Land reclamation using reservoir sediments in Tigray, northern Ethiopia

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Abstract

Accelerated soil erosion leads to sedimentation in reservoirs and a decline in their life span. As many reservoirs in northern Ethiopia are dry at the end of the dry season, we were able to evaluate the potential of using reservoir sediments for land reclamation. Stripped land from which construction material for the reservoirs had been excavated was covered with 0, 15 and 30 cm of sediment and planted with a local garlic cultivar (*Allium sativum*). The applied reservoir sediments had low to medium organic C and total N contents and were high in available P and exchangeable cations. The yield of garlic increased with additional available water and the application of sediments. The results show that total biomass and bulb yield were three times higher on the reclaimed plots than on the control ones (11.7 t/ha vs. 3.6 t/ha for the biomass; 7.7 t/ha vs. 2.0 t/ha for the yield). When sediment transport and labour costs were taken into account, plots with 15 cm of sediments had in the first cropping season a cost-benefit ratio of 3, whilst those with 30 cm had a cost-benefit ratio of 0.9. This study demonstrates that the use of relatively small quantities of reservoir sediments is an economically viable strategy for land reclamation. The result can be improvement in income for resource-poor farmers by as much as 76%, and the life expectancy of the reservoirs is also increased.

Keywords: Sediment, bare land, garlic yield, cost-benefit ratio, Ethiopia

Introduction

Rapid soil degradation is one of the major global environmental problems (UNEP & UNESCO, 1980; UNESCO, 1997; Eswaran *et al*., 2001), and the Ethiopian highlands are amongst the most degraded landscapes in Africa (El-Swaify & Hurni, 1996). The soils in this region have a low capacity to sustain agricultural productivity. The shortage of rainfall in semi-arid areas of northern Ethiopia often results in crop failure given the lack of irrigation. The need for increased availability of water has led to the construction of ca. 87 reservoirs (BoWRD, 2009), each with an average water storage capacity of some 1–3.5 million m^3. However, some 50% of the reservoirs in Tigray in northern Ethiopia have had their life expectancy reduced from 26 to 13 yr because of sedimentation (Haregeweyn *et al*., 2006). Also, sediment-bound nutrients accumulate in the reservoirs (Haregeweyn *et al*., 2006; Tamene *et al*., 2006) because of massive soil erosion (Nyssen *et al*., 2004, 2006). A study by Fonseca *et al.* (1998) in southern Portugal indicates that reservoir sediments may contain high levels of total, exchangeable and soluble nutrients. In northern Ethiopia, Girmay *et al.* (2009) report that organic carbon (OC), total nitrogen (N_{tot}), available P (P_{av}), and exchangeable cations were higher in reservoir sediments than in the soils of the catchment.

Use of nutrient-rich sediment from reservoirs for agriculture is not common and requires excavating the reservoirs (Ryding, 1982). Although excavation costs are high, a local dredging strategy as used at the Koka hydropower dam in Ethiopia keeps outlets clear of sediments and excavation is recommended for reservoirs that are dry during the dry season (Palmieri *et al*., 2003). Yet, there is limited experience of dredging reservoirs in northern Ethiopia although the Tigray Water Works Construction Enterprise (TWWCE, 2009) has dredged sediment from a reservoir using conventional earth moving equipment. Disposal of the

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dredged sediment proved to be problematic because of high transportation costs. Astatke *et al.* (1986) have demonstrated the use of animal power for constructing reservoirs, also applicable to the excavation of the reservoirs. Dredged materials are also of value for developing various habitats and improving marginal soils (USACE, 1985). For instance, excavated sediment from the Cogswell Dam and Reservoir in California has been used as landfill in the hills adjacent to the reservoir (Palmieri *et al.*, 2003).

Extraction of construction materials for earth dams in northern Ethiopia results in bare unproductive land both up- and down-stream of the reservoirs. Such land requires restoration, but there are few studies on crop productivity and benefits from using reservoir sediments. This study had the aim of evaluating the potential of reservoir sediments for reclaiming bare land near to reservoirs in the semi-arid northern Ethiopia for the growth of rainfed garlic. The results are applicable to vast tracts of land in some 70% of Sub-Saharan Africa with a semi-arid or a sub-humid moisture regime.

Materials and methods

Study site

The study was undertaken during the rainy season in 2009 at Maileba reservoir with a catchment area of 18 km^2 at 13°41′N and 39°15′E (Figure 1) and ranging in altitude from 2290 to 2835 m a.s.l. The annual rainfall of the study area varies from 450 to 800 mm (Figure 2). Most of the rainfall (ca. 66%) occurs in July and August, and the average monthly air temperature is between 12 and 19 °C. The Maileba dam was built in 1998 using excavated local soils. The underlying material is weathered marl of the *Agula* formation (Van de Wauw *et al*., 2008). This partly infilled reservoir dries out at the end of the dry season as is common in Tigray.

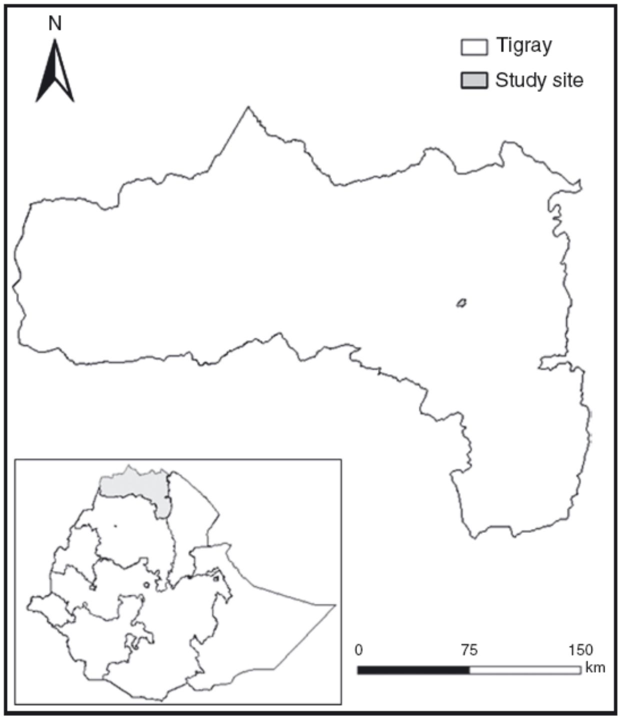

Figure 1 Location of the study site in Ethiopia.

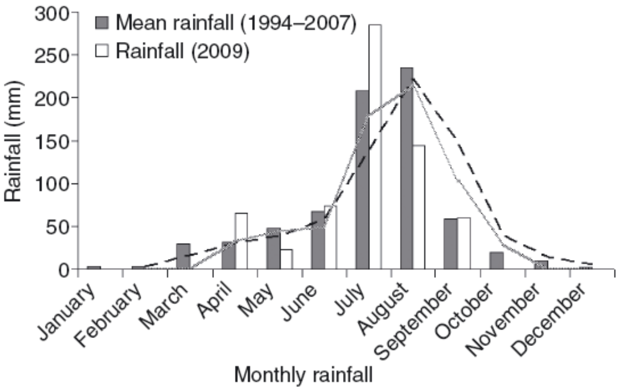

Figure 2 Mean monthly rainfall of the study site. The mean monthly rainfall of the study site in 2009 was compared with long-term rainfall averaged from 1994 to 2007 for the Hagere Selam station (Ethiopian Meteorological Agency, 2008).

Soil sampling and analysis

The sediment in the Maileba reservoir was investigated when it was dry in May 2009 through taking 144 samples from the reservoir bottom (ca. 11.5 ha) at a depth of 0–15 cm in a 20 × 20 m grid. Representative bulk sediment samples (0–15 cm depth) were collected. Coarse sediments occurred at a gully mouth and finer sediments in the centre of the reservoir. The bulk sediments were analysed for particle size, pH, OC, N_{tot}, P_{av} and K_{exch} in the Ethiopian National Soils Laboratory (in Addis Ababa) according to procedures described by Sahlemedhin & Taye (2000). Bulk density, water retention at field capacity and permanent wilting point and the available water holding capacity were also determined by taking undisturbed samples using core samplers. Evaluation of the physical characteristics and nutrient status of the reservoir sediments was based on the Soil Interpretation Guide (Landon, 1991).

Plot layout and experimental data collection

An experimental site was selected on bare land where soil had been excavated for dam construction upstream of the dam. A representative 22 × 5.2 m plot was chosen and subdivided into 18 experimental sub-plots of 2 × 2 m by constructing

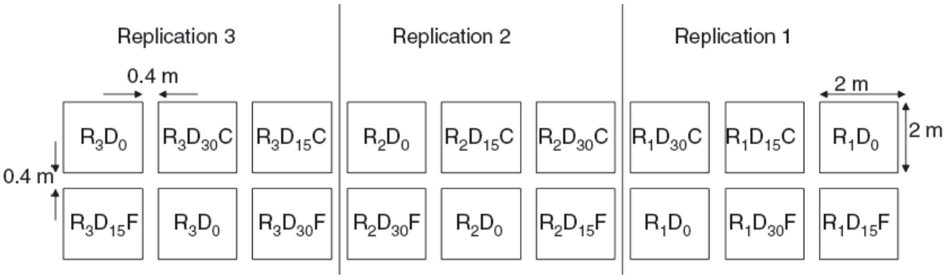

Figure 3 Plot layout. Split plot design. R, replication; D, depth of sediment applied; C, coarse sediment applied; F, fine sediment applied. e.g. R_3D_0 is control in the third replication; $R_3D_{30}F$ is third replication of fine sediment applied over a depth of 30 cm.

stone walls 40 cm in height and width (Figure 3). The experimental sub-plots were relatively small (4 m^2) because there were no larger homogeneous areas.

The field experiment had a split plot design with the application of two sediment types as main-plot treatments (fine sediment and coarse sediment), and three sediment depths as sub-plot treatments (sediment layers of 0, 15 and 30 cm), all replicated three times. All experimental plots in each of the main-plot treatments were randomly placed which were then filled with the sediments to varying depths. The experimental site was flat, and there was neither run-off or flow from neighbouring plots nor from the surrounding land to the experiment. The rain falling on the plot was retained by a stone bund that served as plot border, the aim being to avoid externally induced soil moisture variability within and amongst plots.

The experimental plots were planted with rainfed garlic at a spacing of 20 cm between rows and 15 cm between plants as recommended by the local Office of Agriculture (BoARD, 2007). Plant height was recorded during the growing period. Bulb, leaf and root mass were measured in a 1.4 × 1.4 m plot when harvested 4 months after planting.

Statistical analysis

Descriptive statistics including mean and standard deviation were calculated to evaluate the fertility status of the degraded soil or the control and the applied sediments on the experimental plots. The Kruskal–Wallace test was used to investigate the significance of the differences between mean values from the reservoir. Statistical analysis also included analysis of variance using the statistical software MSTAT-C (Freed *et al*., 1991). Significant means were separated using the least significant difference test at $P < 0.05$.

Economic analysis

The partial budget was analysed following the procedures developed by CIMMYT (1988) using data on costs, crop yields and benefits accrued from the various experimental treatments. Cost-benefit ratios were determined for treatment means to evaluate the productivity of garlic on the reclaimed land using reservoir sediments.

Results and discussion

Effect of sediment application on bare land reclamation

Clay and silt dominated the sediments used for the land reclamation trial (Table 1). The bulk density of the upper 5-cm layer was 1.03 g/cm^3 for the fine sediment plots, 1.08 g/cm^3 for the coarse sediment plots and 1.22 g/cm^3 for the control. Thus, the bulk densities were rather low and in a range suitable for crop growth. In the 15-cm layer, the available water capacity increased from 8.8 mm in the control to 19.9 mm in the coarse sediment and to 26.7 mm in the fine sediment treatment plots. These values correspond to 59 mm/m for the control, 133 mm/m for the coarse sediment and 178 mm/m for the fine sediment treatments. The control plot had a low available water capacity given the high gravel and stone content. FAO (1977) quotes available water capacity of 200 mm/m for fine, 140 mm/m for medium and 60 mm/m for coarse textured soils.

The sediments also had high available nutrients (N_{tot} and P_{av} and K_{exch}). The pH with a range from 7.1 to 7.9 was within the acceptable range for land reclamation. Haigh (1995) suggests $3.5 < pH < 8.5$ for successfully reclaimed land mine spoils. Although the organic matter content in the sediment ranged from low to medium, decomposition would release organic acids that could increase the availability of mineral P. Sen *et al.* (2007) also report that the release of P from sediments could occur at a rate that can supply sufficient P to the top layer of the reservoir deposits. Schepers & Mosier (1991) estimate that about 2% of the total N in the surface of 30 cm is annually mineralized; thus, a soil with 1% OM content could be expected to mineralize and supply ca. 45 kg N/ha/yr. Canavan *et al.* (2006) also report high rates of organic matter decomposition under oxic conditions in the upper 30-cm layer of sediment in coastal fresh water. These

Table 1 Properties of degraded soil and applied sediments in the experimental sub-plots (sampled at 0–15 cm depth of the top layer before and after crop harvest)

	Before crop harvest			After crop harvest		
Parameter	Degraded soil	Coarse sediment	Fine sediment	Degraded soil	Coarse sediment	Fine sediment
Sand (g/kg)	102	86	54	171	192	80
Silt (g/kg)	501	564	508	510	444	393
Clay (g/kg)	397	350	438	319	364	527
BD (g/cm^3)	1.22	1.08	1.03	1.18	1.19	1.16
FC (% v/v)	15.0	25.1	32.5	16.8	29.8	37.1
PWP (% v/v)	9.2	11.8	14.7	9.7	13.4	19.3
AWC (% v/v)	5.9	13.3	17.8	7.2	16.4	17.9
AWC (mm/15 cm depth)	8.8	19.9	26.7	10.8	24.6	26.8
pH (H_2O)	8.1	7.2	7.4	7.9	7.9	8.0
OC (g/kg)	17.6	24.5	24.8	16.5	12.0	15.4
N_{tot} (g/kg)	3.4	2.7	3.8	2.1	1.3	1.9
P_{av} (mg/kg)	8.76	7.19	11.2	9.52	3.03	20.56
K_{exch} (cmol$_c$/kg)	14.1	24.8	25.1	10.6	16.3	21.3

n, number of samples; BD, bulk density; FC, field capacity; PWP, permanent wilting point; AWC, available water capacity; OC, organic carbon; N_{tot}, total nitrogen; P_{av}, available phosphorus; K_{exch}, exchangeable K.

results indicate that the reservoir sediments when used for land reclamation have the potential to support crop growth.

Effect of sediment application on yield of garlic

Bulb yield and other yield indicators for garlic grown on reclaimed sediment revealed significant differences. Total biomass ranged from 3.6 to 11.7 t/ha and bulb yield from 2.0 to 7.7 t/ha (data not shown). Plant height ranged from 48 to 65 cm, and it was significantly ($P < 0.05$) higher when 15 cm of the fine and coarse sediments were applied.

Effects of sediment types. Total biomass and bulb yield on the fine sediment were significantly ($P < 0.05$) higher than on the coarse sediment. Total biomass increased from 7.1 t/ha (data not shown) on coarse sediment to 8.6 t/ha on the fine sediment. Bulb yield increased from 3.9 t/ha on the coarse sediment to 5.1 t/ha on the fine sediment.

Effects of sediment depth. Total garlic biomass (9.6 t/ha, data not shown) was significantly larger ($P < 0.05$) on the 30-cm sediment treatment compared with the 15 cm and the control treatments. Bulb yield was the same for the 15 and 30-cm sediment layer but was twice the value for the control.

Interaction effects of sediment types and depth. The garlic plants were taller on the 15-cm deep fine and coarse sediment plots than on all other treatments and the control (Table 2). However, total biomass (10.9 t/ha) and bulb (6.6 t/ha) yield were significantly higher when 15-cm fine sediment was used compared with the coarse sediment over all depths. Bulb and

Table 2 The interaction effect of sediment types and depths on yield (kg/ha) of garlic

Treatments	*n*	Plant height (cm)	Total biomass	Bulb yield	Above ground biomass	Root biomass
Fine sediment sub-plot						
Control	3	53.3^{b}	4932^{e}	2721^{d}	1531^{e}	510.2^{c}
Fine sediment-15 cm	3	61.5^{a}	10 880^{a}	6633^{a}	3741^{a}	510.2^{c}
Fine sediment-30 cm	3	56.2^{b}	10 030^{b}	5953^{a}	3061^{b}	1020^{a}
Coarse sediment sub-plot						
Control	3	52.1^{b}	4592^{f}	2381^{e}	1871^{d}	510.2^{c}
Coarse sediment-15 cm	3	61.6^{a}	7483^{d}	4252^{c}	2721^{c}	680.3^{b}
Coarse sediment-30 cm	3	53.6^{b}	9184^{c}	4932^{b}	3061^{b}	680.3^{b}
MSE		1.989	1101	662	343	87.82
LSD		4.954	116	90	65.06	32.92

Mean values attached per column by the same letter are non-significant at $P < 0.05$. MSE, mean square error; LSD, least significant difference.

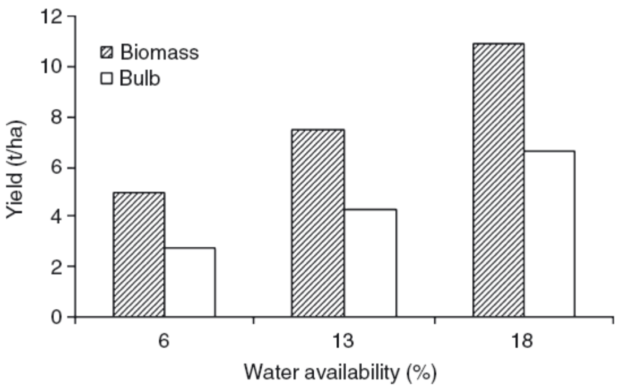

Figure 4 Yield response of garlic to water availability induced by the application of reservoir sediments in the experimental plots.

biomass yield steadily increased as the sediment depth increased across all depths of the coarse sediment. Plots with 15 cm of fine sediment gave better crop growth and development that may be attributed to the higher available nutrient and water content of the sediment on these plots compared with the others. There was also an increase in water availability of ca. 11% (v/v) for the coarse sediment and 18% (v/v) for the fine sediment plots (Figure 4). Garlic biomass and bulb yield doubled on the fine sediment treated plots compared with the coarse sediment ones as a result of this water availability.

The mean garlic bulb yield on the 15-cm deep fine sediment was similar to that obtained on irrigated fields, which was 6.9 t/ha in Tigray and 7.4 t/ha at the national level (BoARD, 2007; MoARD, 2007). The coefficient of variation in bulb yield was 41%. Several studies also report significant differences in yield amongst garlic cultivars (Getachew & Asfaw, 2000; Pantheel *et al*., 2004; Kassahun, 2006). The fine sediment contained more nutrients than either the control or coarse sediments. The available water capacity also increased with increasing clay content of applied sediments. Reduced availability and depletion of nutrients could explain the reasons for the low yield of garlic grown on the degraded soil. Garlic was established on the degraded soil as the plant tolerates low soil nutrient status. Garlic responds to applications of N but not so much to mineral P even on soils with P_{av} contents <8 mg/kg (Tyler *et al*., 1988). This implies that the reclamation of bare land with reservoir sediments may lead to the sustainable production of vegetables such as garlic without the application of mineral fertilizers.

Economic analysis

Costs. Reclamation of the bare land was undertaken in May 2009. The major cost was labour for transportation and application of the sediment. Covering plots with fine sediment cost 10 and 30 birr (1€ = 15.40 birr, May 2009) per plot, and coarse sediment at 7 and 20 birr/plot, for thicknesses of 15 and 30 cm, respectively. As the calculated costs are for small quantities of sediment, it is likely that they are inflated compared with the cost incurred in an actual land reclamation project. Breaking and mixing the dried fine sediment involved higher costs. There were no weeds growing on the plots, and hence no weeding was needed. Most of the weed seeds seemed to remain floating on the surface of the reservoir water and tended to loose their viability. They eventually ended up on the perimeter of the reservoir. Tillage, harvesting and transporting the produce to the market were performed at a total variable cost of 1 birr/plot. The control plot without sediment application involved higher cost for tillage to create a rooting depth for the establishment of the garlic.

The costs were assumed to remain linear with up-scaling from plot scale to catchment, but total costs were over-estimated. Accordingly, the cost to collect and transport fine sediment was 25 000 birr/ha, and 75 000 birr/ha for 15 and

Table 3 Cost-benefit analysis (in birr/ha) of garlic production (t/ha) by using sediment for reclamation of bare lands after one annual crop

		Yield		Cost			Benefit		
Treatments	*n*	GRAY	AY	LC	VC	TC	GFB	FB	CBR
Fine sediment sub-plot									
Control	3	2.72	2.61	15 000	5500	20 500	35 360	33 930	1.66
Fine sediment-15 cm	3	6.64	6.37	25 000	2500	27 500	86 320	82 810	3.01
Fine sediment-30 cm	3	5.95	5.72	75 000	2500	77 500	77 350	74 360	0.96
Coarse sediment sub-plot									
Control	3	2.38	2.31	15 000	5500	20 500	30 940	30 030	1.46
Coarse sediment-15 cm	3	4.25	4.08	17 500	2500	20 000	55 250	53 040	2.65
Coarse sediment-30 cm	3	4.93	4.74	50 000	2500	52 500	64 090	61 620	1.17

GRAY, gross average yield; AY, adjusted yield; LC, labour cost (for transporting and filling sediment in plots); VC, variable cost (for maintenance and management); TC, total cost; GFB, gross field benefit; FB, field benefit (adjusted for 3% non-sellable quality of the GFB); CBR, cost-benefit ratio). 1€ = 19.12 birr based on exchange rates of November, 2009.

30 cm depths, respectively (Table 3). The coarse sediment was brought in at a cost of 17 500 birr/ha and 50 000 birr/ha to provide depths of 15 and 30 cm. The lower cost for coarse sediment is because of the relative ease of digging and spreading this material. The variable costs for tillage, harvesting and transporting the crop to the market ranged from 2500 to 5500 birr/ha.

Yields. The gross average bulb yield of garlic was 2.7 t/ha for the control (Table 3), 6.6 t/ha for the 15-cm deep sediment and 5.9 t/ha for the 30-cm deep fine sediment. The gross average bulb yield was 4.3 t/ha for the 15 cm depth and 4.9 t/ha for the 30 cm depth of coarse sediment. An adjusted yield was determined by subtracting a non-sellable 3% amount from the gross average yield.

Benefits. As land reclamation is a new practice in the area, the gross field benefits were calculated by multiplying the gross average bulb yield (t/ha) for each treatment by the field price that was 13 birr/kg (based on field prices, 1€ = 19.12 birr, November 2009). Although the control had a gross field benefit of 35 360 birr/ha (Table 3), the gross field benefit was highest (86 320 birr/ha) on the 15 cm deep followed by the 30 cm deep (77 350 birr/ha) fine sediment. The cost-benefit analysis was based on the ratio of the field benefits obtained from the sellable amount of the bulb yield to the total costs for each treatment. From Table 3 it is clear that the cost-benefit ratio was significantly higher for the 15-cm deep sediment than for the 30 cm depth of both sediment types compared with the control in the first cropping season. This indicates that sediment applied to stripped land near to reservoirs is an attractive investment.

Given the costs and returns in a garlic production cycle, the reclamation of bare land using reservoir sediments is economic as this may improve income by as much as 76%. As the used reservoir sediments are nutrient-rich, the reclamation of the disturbed lands enhances economic returns. Garlic yield on plots treated with 30-cm fine sediment was the same compared with plots that were covered with 15 cm of fine sediment. On plots covered with coarse sediment, garlic yield increased with increasing depths. The cost of excavating sediments and spreading on plots increased with depth of application with 15-cm deep fine and coarse sediment increasing the cost-benefit ratio to 3 and 2.7, respectively.

Conclusion

Accumulated sediment in reservoirs is a potential resource that can be utilized for reclaiming bare land in their vicinity. Reservoir sediments contain high quantities of clay and silt that are nutrient-rich with low to medium OC and total nitrogen, and high available phosphorus and exchangeable cations. High clay content in the sediments enhances available water and nutrient holding capacities. As a result, the garlic yield response to applied sediment on the bare land was highly significant. The total biomass increased from 3.6 to 11.7 t/ha and the bulb yield from 2.0 to 7.7 t/ha. Reclamation of bare land using a 15-cm layer of sediment and the subsequent growing of garlic resulted in a three-fold increase in yield and benefits compared with the control. The cost of excavating sediments and spreading on plots increased with the depth of applied sediment; 15 cm of fine and coarse sediment improved the economics of garlic production giving a cost-benefit ratio of 3 and 2.7, respectively. This shows that the sediment has potential for supporting high-value horticultural crops. Use of reservoir sediment can be economically viable through creating new land for farming, rehabilitating gullies and riverbanks, providing potting media for seedling production, and for amending degraded soils. However, this will only be possible if there is further research on the fertility status of reservoir sediments and there is secure land tenure for farmers. Various global water forums should take the initiative for devising efficient ways to utilize sediments from existing reservoirs on a sustainable basis.

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References

Astatke, A., Bunning, S. & Anderson, F. 1986. *Building ponds with animal power in the Ethiopian highlands. A manual*. ILRI, Addis Ababa, Ethiopia.

BoARD. 2007. *Crop yield assessment in Tigray*. Annual report 2007. Bureau of Agriculture and Rural Development, Mekelle, Ethiopia.

BoWRD. 2009. *Design and construction of micro earth dams in Tigray*. Annual report 2009, Bureau of Water Resources Development, Mekelle, Ethiopia.

Canavan, R.W., Slomp, C.P., Jourabchi, P., Cappellen, P.V., Laverman, A.M. & van den Berg, G.A. 2006. Organic matter mineralization in sediment of a coastal freshwater lake and response to salinization. *Geochimica et Cosmochimica Acta*, **70**, 2836–2855.

CIMMYT. 1988. *From agronomic data to farmer recommendations*. An economics training manual, pp. 9–38. CIMMYT, Mexico, D.F.

El-Swaify, S. & Hurni, H. 1996. Trans-boundary effects of soil erosion and conservation in the Nile Basin. *Land Husbandry*, **1**, 7–21.

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

Ethiopian Meteorological Agency. 2008. *Mean monthly rainfall (1994–2007)*. Mekelle Office, Ethiopia.

FAO. 1977. *Crop water requirements*. Irrigation and drainage paper. FAO, Rome.

Fonseca, R., Barriga, F.J.A.S. & Fyfe, W.S. 1998. Reversing desertification by using dam reservoir sediments as agriculture soils. *Episodes*, **21,** 218–224.

Freed, R., Eisensmith, S.P., Goetz, S., Reicosky, D., Smail, V.W. & Wolberg, P. 1991. *User's guide to MSTAT-C*. Michigan State University, East Lansing, MI.

Getachew, T. & Asfaw, Z. 2000. *Research achievements in Garlic and Shallot*. Research Report No. 36. Ethiopian Agricultural Research Organization, Addis Ababa, Ethiopia.

Girmay, G., Mitiku, H. & Singh, B.R. 2009. Agronomic and economic performance of reservoir sediment for rehabilitating degraded soils in Northern Ethiopia. *Nutrient Cycling in Agroecosystems*, **84,** 23–38.

Haigh, M.J. 1995. Soil quality standards for reclaimed coal-mine disturbed lands: a discussion paper. *International Journal of Surface Mining, Reclamation and Environment*, **9,** 187–202.

Haregeweyn, N., Poesen, 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.

Kassahun, T. 2006. *Variability and association among bulb yield and yield related traits in Garlic (Allium sativum L)*. M. Sc. Thesis, Alemaya University, Dire Dawa, Ethiopia.

Landon, R.J. 1991. *Booker tropical soil manual. A handbook for soil survey and agricultural land evaluation in the tropics and subtropics*. Longman Scientific and Technical Publishing, New York.

MoARD. 2007. *Crop variety register*. Ministry of Agriculture and Rural Development, Addis Ababa, Ethiopia.

Nyssen, J., Poesen, J., Moeyersons, J., Deckers, J., Haile, M. & 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., Poesen, J., Veyret-Picot, M., Moeyersons, J., Haile, M., Deckers, J., De Wit, J., Naudts, J., Teka, K. & Govers, G. 2006. Assessment of gully erosion rates through interviews and measurements: a case study from Northern Ethiopia. *Earth Surface Processes and Landforms*, **31,** 167–185.

Palmieri, A., Shah, F., Annandale, G.W. & Dinar, A. 2003. Reservoir conservation. The RESCON approach, Vol. 1, pp. 101. Washington D.C.

Pantheel, D.R., Subedi, P.P., Bhattarai, S. & Dhakal, J. 2004. Diversity analysis of garlic (*Allium sativum* L.) germplasm available in Nepal based morphological characters. *Genetic Resources and Crop Evolution*, **53,** 205–212.

Ryding, S.O. 1982. Lake Trehörningen restoration project. Changes in water quality after sediment dredging. *Hydrologia*, **92,** 549–558.

Sahlemedhin, S. & Taye, B. 2000. *Procedures for soil and plant analysis*. Ethiopian Agricultural Research Organization, Technical paper No. 74, Addis Ababa, Ethiopia.

Schepers, J.S. & Mosier, A.R. 1991. Accounting for nitrogen in nonequilibrium soil-crop systems. In: *Managing nitrogen for ground water quality and farm profitability* (eds R.F. Follet, D.R. Keeney & R.M. Cruse), pp. 125–138. SSSA, Madison, WI, USA.

Sen, S., Haggard, B.E., Chaubey, I., Brye, K.R., Castello, T.A. & Matlock, M.D. 2007. Sediment phosphorus release at Beaver reservoir, Northwest Arkansas: a preliminary investigation. *Water, Air and Soil Pollution*, **179,** 67–77.

Tamene, L., Parks, S.J., Dikau, R. & Vlek, P.L.G. 2006. Reservoir siltation in the semi-arid highlands of northern Ethiopia: sediment yield-catchment area relationship and a semi-quantitative approach for predicting sediment yield. *Earth Surface Processes and Landforms*, **31,** 1364–1383.

TWWCE. 2009. *Dredging Maigassa 2 reservoir. Annual report*. Tigray Water Works Construction Enterprise, Mekelle, Ethiopia.

Tyler, K.B., May, D.M., Guerard, J.P., Ririe, D. & Hatakeda, J.J. 1988. Diagnosing nutrient needs of garlic (*Allium sativum*). *California Agriculture*, **42,** 28–29.

& UNESCO. 1980. *Provision map of present land degradation rate and present state of soils.* FAO, Rome.

UNESCO. 1997. *Geo-science in the service of society*, pp. 19. UNESCO, France.

USACE. 1985. *Benficial use of dredged material*, pp. 298. Department of the Army Corps of Engineers, EM 1110-2-5026, Washington D.C.

Van de Wauw, J., Baert, G., Moeyersons, J., Nyssen, J., De Geyndt, K., Nurhussein, T., Amanuel, Z., Poesen, J. & Deckers, J. 2008. Soil–landscape relationships in the basalt-dominated highlands of Tigray, Ethiopia. *Catena*, **75,** 117–127.