fractions and the parent material dissolution and its transport via runoff. However, the fertility status of the deposited sediment is not sufficient by itself to support a sustainable crop growth and hence external addition is necessary, mainly for N and P_{av} fertilizer.

Generally, rates of NE were high. The high OC export on the other hand dictates the potential of reservoir sediments for OC sequestration. The cost price of loss of only N and P_{av}, eroded from the catchment slopes, was estimated at €34·2 million (Euros) in March 2006 for the Tigray. Pity enough, policy makers and beneficiaries do not realize the magnitude of the problem, which forms a major threat for the crop production in the country. Therefore, it is important not only to make the public aware of the problem but also of implementing integrated soil fertility management practices.

KEY WORDS: catchment soils; deposited sediment; fertility status; Tigray; Organic carbon sequestration; soil fertility management

INTRODUCTION

Soil erosion is the most serious form of environmental degradation that threatens agriculture in Africa and other parts of world (UNEP and UNESCO, 1980; Dudal, 1981; Eswaran *et al*., 2001). However, global efforts to assess degradation by soil erosion often measure degradation in terms of erosion rate rather than by its impact on productivity or off-site damages (Pierce and Lal, 1994). Information on the economic costs of erosion is also rarely documented (Robinson and Blackman, 1987; Eswaran *et al*., 2001).

Reservoir sedimentation is a serious off-site consequence of soil erosion by water in northern Ethiopian highlands. Six of the 13 study reservoirs suffer from accelerated sedimentation and will lose their economic life within half of the expected lifetime at the moment of their design (Haregeweyn, 2006). Moreover, soil erosion and sediment delivery processes are not only responsible for high sediment transport rates, but also for associated export of sediment-bound nutrients which finally are deposited in the reservoir and in the river-bed sediments. These could lead to eutrophication of the reservoir water (Krogvang, 1990; Steegen *et al*., 2001; Withers and Lord, 2002) on top of the loss of productivity of the contributing area (Stoorvogel and Smaling, 1990; Bojö, 1996; Eswaran *et al*.,

---

* Correspondence to: N. Haregeweyn, Department of Land Resources Management and Environmental Protection, Mekelle University, P.O. Box 231, Mekelle, Ethiopia.
E-mail: niguha@yahoo.com

2001; Verstraeten and Poesen, 2002; Haileselassie *et al*., 2005; Muchena *et al*., 2005). The first problem is of a serious concern mainly in the developed world where high fertilization inputs are used. The latter case is a much concern in developing countries like Ethiopia where it cannot even be afforded that chemical fertilizers replace the loss of nutrients due to erosion. Soil fertility depletion in smallholder farms in Ethiopia is identified as one of the fundamental biophysical causes for declining per capital food production (Haileselassie *et al*., 2005).

To minimize erosion effects, control measures should be taken. However, before the implementation of control measures, the extent of the problem has to be studied. So far, however, no scientific studies that relate the soil loss and sediment delivery to that of productivity loss in Ethiopia as a whole were available, except the empirical-based estimate by Ethiopian Highlands Reclamation Study (FAO, 1986) and its derivative by Bojö and Cassells (1995). However, the report emphasized that there were methodological weaknesses such as the relationship between soil losses and yield reductions and the difficulties inherent in projecting soil losses. Moreover, the link between nutrient losses from the erosion source area and nutrient input in the deposited sediment has never been analyzed. Despite the current global concern to quantify the potential of the reservoir sediment to sequester carbon (Stallard, 1998; Lal, 2005; Van Oost *et al*., 2004, 2005), this aspect has never been studied in the tropical Ethiopian reservoirs.

Therefore, the objectives of the study were: (1) to assess the spatial variability in nutrient content (NC) in the catchment (erosion source) soils and the deposited sediment in the reservoirs and to understand their relationship and controlling factors, (2) to evaluate the fertility status of the deposited sediment and its potential use for land reclamation of the surrounding degraded croplands, (3) to assess and evaluate rate of nutrient export (NE) and to compare the Ethiopian situation (low fertilization input) with a high-input region, (4) to evaluate the potential for carbon sequestration in the deposited sediment and (5) to quantify the costs of land degradation by soil erosion.

MATERIALS AND METHODS

Study Area and Site Characteristics

This study was carried out on 13 representative micro-dam catchments in Tigray located in a radius of 120 km from Mekelle, Tigray's regional capital (Figure 1). Their characteristics are given in Table I. Tigray is one of the Ethiopian regional states, located in the northern part of the country between 12° 15′N and 14° 50′N and 36° 27′E and 39° 59′E. The region has a total area of 50 078 km^2 (out of which 19 per cent is suitable for cultivation) and a population of more than 3·8 million (CSA, 2001). The climate is generally characterized as tropical semi-arid (Virgo and Munro, 1978) with an annual rainfall ranging from 450 mm in the north, east and central zones to 980 mm in the southern and western parts of the region. Most of the rainfall occurs within July, August and September. The topography of the region mainly consists of highland plateaux up to 3900 m a.s.l., which are dissected by gorges. However, the north west of the region is characterized by lowlands with elevations as low as 500 m a.s.l. The highlands support a high population density (40–70 persons km^{-2}; FAO, 2004) and are seriously affected by land degradation due to their long cultivation history (starting 3000 BC, Hurni, 1989; Bard *et al*., 2000; Moeyersons *et al*., 2005), steep topography and erosive rains (Nyssen *et al*., 2005). In contrast, the lowlands are sparsely populated and have soils that are less eroded and exploited (TFAP, 1996). In Tigray, about 54 reservoirs have been built since 1994 with the aim to bring food self sufficiency in the region by employing irrigation. Their storage capacity ranges from 0·1 to 3·1 10^6 m^3 and catchment area from 0·36 to 52 km^2. More details on reservoirs can be found in Haregeweyn (2006).

Analysis of Nutrient Content in the Catchment Soils and in the Deposited Sediment Within the Reservoirs

For the analysis of NC in the deposited sediment, 5–11 pits were dug per reservoir and representative composite samples per pit were taken. For the analysis of NC from the catchments, it would have been more logical to follow an erosion-weighted approach for representative samples taken from all erosion classes. This was not possible for lack of spatial data on erosion-deposition for all catchments. Hence, an alternative approach, which was based on field observation, was adopted in the following manner: for every catchment, sediment-contributing areas were identified and from these contributing areas, smaller land units (polygons) were delineated where the soil fertility

DOI: 10.1002/ldr

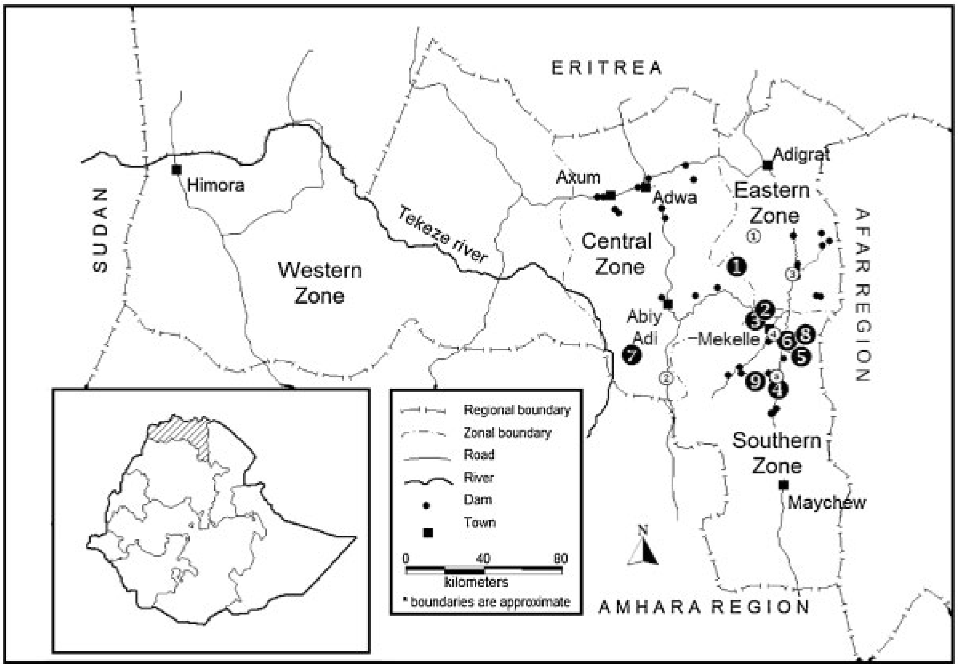

Figure 1. Location of the study area and the studied reservoirs. Dots represent reservoirs visited, numbers with black fill represent reservoirs for which sediment yield was measured: 1, Gindae; 2, Gereb Shegel; 3, Sewhimeda; 4 (Gereb Segen, Grashitu, Mejae, Maideli, Gum Selassa); 5, Adiakor; 6, Adihilo; 7, Agushella; 8, Endazoey; 9, Adikenafiz. Numbers without fill represent rainfall stations: 1, Hawzen; 2, Yechila; 3, Wukro; 4, Mekelle airport; 5, Adigudom. The stations are owned and run by the Ethiopian Meteorological Authority.

was thought to be homogenous taking into account parent material, land use, slope and agricultural practices. However, topographic position, at the scale of larger catchments, is identified as a principal factor determining soil distribution in the study area (Virgo and Munro, 1978). From each polygon, the top 20 cm was sampled for analysis based on a systematic random sampling. The number of sampling places varied from 6 to 28.

Table I. The study catchments characteristics (Haregeweyn, 2006)

Catchment	Lithology (%)					Land use (%)					Soil texture	Av_slope (%)
	LS	ST	SL	DT	Colluviums/alluvium	Cul	Grazing	Shrub	Settlement	Others		
Adiakor	0	0	26	2	72	72	24	0	1	3	Silt-loam	7·12
Adihilo	0	0	0	37	63	26	13	60	0	1	Silt-clay	13·36
Adikenafiz	0	36	0	0	64	65	9	24	6	3	Sandy-loam	15·39
Agushella	n.a.	n.a.	n.a.	n.a.	n.a.	32	18	35	0	15	Clay-loam	4·98
Endazoey	50	0	0	0	50	45	20	31	0	4	Sandy-clay-loam	11·25
Gereb Segen	0	0	14	0	86	86	5	8	0	1	Clay	3·28
Gereb Shegel	65	0	0	16	23	19	34	42	1	3	Loam	19·36
Gindae	35	24	15	0	26	25	32	37	4	2	Clay-loam	14·19
Grashitu	4	0	0	10	86	85	7	4	2	1	Clay	5·36
Gum Selassa	9	0	0	1	90	79	15	1	4	1	Clay	3·38
Maideli	3	0	25	0	72	56	6	32	6	0	Clay	8·00
Mejae	7	0	6	3	84	77	10	7	5	1	Clay	6·70
Sewhimeda	41	0	0	33	26	26	31	23	7	3	Loam	8·45

LS, limestone; ST, sandstone; SL, shales; DT, dolerite; CUL, cultivated land; Av_slope, average slope; n.a., not available.
Soil texture based on own analysis using USDA Soil Textural Classification System. Average slope was derived from Digital Elevation Model in IDRISI®.

This study, however, focused manly on those nutrients that have been transported down to the reservoir. It did not consider (1) nutrients lost due to erosion but deposited on their way to the reservoirs and (2) inputs (atmospheric, dung) and outputs (leaching of dissolved nutrients lost through the reservoir bottom and below the dam body).

The parameters considered in the analysis were: hydrogen ion concentration (pH), total nitrogen (N), available phosphorus (P_{av}), organic carbon (OC), basic cations like potassium (K), calcium (Ca), magnesium (Mg). Moreover, the three major soil/sediment textural classes were analyzed. Finally, a simple average NC of the sediment samples and an area-weighted average NC for catchment samples were calculated for each nutrient.

Laboratory analysis was done in Holetta National Agricultural Research Laboratory located at about 40 km west of Addis Ababa. Standard soil test procedures adopted by the Ethiopian National Soil Laboratory were used in observation and analysis for all nutrients: OC and total N by Walkley Black and Kjeldahl, respectively (Bremmer and Mulvaney, 1982), P_{av} by Olsen (Olsen and Sommers, 1982). Total phosphorus was not analyzed for lack of laboratory facilities. Ammonium and sodium acetate extraction used to determine the exchangeable bases and cation exchange capacity, respectively (Thomas, 1982). Ca and Mg values were read using Atomic Absorption Spectrophometer while K was determined using Flame Photometer. The pH was determined by pH meter using supernatant suspension of 1:1 soil water ratio. Major soil/sediment texture classes (sand, silt and clay) were analyzed in soil suspension by hydrometer method (Gee and Bauder, 1982).

Interviews with farmers in the catchments and with local development officers (like Office of Agriculture) were carried out in each catchment to assess the type, amount of fertilizer inputs and also the constraints toward managing the fertility status of the farm lands. Moreover, a related report (BoANR, 2002) at regional level was consulted.

Understanding the Relationship in Nutrient Content Between the Catchment Soils and the Sediment

The degree of association between catchment soils and the deposited sediment and the factors responsible for the association were assessed by using the mean comparison, bi-variate correlation matrixes in SAS® (SAS, 2002) and by calculating the enrichment ratio (ER). The ER was quantified as (Wan and El-Swaify, 1998):

$$\mathrm{ER} = \frac{\text{The concentration of a constituent (such as OC, N and others) in the sediment}}{\text{The concentration of the same constituent in the } \textit{in situ} \text{ soil}} \tag{1}$$

Since finer soil fractions have high specific surface area, nutrients are strongly adsorbed to these finer fractions which are preferentially transported by the sedimentation processes. The nutrient status of the deposited sediment was evaluated based on the Soil Interpretation Guide given by Marx *et al*. (1999) and Landon (1984).

Quantification and Evaluation of Nutrient Export Rates

The sediment-bound NE value for each catchment draining to the respective reservoirs was calculated by:

$$\mathrm{NE} = \frac{\mathrm{SM} \times \mathrm{NC}}{A \times Y \times \mathrm{NTE} \times 10} \quad \text{(modified after Verstraeten and Poesen, 2002)} \tag{2}$$

$$\mathrm{SM} = \mathrm{SV} \times \mathrm{dBD} \tag{3}$$

where, NE represents the nutrient export (kg $\mathrm{ha}^{-1}\,\mathrm{y}^{-1}$), SM is total measured sediment mass (Mg); NC is average nutrient content of the sample (Mg of nutrient per kg of sediment); A is catchment area (ha); Y is age of the reservoir for a duration of sediment accumulation (y); NTE (=STE) is the nutrient (=sediment) trap efficiency of the reservoirs (per cent); SV is total measured sediment volume (m^3) in the reservoirs and dry bulk density (dBD; Mg m^{-3}).

Sediment thickness was measured by observing sediment profiles (up to 4 m deep) in pits along transects, with 15–39 pits per reservoir depending on the size and nature of the original bottom surface of the reservoir (see Figure 2). Sediment volume was computed by constructing a digital elevation model (DEM) with a resolution of 1 m using TIN interpolation in IDRISI® and taking sediment thickness as the z value.

DOI: 10.1002/ldr

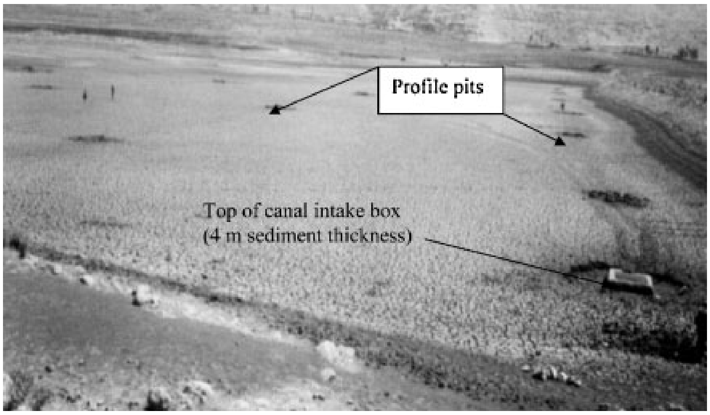

Figure 2. Adikenafiz reservoir. The top of inlet canal is clogged due to excessive sediment deposition and is shown cleared from sediment.

Sediment trap efficiency (STE) is the percentage of the total incoming sediment which is retained in the reservoir. The STE was assessed based on one season field monitoring (summer 2003) and interviewing the local farmers about the history of the reservoir. All reservoirs were less than 7 years old and spillage never occurred for most of the reservoirs since their construction. Sediment yield data are generally expressed in mass units (t). Hence, the measured sediment volumes need to be converted to sediment masses using representative values of sediment bulk density. dBD was determined by the gravimetric method. Undisturbed representative sediment samples were taken using core rings (volume $1\ 10^{-4}\ \mathrm{m}^3$) from 8 to 12 sampling sites per reservoir (near the dam axis, in the middle, side and at the inlet of the reservoir), and at a minimum of two different depths in the profile pit. Details on reservoir sediment survey can be found in Haregeweyn *et al*. (2006).

The measured sediment yield data (Table II) was used in the analysis of NE. In this study, the nutrient trap efficiency was considered to be equal to the STE for the following main reasons: (1) the reservoirs have high runoff trap efficiency as no spillage occurred (i.e. STE = 100 per cent, see Table II) since constructions in most of reservoirs because of insufficient runoff inflow (Haregeweyn *et al*., 2006) and (2) the stored water is being used for irrigation during the dry period once the sediment settled in the reservoirs. However, such assumptions may not be

Table II. Sediment yield studies of 13 catchments in Tigray, northern Ethiopia (Haregeweyn, 2006)

Reservoirs	SV (m^3)	SM (t)	Age (y)	A (km^2)	dBD ($\mathrm{t\,m}^{-3}$)	STE (%)	SSY ($\mathrm{t\,km}^{-2}\,\mathrm{y}^{-1}$)
Adiakor	4599	5803	5	2·92	1·27	100	397
Adihilo	2452	3420	5	0·72	1·38	100	950
Adikenafiz	109 186	110 039	6	14·3	1·06	95	1350
Agushella	6533	9125	5	9·64	1·42	100	189
Endazoey	4475	4866	5	1·4	1·07	100	695
Gereb Segen	12 357	15 421	3	4·35	1·23	100	1182
Gereb Shegel	19 114	20 902	5	8·58	1·11	100	487
Gindae	56 460	72 190	5	11·87	1·27	100	1216
Grashitu	36 340	39 451	5	5·11	1·14	85	1817
Gum Selassa	110 679	111 932	7	24·14	1·01	90	736
Maideli	66 695	70 357	5	10·05	1·08	98	1429
Mejae	5581	7900	5	2·56	1·42	100	617
Sewhimeda	4153	5576	5	5·8	1·30	100	192
Average	33 740	36 691	5	7·80	1·21	98	866
SD	39 775	40 594	1	6·46	0·14	5	506

SV, annual volumetric sediment yield; SM, annual sediment mass yield; A, drainage area; dBD, dry bulk density; STE, trap efficiency; SSY, specific sediment yield; SD, standard deviation.

applicable for small flood retention ponds whose retention capacity is limited as observed in central Missouri (Rausch and Schreiber, 1981), southern Germany (Weigand *et al*., 1998), central Belgium (Verstraeten and Poesen, 2002).

Estimating Costs of Erosion-Caused Nutrient Loss

To assess the costs of erosion-caused nutrient loss, a 'replacement cost' approach (Bojö, 1996) has been applied, which is the first of its kind in Ethiopia. The logic behind this approach is to calculate the loss of nutrients and put a value on it using the equivalent cost price of commercial fertilizers (urea and di-ammonium phosphate (DAP)). First, the total N and P_{av} export was assessed from the deposited sediment. Second, the P_{av} was converted to an equivalent P_2O_5 and then to DAP fertilizer, as P_{av} was limited in the soil. Third, from this DAP, amount of N required was estimated. Fourth, the remaining N was converted to urea fertilizer. Finally, the cost of nutrient loss was estimated in terms of the amount of money required for nutrient addition to replace the loss. The conversion of P_{av} to P_2O_5 and *vice versa* is given as: per cent P_{av} = per cent $P_2O_5 \times 0{\cdot}43$ and per cent P_2O_5 = per cent $P_{av} \times 2{\cdot}29$. The current local price of urea and DAP was used to estimate the cost. The cost price of annual nutrient loss was projected to the scale of Tigray region and to the scale of the Ethiopian highlands and then compared with the respective annual gross budget. Details on measures of economic costs to assess economic impacts of land degradation can be found in Bojö (1996).

RESULTS AND DISCUSSIONS

Assessment of Practices of Fertilizer Inputs in the Catchments in Tigray

Farmers in Tigray are small holders growing cereals mainly for subsistence. Use of inorganic fertilizers dated back to 1973 (BoANR, 2002), focusing on the midland agro ecology (1500–2500 m a.s.l.). There has been a relatively progressive development in using mineral fertilizer from 1976 to 1987, with an average annual application rate to the total cultivated land ranging from 0·2 kg ha^{-1} in 1983 to 2 kg ha^{-1} in 1987. During the years 1988–1990, fertilizers were not distributed in the region because the area was under war. After 1991, fertilizer consumption has increased progressively; during the years 1992–1995 fertilizer use rate increased from 2·8 to 4·5 kg ha^{-1} (BoANR, 2002). Agricultural extension became strengthened. The fertilizers were mainly urea and DAP as a source of N and P_{av}. Fertilizer trials conducted on major cereals crops (for N, P_{av} and K) showed that cereals are not responsive to K (FAO, 1991). While Haileselassie *et al*. (2005) stressed that the long-term K fertilization should not be overlooked.

Moisture stress in some years has also restricted the progressive increase of fertilizer utilization. For example, in 2003, 200 tons of DAP and urea fertilizers has been distributed and used by the farmers in Tigray region. In 2004, 143 tons of DAP and urea fertilizers were supplied to Tigray region, while only 90 tons of DAP and urea were used by the farmers. This was due to the late on-set and the limited amount of rainfall in the year especially in the eastern and southern zones of the region (personal communication with Mr Atakilt, head for Crop Department in Tigray Bureau of Agriculture and Natural Resources).

The practice of fertilizer application in the studied catchments is limited. Inorganic fertilizers like DAP and urea are applied by only 10–20 per cent of the farmers at an average application rate of 50 kg ha^{-1} y^{-1} each. There is only a limited application of organic fertilizer, mainly manure, restricted to the homestead farms. Application of manure in the homestead farms is a traditional way of soil fertility replenishment in Ethiopia (Haileselassie *et al*., 2005). On the other side, dung is a major source of fuel for the rural farmers which limits its use for fertilization. Even if there is availability, there remains the problem of transport from the villages to the farm fields. In most cases, the farm fields are located far from the villages. Another potential source of nutrient input is sedimentation either from irrigation water or upslope eroded fertile soil. However, irrigation practices are not practiced in any of the studied catchments.

The future trend in the region is towards shifting to the use of organic fertilizers, as the inorganic fertilizers are getting unaffordable for the small holder subsistence farmers in the region. The price of 100 kg of DAP has

DOI: 10.1002/ldr

increased from 70 Ethiopian Birr (ETB) ($14 USD) in 1992 to 300 ETB ($35 USD) in 2003, an increase by more than 340 per cent in 11 years, while the amount of production is still at subsistence level. The high price is resulting from government's withdrawal from subsidizes (Nyssen *et al.*, 2004). Alternative sources of energy for the rural people are not made available. It is observed that there is constraint in resource and policy to maintain the soil fertility of the small holders in the study area.

Variability and Controlling Factors of Plant Nutrients and Soil Textures Between Catchments and Reservoirs

Hydrogen ion concentration

The pH ranges from 7·23 to 8·02 with a mean value of 7·78 in the catchments and from 7·64 to 8·15 with a mean value of 7·76 in the reservoirs (Tables III and IV). In all cases, the environment is found to be calcium carbonate rich. This has advantage that there will not be a problem of sodicity. When analyzing the pH between the reservoirs and their respective catchments, the pH values are not significantly different (Table VI), moreover, they are not significantly correlated (Table VI). The poor correlation could be due to variation in environment mainly in moisture content and variation in concentration of basic cations. In all cases, however, the effect of pH on nutrient unavailability is minimal for most crops growing in the area.

Total nitrogen

The N content ranges between 0·1 per cent and 0·18 per cent with a mean value of 0·14 per cent in the catchments and from 0·1 to 0·21 per cent with a mean value of 0·15 per cent in the reservoirs (Tables III and IV). The mean ER is 1·11 that corresponds to the lower ER boundary of the ranges (1·1–5) given by Olarieta *et al.* (1999). Moreover, the mean N in the catchment soils and in the sediment is not significantly different (Tables V and VI). There is a significant positive correlation with $r = 0{\cdot}49$ between the catchment soil and deposited sediment (Table VI) and the N in the reservoir is shown to be of organic origin as it is strongly correlated with OC ($r = 0{\cdot}88$, Table VII). The low ER can be explained due to the low N level in the catchment soils.

Available phosphorus

P_{av} ranges from 2·19 to 9·61 mg kg^{-1} with a mean value of 4·97 mg kg^{-1} in the catchments and from 4·4 to 12·54 and with a mean value of 8·13 mg kg^{-1} in the reservoirs (Tables III and IV). The P_{av} level in the reservoirs is significantly higher in reservoirs with mean ER = 1·82 (Table V) and with $r = 0{\cdot}68$ (Table VI). The high ER is partly explained by the strong correlation ($r = 0{\cdot}73$) between the silt fraction (easily erodible soil fractions) and

Table III. Weighted average nutrient content from 13 catchments in Tigray, northern Ethiopia

Catchments	*n*	pH	N (%)	P_{av} (mg kg^{-1})	OC (%)	K (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	OC:N	Ca:Mg	K:Mg
Adiakor	23	7·63	0·15	9·61	1·33	98	n.a.	n.a.	9	n.a.	n.a.
Adihilo	10	7·9	0·11	3·17	0·7	257	11 468	82	6	139	3
Adikenafiz	28	7·23	0·10	5·17	0·91	160	3684	306	10	12	1
Agushella	23	8·02	0·17	8·83	1·98	374	14 354	394	12	36	1
Endazoey	15	7·78	0·18	5·53	1·95	285	11 200	188	11	60	2
Gereb Segen	6	7·76	0·11	2·19	1·1	456	12 656	336	10	38	1
Gereb Shegel	8	7·96	0·10	5·7	1·52	203	9820	54	15	180	4
Gindae	10	7·9	0·18	3·09	2·22	203	13 518	68	12	199	3
Grashitu	9	7·79	0·11	4·54	1·27	581	11 262	180	12	62	3
Gum Selassa	16	7·87	0·14	2·91	1·57	347	13 478	169	11	80	2
Maideli	10	7·84	0·17	2·91	2·03	261	9370	103	12	91	3
Mejae	14	7·62	0·11	3·08	1·61	215	7570	115	15	66	2
Sewhimeda	11	7·8	0·17	7·92	1·67	109	n.a.	n.a.	10	n.a.	n.a.
Average	14	7·78	0·14	4·97	1·53	273	10 762	182	11	59	2
SD	6	0·2	0·03	2·46	0·46	137	3090	116	15	27	1

n, number of samples; pH, hydrogen ion concentration; N, total nitrogen; P_{av}, available phosphorus; OC, organic carbon; K, potassium; Ca, calcium; Mg, magnesium; n.a., not available.

DOI: 10.1002/ldr

Table IV. Nutrient content of sediment deposits in 13 reservoirs in Tigray, northern Ethiopia

Reservoirs	*n*	pH	N (%)	P_{av} (mg kg^{-1})	OC (%)	K (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	OC:N	Ca:Mg	K:Mg
Adiakor	6	7·43	0·18	9·53	1·57	503	n.a.	n.a.	9	n.a.	n.a.
Adihilo	8	7·64	0·14	6·80	1·35	425	14 472	63	10	230	7
Adikenafiz	8	8·11	0·11	11·33	0·99	197	11 432	432	9	26	0
Agushella	5	7·92	0·19	12·16	2·03	512	16 060	454	11	35	1
Endazoey	7	7·92	0·21	7·86	2·63	369	16 366	386	13	42	1
Gereb Segen	6	7·54	0·12	4·40	0·88	577	15 210	178	7	86	3
Gereb Shegel	9	8·15	0·15	6·73	0·78	320	17 544	175	5	100	2
Gindae	7	7·74	0·1	6·03	0·76	222	13 688	52	8	263	4
Grashitu	11	7·78	0·12	5·47	0·73	585	14 844	172	6	86	3
Gum Selassa	10	7·7	0·14	5·75	1·24	632	15 046	313	9	48	2
Maideli	11	7·72	0·13	6·60	1·04	550	14 830	207	8	72	3
Mejae	7	7·7	0·14	10·53	1·24	550	14 694	200	9	74	3
Sewhimeda	8	7·55	0·2	12·54	1·74	140	n.a.	n.a.	9	n.a.	n.a.
Average	8	7·76	0·15	8·13	1·31	429	14 926	240	9	97	3
SD	2	0·21	0·04	2·75	0·56	164	1560	138	2	78	2

n, number of samples; pH, hydrogen ion concentration; N, total nitrogen; P_{av}, available phosphorus; OC, organic carbon; K, Potassium; Ca, calcium; Mg, magnesium.

Figure 3. Cattle and birds population as potential source of nutrient addition to the reservoirs in the form of urine and droppings.

Table V. Enrichment ratio of nutrients and soil textures from 13 catchments in Tigray, northern Ethiopia

Reservoirs	N	P_{av}	OC	K	Ca	Mg	Clay	Silt	Sand
Adiakor	1·20	0·99	1·18	5·16	n.a.	n.a.	1·44	0·74	0·52
Adihilo	1·27	2·15	1·93	1·65	1·26	0·76	1·06	0·85	1·27
Adikenafiz	1·16	2·19	1·09	1·23	3·10	1·41	1·89	1·83	0·38
Agushella	1·12	1·38	1·03	1·37	1·12	1·15	2·09	1·19	0·35
Endazoey	1·17	1·42	1·35	1·30	1·46	2·06	2·04	1·25	0·44
Gereb Segen	1·09	2·01	0·80	1·26	1·20	0·53	1·14	0·79	0·50
Gereb Shegel	1·50	1·18	0·51	1·58	1·79	3·22	2·36	1·27	0·21
Gindae	0·56	1·95	0·34	1·10	1·01	0·77	0·98	1·08	0·97
Grashitu	1·09	1·20	0·57	1·01	1·32	0·95	1·37	0·86	0·33
Gum Selassa	1·00	1·98	0·79	1·82	1·12	1·85	1·42	0·83	0·11
Maideli	0·76	2·27	0·51	2·10	1·58	2·01	1·34	1·32	0·14
Mejae	1·27	3·42	0·77	2·56	1·94	1·74	1·45	1·19	0·14
Sewhimeda	1·24	1·58	1·18	1·38	n.a.	n.a.	1·86	0·74	0·09
Average	1·11	1·82	0·93	1·81	1·54	1·50	1·57	1·07	0·42
SD	0·24	0·64	0·43	1·09	0·60	0·79	0·43	0·31	0·35

The Table shows the enrichment ratio for various nutrients and soil textural classes. Except for OC and sand, the $ER > 1$. The ER values in this study for all cases correspond to the lower boundary of ER ranges given by Olarieta *et al*. (1999) quoting various sources as: potassium 1·3–13, nitrogen 1·1–5, OC 2–4, phosphorus 1–6.

Table VI. Paired mean comparison and samples correlations ($n = 13$)

Pairs	Mean comparison		Correlation	
	Paired mean difference	df	*R*	*n*
pH_C and pH_R	0·01 n.s.	12	−0·01 n.s.	13
N_C and N_R	−0·01 n.s.	12	0·49 n.s.	13
P_{av}_C and P_{av}_R	−3·00**	12	0·68**	13
OC_C and OC_R	0·22 n.s.	12	0·28 n.s.	13
K_C and K_R	−0·40*	12	0·63*	13
Ca_C and Ca_R	−21·00**	10	0·52*	11
Mg_C and Mg_R	−0·48*	10	0·70*	11

R, correlation coefficient; df, degree of freedom; n, number of samples, n.s., non significant; *and ** significant at <0·05 and 0·01 levels, respectively.
Underscores 'C' and 'R' stand for catchment and reservoir, respectively.

Table VII. Pearson's correlations matrix for sediment nutrients and textural classes for the studied reservoirs ($n = 13$)

	N	P_{av}	OC	K	Ca	Mg	Clay	Silt	Sand
pH	−0·11 n.s.	0·11 n.s.	−0·04 n.s.	−0·31 n.s.	0·08 n.s.	0·51 n.s.	−0·15 n.s.	0·32 n.s.	0·43 n.s.
N		0·55*	0·88**	−0·14 n.s.	0·65*	0·55*	−0·35 n.s.	0·22 n.s.	−0·08 n.s.
P_{av}			0·49 n.s.	−0·43 n.s.	−0·22 n.s.	0·63*	−0·67**	0·73**	0·13 n.s.
OC				−0·08 n.s.	0·33 n.s.	0·60*	−0·32 n.s.	0·12 n.s.	0·17 n.s.
K					0·34 n.s.	−0·01 n.s.	0·72*	−0·32 n.s.	−0·54 n.s.
Ca						−0·03 n.s.	0·30 n.s.	−0·16 n.s.	−0·30 n.s.
Mg							−0·23 n.s.	0·31 n.s.	0·12 n.s.
Clay								−0·66**	−0·50 n.s.
Silt									0·12 n.s.

* and ** significant at <0·05 and 0·01 levels, respectively.

the P_{av} level in the reservoir (Table VII), that is, due to the selectivity of erosion processes (Le Roux and Roos, 1983). On the other hand, the negative correlation between P_{av} and clay fractions ($r = -0{\cdot}67$, Table VII) can be explained by the decreased availability of P_{av} as a result of high adsorption of phosphate ions between the clay minerals. It is known that soils containing large quantities of clay (i.e. large surface area) will fix (i.e. adsorb) more phosphorus than soils with low clay content. P_{av} is also associated with OC (Table VII).

The other possible reason for high P_{av} level in the reservoirs, although the contribution was not quantified, is an addition from cattle and bird manure which visit most reservoirs to drink water, especially during the dry season (Figure 3). At Adiakor reservoir, as an example, it was counted that about 500 cows, oxen and goats visit the reservoir for drinking water in a single day alone. However, this merits further quantitative study.

Organic carbon

OC ranges from 0·70 to 2·22 per cent with a mean value of 1·53 per cent in the catchments and from 0·73 to 2·63 per cent with a mean value of 1·31 per cent in the reservoirs (Tables III and IV). However, the mean OC in the catchment soils is relatively high with an ER = 0·93, but not significantly different from the reservoir sediment (Tables V and VI). Moreover, there is no significant relationship between the catchment soil and the reservoir sediment (Table VI). The relative low OC level in the reservoirs can be an indication of rapid decay (humification) as the OC:N ratio is 9 ± 2, which encourages microbial activity (Landon, 1984). All reservoirs become completely dry for some part of the year (May to mid June) so that there are relatively well-drained periods that could

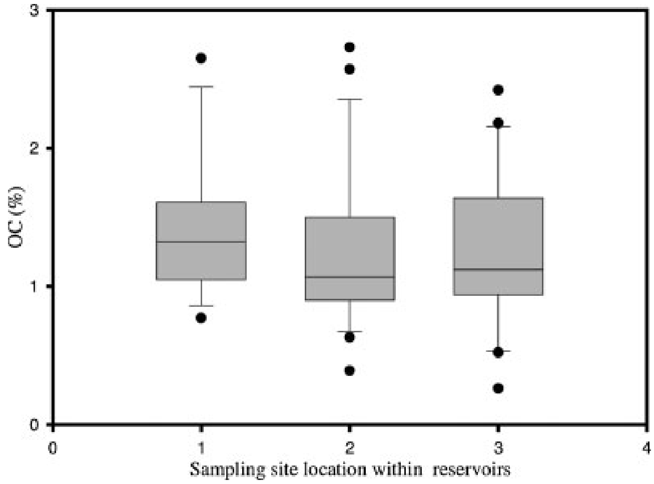

Figure 4. Box plots showing organic carbon (OC) level variability in three hydrologic regimes in the reservoirs. 1 near the dam; 2 in the centre of the reservoir and 3 in the inlet and edge of the reservoir.

encourage rapid decay of OC. To verify whether OC decay is a significant process, spatial variability of OC within reservoirs was analyzed based on three hydrological regimes coexisting in the reservoirs. Regime 1 includes areas near the dam where there is water for most part of the year; regime 2 covers the central part where there is submersion for half of the year and regime 3 the inlet and the edges of the reservoir that dry up for most of the year. The analysis (Figure 4) shows that the OC level is high in regime 1 and low in regime 3 which could support the argument that there might be mineralization, though the variation is not statistically significant.

Exchangeable potassium

The K content ranges from 98 to 581 $\mathrm{mg\,kg^{-1}}$ with a mean value of 273 $\mathrm{mg\,kg^{-1}}$ of soil in the catchments and from 140 to 632 $\mathrm{mg\,kg^{-1}}$ and with a mean value of 429 $\mathrm{mg\,kg^{-1}}$ soil in the reservoirs (Tables III and IV). It is significantly higher in the reservoirs than in the catchments with an ER = 1·81 (Table V) and with a highly significant positive correlation between the catchment soils and the sediment ($r = 0{\cdot}63$, Table VI). The high level of K in the sediment can be explained mainly by the selectivity of erosion processes. The K and clay fraction of the deposited sediment are shown to be strongly correlated ($r = 0{\cdot}72$, Table VII) as a result of higher electro-magnetic attraction between the negative clay surface and K cation.

Exchangeable calcium

The Ca content varies from 3684 to 14 354 $\mathrm{mg\,kg^{-1}}$ with a mean value of 10 762 $\mathrm{mg\,kg^{-1}}$ in the catchment soils and from 11 432 to 17 544 $\mathrm{mg\,kg^{-1}}$ with a mean value of 14 926 $\mathrm{mg\,kg^{-1}}$ in the sediment (Tables III and IV). The mean difference is significant with an ER = 1·54 (Tables V and VI) and the means are strongly correlated ($r = 0{\cdot}52$, Table VI). The high level of Ca in the sediment is a result of catchments' domination by limestone and shale/marl formations (Table I). The lime will be easily dissolved by runoff and transported into the reservoirs. In the reservoirs, there is sufficient settling time as most of the reservoirs have high trap efficiency for runoff. The Ca will precipitate in the reservoirs and; as a consequence, there will be significant deposition of Ca. The runoff is the main transporting agent for Ca from the catchments to reservoirs and this is indirectly evidenced by the poor correlation of Ca with clay and silt fractions in the reservoir sediment (Table VII). The poor correlation between Ca and clay or silt is due to preferential attraction of K cation by the finer soil surface. K is located at a higher activity series in the Periodic Table of Elements, followed by Ca and then by Mg.

The other point to note from Table IV is that the standard deviation is much less in the sediment and it stays around 15 000 gm kg^{-1} for all reservoirs irrespective of the Ca concentration in catchment soils. This shows that once runoff is saturated with lime, no more lime will be dissolved and transported into the reservoirs.

Exchangeable magnesium

The Mg content varies from 54 to 394 mg kg^{-1} and with a mean value of 182 mg kg^{-1} of soil in catchments and from 63 to 454 mg kg^{-1} and with a mean value of 240 mg kg^{-1} in the reservoirs (Tables III and IV). The Mg level in reservoirs is generally higher with an ER = 1·5 (Tables V and VI) and yet significantly correlated with the catchment Mg level ($r = 0{\cdot}70$, Table VI). This could indicate that the Mg source is probably the precipitation of dissolved dolomite transported via runoff. In the Mekelle Outlier, dolomite and limestone outcrop are occurring all over the place (Ferriz and Bizuneh, 2002). The associated transport via runoff is, however, indirectly evidenced by the poor correlation between Mg level and soil fractions in the reservoir.

Fertility Status of the Reservoir Sediments

Based on the Soil Interpretation Guide given by Marx *et al.* (1999), the average level of individual nutrients in the reservoirs (Table IV) was rated as follows: extremely low for P_{av}, medium for N and K and high for Ca and Mg. The level of P_{av} is also rated as deficient irrespective for any crop, based on the interpretation given by Cooke (1967). The problem with P_{av} unavailability is limited as the pH level in the reservoir is in the optimal range, that is, mean pH = 7·76. The organic matter (applying OM = 1·732 × OC, Vanongeval *et al.*, 1996) varies from 1·26 to 4·53 for sediment, which can be rated from low (<2 per cent) to marginal (2–4 per cent) (Landon, 1984). On the other hand, the K content both in the catchment and deposited soils is high based on the rating given by Landon (1984). However, exchangeable K levels are of limited value for predicting crop response since they give direct indication of the capacity of the soil to release currently available K over a period of time. Indices of plant available Ca are of little value since the availability varies enormously from soil to soil and is highly dependent on a number of other factors. Normally, Ca deficiency as a plant nutrient occurs only in soils of low cation exchange capacity at pH values of 5·5 or less.

The level of individual nutrient alone may not reflect the fertility status of a soil. The interaction between each nutrient is equally important. As an example, the OC:N ratio is usually mentioned in soil reports as an indicator of organic matter present and in particular the degree of humification. Table IV shows that OC:N ratio is varying from 5 to 13 with mean of 9. This range of values indicates that the environment encourages microbial activity to humify the OC.

There is a wide range of the Ca:Mg ratio. It varies from 26 to 263 with a mean value of 97 (Table IV). This value is so high from the threshold Ca:Mg ratio of >5:1 (Landon, 1984) that Mg is most likely rather deficient in the soil. Moreover, the K:Mg ratio varies from 0·46 to 7 with mean value of 3 (Table IV), which again points to the fact that Mg uptake can be inhibited irrespective of the crop type.

The presence of Mg deficiency in a crop may not only be associated with low Mg deficiency in the soil, but also with the presence of a large amount of other cations, particularly Ca and K. With increasing Ca:Mg ratios above 5:1, Mg may become progressively less available to plants, although soils remain fertile over a wide range of Ca:Mg ratios (Landon, 1984).

In general, the deposited sediment has huge potentials for agricultural productivity given that it enriched in nutrients as compared to the average catchment soils. It is, however, important to note that the fertility status of the deposited sediment is not sufficient to support a sustainable crop growth and, therefore, requires external addition mainly for N and P_{av}. Moreover, field experiments may be conducted on crop productivity to assess the feasibility of using the dredged sediment as an option for reclaiming degraded lands. If the potential is verified under field experiments, it encourages the local farmers to dredge and use the sediment for rehabilitation of their land on own labour. This practice on the other hand increases the life of the reservoir at no cost.

On the other hand, the addition of nutrients from fertilizers is limited as a result there are always negative balances, that is, depletion rate is greater than addition rate as confirmed with similar studies (Haileselassie *et al.*, 2005). However, a detailed nutrient balance analysis at catchment scale merits further study.

Evaluation of Nutrient Export and Its Association With Specific Sediment Yield Variability

Evaluation of nutrient export

NE rates for the studied nutrients are given in Table VIII. 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_{av}, 97·11 (±44·96) for OC, 3·85 (±2·85) for K, 140·97 (±62·83) for Ca and 2·11 (±1·49) for Mg.

In Ethiopia, data on OC, Ca and Mg export rates are limited. Since recently, there have been efforts to show N, P_{av} and K balances at regional scale (Haileselassie *et al*., 2005) and field-scale (Elias *et al*., 1998; Hengsdijk *et al*., 2005) mainly based on application of empirical models. Haileselassie *et al*. (2005) assessed the nutrient balance for N, P_{av} and K at regional scale and country level using the input–output fluxes of nutrient balance presented in Smaling and Fresco (1993). They estimated two different loss values of N, P_{av} and K by erosion using two different soil loss estimates (1) universal soil loss equation (USLE) adapted for Ethiopian conditions by Hurni (1985) and (2) landscape process model (LAPSUS). The values (in kg ha^{-1} y^{-1}) reported were: 37·7 and 6·0 for N, 7·8 and 3·0 for P_{av} and 28·3 and 4·0 for K, for USLE and LAPSUS soil loss estimates, respectively. In both cases, soil erosion is found to be the prime responsible factor for nutrient depletion, that is, accounts for loss of 70, 80 and 63 per cent for N, P_{av} and K, respectively. In their calculation, however, they assume a constant ER ratio of 1·5 for all nutrients. This ER has a higher value; moreover, there is variability in ER values between nutrients as reported in this study (Table V).

For N, P_{av} and K, the export rate is much higher compared to this study. One of the reasons might be due to the assumption of high ER especially for N. Table V shows the ER of various nutrients and the ER for N is found to be 1·1. The over prediction is higher in the case of the USLE application. This might be due to the misuse of USLE to predict regional soil loss which the model was not designed for (Hudson, 1995).

Hengsdijk *et al*. (2005) studied the N balance in Gobo Deguat (within this study region) at farmers' field using nutrient monitoring model (NUTMON) and estimated N loss by erosion at 12·6 kg ha^{-1} y^{-1}, which corresponds well with the average rate found in this study. However, organic inputs from purchased manure and feeds account the highest proportion (34·2 kg ha^{-1} y^{-1}) seem exaggerated, which is inconsistent to the findings of this study (see Sub Section Assessment of Practices of Fertilizer Inputs in the Catchments in Tigray). Moreover, the role of erosion in nutrient outflow is in the fourth place after harvested products (22·9 kg ha^{-1} y^{-1}), crop residue in manure (13·2 kg ha^{-1} y^{-1}), gaseous losses (4·9 kg ha^{-1} y^{-1}) and is inconsistent with the work by Haileselassie *et al*. (2005)

Table VIII. Nutrients export for 13 catchments in northern Ethiopia

Reservoir	Rate of nutrient export (kg ha^{-1}y^{-1})					
	N	P_{av}	OC	K	Ca	Mg
Adiakor	7·15	0·038	62·40	2·00	n.a.	n.a.
Adihilo	13·30	0·065	128·25	4·04	137·48	0·60
Adikenafiz	14·85	0·153	133·65	2·66	154·33	5·83
Agushella	3·60	0·023	38·43	0·97	30·40	0·86
Endazoey	14·60	0·055	182·82	2·56	113·77	2·68
Gereb Segen	14·18	0·052	103·99	6·82	179·73	2·10
Gereb Shegel	7·31	0·033	38·00	1·56	85·48	0·85
Gindae	12·16	0·073	92·44	2·70	166·49	0·63
Grashitu	21·80	0·099	132·61	10·63	269·65	3·12
Gum Selassa	10·30	0·042	91·26	4·65	110·74	2·31
Maideli	18·57	0·094	148·59	7·86	211·88	2·96
Mejae	8·64	0·065	76·53	3·39	90·69	1·23
Sewhimeda	3·85	0·024	33·46	0·27	n.a.	n.a.
Average	11·56	0·063	97·11	3·85	140·97	2·11
SD	5·22	0·035	44·96	2·85	62·83	1·49

DOI: 10.1002/ldr

and by Smaling and Fresco (1993). Those authors show that there are uncertainties in the nutrient balance calculation probably due to a lack of measured inputs and outputs and therefore merits further study. The N export in this study is, however, low compared to the ranges given in literature elsewhere in the world that ranges between 22 to 292 kg ha^{-1} y^{-1} (Johnson, 1999). The low export rate is associated to the low level of N in Ethiopian soils.

Organic carbon export and sequestration

The OC export is relatively high and varies spatially between catchments from 33·46 to 182·82 kg ha^{-1} y^{-1} with a mean value of 97·11 kg ha^{-1} y^{-1}. This equals to an average annual deposition of 980 tons of OC from 13 catchments. In Tigray alone, there are about 64 such dams with total drainage area of 642 km^2, constructed for irrigation purpose since 1977 in which more than 90 per cent were built after 1994 (Haregeweyn, 2006). Calculation of OC stock in the 64 reservoirs yielded an average total OC of about 6640 t y^{-1} (i.e. 0·11 t ha^{-1} y^{-1}). This carbon storage rate falls within the range of 0·03–2·67 t ha^{-1} y^{-1} observed in the 44-years check dams in the Nianzhuanggou China watershed (Li *et al*., 2006). Their OC sequestration estimate is found to be 3·25 times higher than annual amount of soil carbon (0·04 Gt y^{-1}) eroded and deposited across US, and accounts for 18 per cent of total amount of carbon sequestration (0·72 Gt OC) by Chinese forests for the period from 1994 to 1998. Stallard (1998) has shown that erosion-sedimentation leads to a global net OC sequestration of 0·6–1·5 Gt OC y^{-1}. Therefore, the contribution of the 64 reservoirs in Tigray alone towards global net carbon sequestration is estimated between 0·0005 to 0·001 per cent, taking the assumption by Stallard (1998) that the eroded OC replacement ranges from 50 to 100 per cent. Therefore, the amount of stock underlines the potential of reservoirs as an important store for OC in the global carbon balance.

Association of nutrient export with specific sediment yield

Export rates of the studied nutrients were correlated with SSY for the 13 catchments (Figure 5). There is a 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_{av}, OC and Mg, respectively. These relationships illustrate that (1) soil erosion is playing a major role for the nutrient stocking

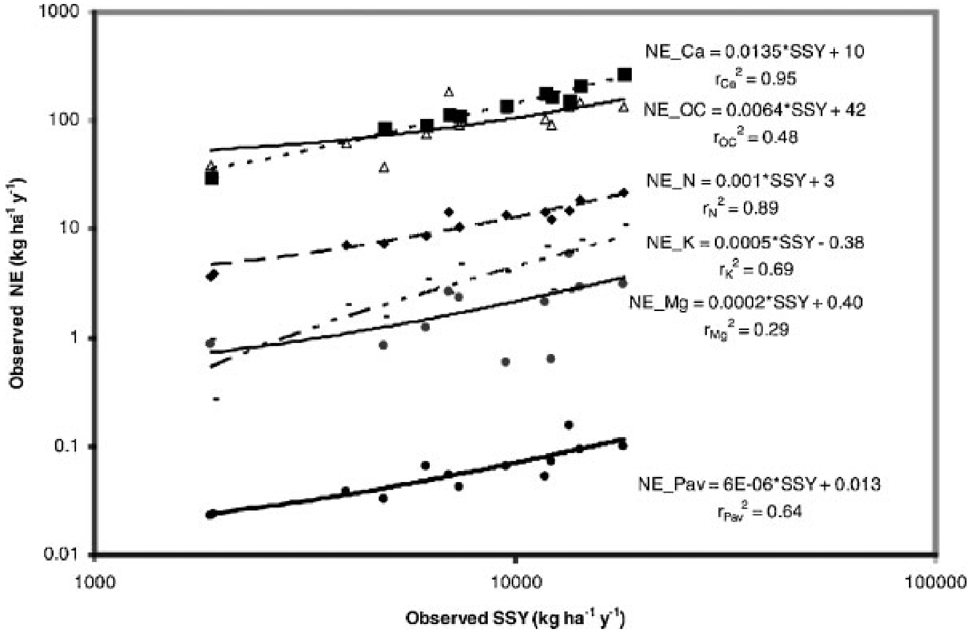

Figure 5. Relationship between specific sediment yield (SSY) and nutrient export (NE) rates in Tigray, northern Ethiopia. r^2 = coefficient of determination.

in the sediment and (2) the less pronounced spatial variation of fertility status between catchments. Relationships between SSY and the corresponding NE can be useful predictive tools (see Figure 5). It is, however, important to identify other factors, which are responsible for the major spatial variation between catchments, especially in the case of Mg.

Costs of Soil Erosion-Caused Soil Fertility Degradation

Table IX shows that an average of 68 ETB (6·8 € in March 2006) $ha^{-1} y^{-1}$ is needed to maintain the loss of N and P_{av} on the site due to erosion. This totals at 694 560 ETB (69 456 €) per year in 2006 from 13 catchments (101·44 km^2). This information could be scaled up to Tigray's Regional State (area of 50 078 km^2) and up to Ethiopian highlands ($4·48 \times 10^5 km^2$, which accounts 40 per cent of the country's landmass including the highlands of Tigray); it is estimated at 342 million ETB (34·2 million €) and 3·06 billion ETB (0·306 billion €) annually for Tigray and the Ethiopian highlands, respectively. The cost of erosion is generally high for Ethiopia where average annual income is only between 100 and 150 € *per capita*. The inclusion of OC and other nutrient losses and the losses in physical soil fertility increases the cost. However, the extrapolation of soil erosion for the Ethiopian highlands is probably an underestimation, because (1) due to previous erosion, soil erosion rates are now less in Tigray than elsewhere in the other parts of the Ethiopian highlands and (2) soils are more fertile in those other parts of the Ethiopian highlands.

FAO (1986) presented only indicative cost estimates of erosion in the Ethiopian highlands which accounted only to reduce agricultural production estimated at an annual average of 600 million ETB for 1985–2010 years (60 million € at present value). This study indicates also annual costs for cropped and grazed area ranging from 29 to 44 (2·9–4·4 € at present) and 3–25 ETB (0·3–2·5 € at present) $ha^{-1} y^{-1}$, which is much less than what is estimated in our study. However, the report emphasized that there were methodological weaknesses such as on the relationship between soil losses and yield reductions and the difficulties inherent in projecting soil losses. Therefore, even under the partial accountancy of cost of erosion in this study, information presented in the FAO study is shown to underestimate the costs of soil erosion. Though there are uncertainties in extrapolation of cost of erosion from a region to a country, the national figure quantified by this study is the best estimate which was obtained for Ethiopia so far.

Table IX. Erosion costs in March 2006 due to loss of N and P from mixed land uses of Tigray catchments, northern Ethiopia

Reservoir	Urea addition		DAP addition		Total cost*
	($kg\,ha^{-1} y^{-1}$)	Cost ($ETB\ ha^{-1} y^{-1}$)	($kg\,ha^{-1} y^{-1}$)	($ETB\ ha^{-1} y^{-1}$)	($ETB\ ha^{-1} y^{-1}$)
Adiakor	15·48	41·79	0·189	0·57	42·36
Adihilo	28·79	77·73	0·322	0·96	78·69
Adikenafiz	31·98	86·36	0·761	2·28	88·64
Agushella	7·77	20·99	0·115	0·34	21·34
Endazoey	31·63	85·40	0·272	0·82	86·21
Gereb Segen	30·73	82·96	0·259	0·78	83·73
Gereb Shegel	15·82	42·72	0·163	0·49	43·21
Gindae	26·30	71·01	0·365	1·10	72·10
Grashitu	47·19	127·43	0·495	1·48	128·91
Gum Selassa	22·32	60·26	0·211	0·63	60·89
Maideli	40·19	108·52	0·469	1·41	109·93
Mejea	18·66	50·37	0·324	0·97	51·35
Sewhimeda	8·31	22·44	0·120	0·36	22·80
Average	25·01	67·54	0·31	0·94	68·47

DAP, di-ammonium phosphoate; ETB, Ethiopian Birr.
*10 ETB = 1 € in March 2006.

DOI: 10.1002/ldr

CONCLUSIONS

Selective erosion was observed and this is indicated by ER values of 1·57, 1·07 and 0·42 for clay, silt and sand fractions, respectively and ER values of 1·82, 1·81, 1·54 and 1·5 for P_{av}, K, Ca and Mg, respectively. The high ER for P_{av} and K is mainly due to their preferential transport bound with fine soil fractions while the high ER for Ca and Mg is mainly associated with parent material dissolution and its transport via runoff. As a result, the nutrient concentration is significantly higher in the deposited sediment except for OC and N and there is no problem on the sediment associated with alkalinity and acidity. Field experiments may be conducted on crop productivity to assess the feasibility of using the dredged sediment as an option for reclaiming degraded lands. This practice on the other hand increases the life of the reservoir at no cost.

A strong positive relationship between NE and SSY was observed for all nutrients, which can explain (1) the less pronounced spatial variation of fertility status between catchments (2) the principal role of erosion for nutrient exporting into the reservoirs. The high OC export on the other hand suggests the potential of reservoir sedimentation in OC sequestration. An important global potential, that is, about 6640 tons of OC from 642 km^2 sequester in Tigray alone, which accounts between 0·0005 to 0·001 per cent of the global potential due to erosion-sedimentation.

The yearly cost due to loss of N and P_{av} only was estimated at 342 million ETB (34·2 million €) and 3·06 billion ETB (0·306 billion €) in March 2006 form Tigray and the Ethiopian highlands, respectively, which is more than 1/3 of the gross annual budget in the case of Tigray. The inclusion of OC and other nutrient losses and the losses in physical soil fertility brings the cost much higher. In general, the extent of fertility degradation is high and, hence, is a major threat for a sustainable agriculture, even on the short and medium-term. Pity enough, neither policy makers nor beneficiaries are aware about the magnitude of the problem. Therefore, it is not only important to make the public aware of the problem but also of the solution, which consists of integrated soil fertility management practices.

ACKNOWLEDGEMENTS

We thank Flemish Interuniversity Council (VLIR) for the financial support of this study as part of the Zala Daget Project ‘Fighting desertification in the Tigray Highlands: lessons to be learnt from successes and failures of soil erosion control techniques’. Partners include: Mekelle University and REST from Ethiopia and K.U. Leuven and the Royal Museum for Central Africa from Belgium. We thank Zala Daget Project research assistant Alemseged Gebreegziabher and driver Adam Haile for their assistance during the fieldwork. We thank also Co-SAERT and REST for providing access to the technical reports on the dams and catchments. Woreda authorities and farmers in the study area have facilitated our fieldwork as well.

REFERENCES

Bard K, Coltorti M, Diblasi MC, Dramis F, Fattovich R. 2000. The environmental history of Tigray (Northern Ethiopia) in the middle and late Holocene: A preliminary outline. *African Archeological Review* **17**: 65–68.

BoANR. 2002. Impact Assessment of Extension. *Bureau of Agriculture and Natural Resources intervention (1996–2000), Tigray, Ethiopia. vol. 1* (*main technical report*); 110.

Bojö J. 1996. The costs of land degradation in Sub-Saharan Africa. *Ecological Economics* **16**: 161–173.

Bojö J, Cassells D. 1995. Land Degradation and Rehabilitation in Ethiopia: A Reassessment. *The World Bank, Environmentally Sustainable Development Division, AFTES Working Paper* No. 17; 48.

Bremmer JM, Mulvaney CS. 1982. Nitrogen total. In *Method of Soil Analysis: Part 2. Chemical and Microbiological Properties*, Page AL (ed.). ASA Monograph Number 9. ASA: Wisconsin, WI; 595–624.

CSA. 2001. *Statistical Abstract 2000*. Federal Democratic Republic of Ethiopia, Central Statistical Authority: Addis Ababa; 403.

Cooke GW. 1967. *The Control of Soil Fertility.* Crosby Lockwood: London.

Elias E, Morse S, Belshaw DGR. 1998. Nitrogen and phosphorus balances of Kindo Koisha farms in southern Ethiopia. *Agriculture, Ecosystems and Environment* **71**: 93–113.

Eswaran H, Lal R, Reich PF. 2001. Land degradation: An overview. In *Response to Land Degradation*, Bridges EM, Hannam ID, Oldeman LR, Penning de Vries FWT, Scherr JS, Sombatpanit S (eds). Science Publisher, Inc.: Enfield, NH; 20–35.

FAO. 1986. *Ethiopian Highlands Reclamation Study, Vol. 1 and 2.* Food and Agricultural Organization of the United Nations: Rome, Italy.

DOI: 10.1002/ldr

FAO. 1991. Results of Fertilizer Trials Conducted on Major Cereal Crops. *Working Paper* No. 34, Ministry of Agriculture, Addis Ababa, Ethiopia.

FAO. 2004 http://www.fao.org/giews/english/basedocs/eth/ethpop1e.stm. Food and Agricultural organization of the United Nations, Rome, Italy [Accessed 20 January 2005].

Ferriz H, Bizuneh G. 2002. Development and Management of Water Resources. ESRDF: Community driven poverty eradication and restorative development in Ethiopia. http://geology.csustan.edu/ferriz/Water_Resources_Ethiopia.pdf [Accessed on 10 August 2006].

Gee GW, Bauder JW. 1982. Particle size analysis. In *Method of Soil Analysis: Part 1. Physical and Mineralogical Methods*, Klute A (ed.). ASA Monograph Number 9. ASA: Wisconsin, WI; 383–411.

Haileselassie A, Priess J, Veldkamp E, Teketay D, Lesschen JP. 2005. Assessment of soil nutrient depletion and its spatial variability on stallholder's mixed farming systems in Ethiopia using partial versus full nutrient balances. *Agriculture, Ecosystem and Environment* **108**: 1–16.

Haregeweyn N. 2006. Reservoir Sedimentation in the North Ethiopian Highlands: Assessment and Modelling of Controlling Factors and Impacts. *PhD thesis Katholieke Universiteit Leuven, Department of Geography and Geology*, ISBN 90-8649-017-4; 245.

Haregeweyn N, Poesen J, Nyssen J, De Wit J, Haile M, Govers G, Deckers J. 2006. Reservoirs in Tigray: Characteristics and sediment deposition problems. *Land Degradation & Development* **17**: 211–230. DOI: 10·1002/ldr.698.

Hengsdijk H, Meijerink GW, Mosugu ME. 2005. Modelling the effect of three soil and water conservation practices in Tigray, Ethiopia. *Agriculture, Ecosystems and Environment* **105**: 29–40.

Hudson NW. 1995. *Soil Conservation*, 3rd ed. B T Batsford: London; 391.

Hurni H. 1989. Late quaternary of Simen and other mountains in Ethiopia. In *Quaternary and Environmental Research on East African Mountains*, Mahaney W (ed.). Balkema: Rotterdam; 105–120.

Hurni H. 1985. Soil Conservation Manual for Ethiopia: A Field Manual for Conservation Implementation. *Soil Conservation Research Project*, Addis Ababa.

Johnson GP. 1999. Water, Sediment, and Nutrient Budgets, and Bathymetric Survey of Old and New Gillespie Lakes, Macoupin County, Illinois, May 1996–April 1997 (with a Discussion of Lake Management Practices). *Open-File Report 99–69. USGS Science for Changing the World*.

Krogvang B. 1990. Sediment associated phosphorus transport from two intensively farmed catchments areas. In *Soil Erosion on Agricultural Land*, Boardman J, Foster ILD, Dearing JA (eds). John Wiley and Sons: Chichester; 313–330.

Lal R. 2005. Soil erosion and carbon dynamics. Editorial. *Soil and Tillage and Research* **81**: 137–142.

Landon JR. 1984. *Booker Tropical Soil Manual. A handbook for Soil Survey and Agricultural Land Evaluation in the Tropics and Subtropics*. Longman group: UK.

Le Roux JS, Roos ZN. 1983. The relationship between top soil particles sizes in the catchment of Wuras Dam and the particles sizes of the accumulated sediment in the reservoir. *Zeitschrift für Geomorphologie* **27**: 161–170.

Li Y, Valentin C, Zhang QW, Poesen J, Coleman D, Funk R, Loughran R, Bai LY, Bork HR, Zhang XC, Li L. 2006. Variation of sediment yield and organic carbon storage by checkdams on the Chinese Plateau. *Nature*, (in press).

Marx ES, Hart J, Stevens RG. 1999. *Soil Interpretation Guide*. Oregon State University Extension Service: Covallis, OR.

Moeyersons J, Nyssen J, Poesen J, Deckers J, Mitiku Haile. 2005. Age and backfill/overfill stratigraphy of two tufa dams, Tigray Highlands, Ethiopia: Evidence for Late Pleistocene and Holocene wet conditions. *Palaeogeography, Palaeoclimatology and Palaeoecology* **230**: 162–178.

Muchena FN, Onduru DD, Gachini GN, Jager A. 2005. Turning the tides of soil degradation in Africa: Capturing the reality and exploring the opportunities. *Land Use Policy* **22**: 23–31.

Nyssen J, Poesen J, Moeyersons J, Deckers J, Mitiku Haile, Lang A. 2004. Human impact on the environment in the Ethiopian and Eritrean highlands-a state of the art. *Earth Science Reviews* **64**: 273–320.

Nyssen J, Vandenreyken H, Poesen J, Moeyersons J, Deckers J, Mitiku Haile, Salles C, Govers G. 2005. Rainfall erosivity and variability in the Northern Ethiopian Highlands. *Journal of Hydrology* **311**: 172–187.

Olarieta JR, Besga G, Rodriguez R, Uson A, Pinto M, Virgel S. 1999. Sediment enrichment ratios after mechanical site preparation for Pinus radiata plantation in the Basque Country. *Geoderma* **93**: 255–267.

Olsen SR, Sommers LE. 1982. Phosphorus. In *Method of Soil Analysis: Part 2. Chemical and Microbiological Properties*, Page AL (ed.). ASA Monograph Number 9. ASA: Wisconsin, WI; 403–430.

Pierce FJ, Lal R. 1994. Monitoring the impact of soil erosion on crop productivity. In *Soil Erosion Research Methods*, Lal R (ed.). Soil and Water Conservation Society: Ankeny, IA; 234–263.

Rausch DL, Schreiber JD. 1981. Sediment and nutrient trap efficiency of a small flood-detention reservoir. *Journal of Environmental Quality* **10**(3): 288–293.

Robinson DA, Blackman JD. 1987. Some costs and consequences of soil erosion and flooding around Brighton and Hove, Autumn. In *Soil Conservation, Problems and Prospects*, Morgan RPC (ed.). John Wiley and Sons: Chichester; 369–382.

SAS. 2002. *SAS 9·1*. Institute Inc.: Cary, NC.

Smaling EMA, Fresco LO. 1993. A decision support model for monitoring nutrient balances under agricultural land uses. *Geoderma* **60**: 235–256.

Stallard RF. 1998. Terrestrial sedimentation and carbon cycle: Coupling weathering and erosion in the carbon burial. *Global Biogeochemical Cycles* **12**: 231–257.

Steegen A, Govers G, Takken I, Nachtergaele J, Poesen J, Merckx R. 2001. Factors controlling sediment and phosphorus export from two Belgian agricultural catchments. *Journal of Environmental Quality* **30**: 1249–1258.

Stoorvogel JJ, Smaling EMA. 1990. *Assessment of Soil Nutrient Depletion in Sub-Saharan Africa: 1983–2000*. Winand Staring Centre: Wageningen; 102.

TFAP. 1996. *Tigray Forest Action Program*. Tigray Bureau of Agriculture and Natural Resources Development: Mekelle, Ethiopia; 122.

Thomas GW. 1982. Exchangeable cations. In *Method of Soil Analysis: Part 2. Chemical and Microbiological Properties*, Page AL (ed.). ASA Monograph Number 9. ASA: Wisconsin, WI; 159–165.

UNEP and UNESCO. 1980. *Provision map of Present Land Degradation Rate and Present State of Soil*. FAO: Rome.

Van Oost K, Govers G, Quine TA, Heckrath G. 2004. Comment on ''managing soil carbon''(I). *Science* **305**: 1567b.

Van Oost K, Govers G, Quine TA, Heckrath G, Olesen JE, De Gryze S, Merckx R. 2005. Landscape-scale modeling of carbon cycling under the impact of soil redistribution: The role of tillage erosion. *Global Biogeochemical Cycles* **19**: 1–13.

Vanongeval L, Ver Elst P, Boon W, Bries J, Vandendriessche H, Geypens M. 1996. *De Chemische Bodemvruchtbaarheid van Het Belgische Akkerbouw-en Weilandareaal (1992–1995)*. Bodemkundige Dienst van België vzw: België; 104.

Verstraeten G, Poesen J. 2002. Regional scale variability in sediment and nutrient delivery from small agricultural catchments. *Journal of Environmental Quality* **31**: 870–879.

Virgo KJ, Munro RN. 1978. Soil and erosion features of the central pleatux of Tigray, Ethiopia. *Geoderma* **20**: 131–157.

Wan Y, El-Swaify SA. 1998. Sediment enrichment mechanisms of organic carbon and phosphorus in a well-aggregated Oxisol. *Journal of Environmental Quality* **27**: 132–138.

Weigand S, Schimmack W, Auerswald K. 1998. The enrichment of ^{137}Cs in the soil loss from small agricultural watersheds, Z. Pflanzenernahr. *Bodenkd* **161**: 479–484.

Withers PJA, Lord EI. 2002. Agricultural nutrient inputs to rivers and groundwater in the UK: Policy, environmental management and research needs. *The Science of the Total Environment* **282–283**: 9–24.

DOI: 10.1002/ldr