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Soil erosion and conservation in Ethiopia: A review

Authors: Nigussie Haregeweyn[1,2*], Atsushi Tsunekawa[1,2], Jan Nyssen[3], Jean Poesen[4], Mitsuru Tsubo[5], Derege Tsegaye Meshesha[6], Brigitta Schütt[7], Enyew Adgo[6], Firew Tegegne[2,6]

[1]International Platform for Dryland Research and Education, Japan
[2]Arid Land Research Center, Tottori University, Japan
[3]Geography Department, Gent University, Gent, Belgium
[4]Department of Earth and Environmental Sciences, Division of Geography, KU Leuven, Heverlee, Belgium
[5]Institute for Soil, Climate and Water, Agricultural Research Council, South Africa
[6]Bahir Dar University, Bahir Dar, Ethiopia
[7]Institute of Geographical Sciences, Department of Earth Sciences, FU Berlin, Germany

*Corresponding author: Nigussie Haregeweyn,
Address: International Platform for Dryland Research and Education, Tottori University, 1390 Hamasaka, Tottori 680-0001, Japan;
Phone (office): +81 857 21 7251; Fax: +81 857 29 6199;
E-mail: nigussie_haregeweyn@alrc.tottori-u.ac.jp; nigussie_haregeweyn@yahoo.com.

Abstract

This paper reviews Ethiopia's experience and research progress in past soil and water conservation (SWC) efforts and suggests possible solutions for improvement. Although indigenous SWC techniques date back to 400 BC, institutionalized SWC activity in Ethiopia became significant only after the 1970s. At least six national SWC related programs have been initiated since the 1970s and their focus over time has shifted from food relief to land conservation and then to livelihoods. The overall current soil erosion rates are highly variable and large by international standards, and sheet, rill, and gully erosion are the dominant processes. The influence of human activities on the landscape has traditionally been deleterious, but this trend seems to have recently reversed in some parts of the country following the engagement of the communities in land management. The efficiency of SWC measures show mixed results that are influenced by the type of measures and the agro-ecology under which they were implemented; in general, the relative performance of the interventions is better in the drylands as compared to humid areas. Methodological limitations also occur when addressing the economic aspects related to benefits of ecosystem services and other externalities. Although farmers have shown an increased understanding of the soil erosion problem, SWC efforts face a host of barriers related to limited access to capital, limited benefits, land tenure insecurity, limited technology choices and technical support, and poor community participation. In general SWC research in Ethiopia is fragmented and not comprehensive, mainly because of a lack of participatory research, field observations, and adoptable methods to evaluate impacts. A potentially feasible approach to expand and sustain SWC programs is to attract benefits from global carbon markets. Moreover, a dedicated institution responsible for overseeing the research–extension linkage of SWC interventions of the country should be established.

Keywords: Drylands; Climate variability; Soil and water conservation; Carbon markets; Research–extension linkage

I Introduction

The Ethiopian drylands in general (which account for 67% of the country's total land area — 1.1×10^6 km^2) and the agriculture sector in particular have been identified as vulnerable to climate variability and land degradation (GoE, 2007; Niang et al., 2014; Nyssen et al., 2004a; UNEP, 2013). Several studies have stressed the importance of land degradation adaptation strategies (Feoli et al., 2002a; Gebremedihn and Swinton, 2003; Girmay et al., 2009; GoE, 2007; Haregeweyn et al., 2006, 2015a; Hurni, 1988; Nyssen et al., 2004a; Sonneveld and Keyzer, 2003; UNEP, 2013). Although indigenous soil conservation techniques have been applied for centuries in Ethiopia (Beshah, 2003; Ciampalini et al., 2012), institutionalized soil and water conservation (SWC) programs have been significant only since the 1970s (Osman and Sauerborn, 2001). Several researchers have reported on the effectiveness of various SWC interventions at various spatial scales in erosion control (Nyssen et al., 2007, 2009a; Taye et al., 2013), soil moisture conservation (Haregeweyn et al., 2012b, 2015a; Nyssen et al., 2010; Vancampenhout et al., 2006), vegetation regeneration and soil build up (Descheemaeker et al., 2006a; Mekuria et al., 2007), and sediment yield reduction (Haregeweyn et al., 2006, 2008a; Nyssen et al., 2009b). Other studies have also reported on the economic aspects of SWC interventions (Adgo et al., 2013; Gebremedhin et al., 1999; Herweg and Ludi, 1999; Kassie et al., 2011; Nyssen et al., 2007) and the barriers to implementation of SWC activities (Adimassu et al., 2013; Amsalu and de Graaff, 2006; Asrat et al., 2004; Bewket, 2007; Bewket and Sterk, 2002; Tefera and Sterk, 2010).

Studies that aim at a better understanding of the extent, causes, and impacts of soil erosion as well as the SWC practices implemented through the various initiatives are fragmented. In addition, comprehensive studies that evaluate past activities and draw lessons from experiences with the aim of aiding future development both at the regional and national levels are scarce. Osman and Sauerborn (2001) is the latest review study that can be found. In this paper, we review Ethiopia's experiences in SWC, the institutional frameworks for SWC, relevant soil erosion research, and major constraints of past SWC activities. On the basis of this review, we evaluate future trends and suggest possible solutions for improvement. We do an extensive review of scientific journal articles, case studies, and other reports that have assessed soil conservation efforts. As shown in Figure 1, more than 258 studies have dealt with either soil erosion or SWC in Ethiopia, of which 162 focus on the Ethiopian highlands and 112 in the northern Ethiopian highlands.

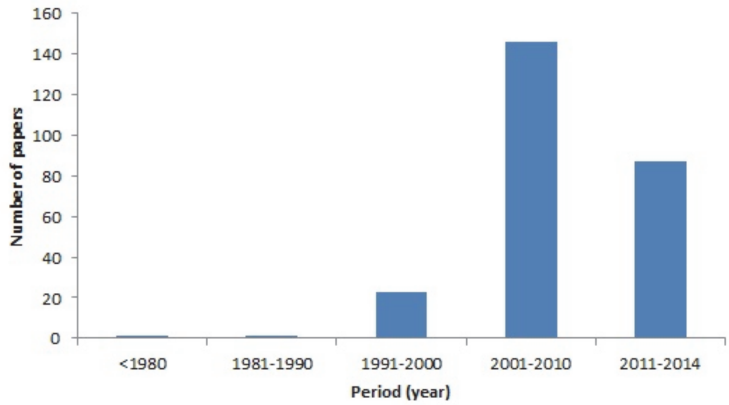

Figure 1. Number of studies published on soil erosion and conservation in Ethiopia, as documented in the Web of ScienceTM database (accessed in February 2015).

II History of SWC technologies in Ethiopia

Ciampalini et al. (2012) reported that in the Aksum area (Tigray, northern Ethiopia), SWC measures have been applied for centuries, most likely first implemented during the Aksumite Kingdom (400 BC to 800 AD). The traditional terraces in Konso constitute a spectacular example of a living cultural tradition stretching back 21 generations (more than 400 years) (Beshah, 2003). Virgo and Munro, (1977) reported that terracing was developed under traditional agriculture in the Tigray Highlands and in the Chercher Highlands. In the first half of the 20th century, Italian (Giglioli, 1938) and British (Joyce, 1943) chroniclers noted the indigenous SWC measures of northern Ethiopia (reviewed by Nyssen et al., 2004a). In addition, scattered contributions have been made on bench terracing for khat (*Catha edulis*) (Reij, 1991), the traditional technique of using lynchets in Tigray (Nyssen et al., 2000a), on fallowing in the Wolyta Zone (Amede et al., 2001), ditches for seasonal surface drainage in farmlands in the northwest highlands (Monsieurs et al., 2015). The Ethiopian Overview of Conservation Approaches and Technologies (EthiOCAT) network (Dale, 2010) catalogued and classified implemented SWC techniques. The work describes three physical and eight vegetative and agronomic indigenous measures, and over 20 introduced structural and biological measures.

Institutionalized SWC activities in Ethiopia were very localized and insignificant before the mid-1970s (Osman and Sauerborn, 2001). The most widely applied interventions include the use of (1) soil or stone bunds that have walls 0.3–1.2 m high and may also include trenches (Figure 2a) and/or agroforestry (Figure 2b) in croplands and on slopes (Herweg and Ludi, 1999; Nyssen et al., 2007; Taye et al., 2013) and (2) exclosures on steep slopes (Figure 2c), in which natural vegetation is protected from humans and livestock, which are enhanced with plantings and stone bunds (Descheemaeker et al., 2006a, 2006b; Haregeweyn et al., 2012b) and may also include check dams (Figure 2d) in gullies (Frankl et al., 2013; Haregeweyn et al., 2012b; Mekonnen et al., 2014; Nyssen et al., 2004b, 2009b, 2010).

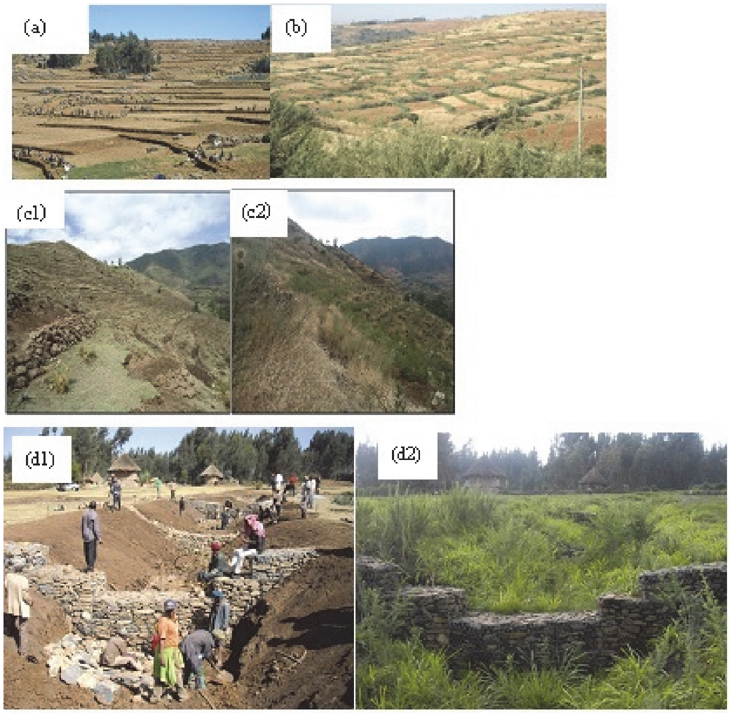

Figure 2. Commonly implemented SWC measures in Ethiopia: (a) Soil bunds combined with trenches in croplands, which are constructed by mobilizing the community through the free-labor-day scheme; (b) soil bunds integrated with *Sesbania* trees in croplands, where the trees are also being used for animal feed through a cut-and-carry system; (c) exclosures combined with trenches in degraded steep slopes (c1 is before [2011] and c2 is after [2013] intervention), where the grasses/trees are harvested on a regular basis through a cut-and-carry system; and (d) check dams constructed across gullies (d1 is before [2012] and d2 is after [2013] intervention).

Since the beginning of the 1990s, watershed management approaches that integrate SWC, intensified natural resource use, and livelihood objectives have been implemented in several micro-watersheds (Haregeweyn et al., 2012b; MoARD, 2006; SLMP, 2013a). The concept of participatory watershed development and management emphasizes a multi-disciplinary and multi-institutional approach for multiple interventions (German et al., 2006a). Overall, indigenous soil conservation practices in Ethiopia are generally poorly recorded and not considered by SWC experts and policymakers (Haile et al., 2006; Kruger et al., 1996; Reij, 1991). It is well known, however, that the integration of indigenous practices into development work improves adoption to local socio-economic situations and increases acceptance. The need to integrate both scientific and local knowledge has been emphasized in the recent special mission report released by the United Nations Convention to Combat Desertification (UNCCD, 2015).

III Soil and water conservation program initiatives

Outcomes of erosion surveys in the late 1960s and 1970s (Ware-Austin, 1970; HTS, 1976, as cited by Munro et al., 2008) led to the initiation of SWC programs. Various nationwide SWC initiatives have been undertaken, especially since the 1980s supported by multiple donors, and they have undergone a series of changes in terms of approach, technologies, and technical standards (TANGO, 2012). These initiatives include Food-for-Work (FFW) (1973-2002), Managing Environmental Resources to Enable Transition to more sustainable livelihoods (MERET, 2003-2015), Productive Safety Net Programs (PSNP, 2005-present), Community Mobilization through free-labor days (1998-present), and the National Sustainable Land Management Project (SLMP, 2008-2018). The FFW program started in the form of food aid and gradually shifted in the 1980s to a development-oriented program through engaging the community in rehabilitation of degraded lands (Devereux et al., 2006). However, Humphrey (1999) reported that the project locations were not correlated with the areas in most need; indicating that accessibility was a priority in selecting the target areas. The MERET project emerged to link land rehabilitation with income generating activities and livelihoods through a Community-based Participatory Watershed Management Development Approach, with direct beneficiaries estimated to be 1–1.5 million people annually (Nedessa and Wickrema, 2010). The PSNP provides resources to chronically food insecure households through food and cash transfers to able-bodied members for participation in labor-intensive public works including SWC activities (TONGA, 2012). About 7.8 million people take part in a normal year and by reducing seasonal liquidity constraints, it is also intended to stimulate investment as well (Tongul and Hobson, 2013).

The lack of coordination between similar projects was documented by a case study in Tigray that showed that two essentially unrelated rural development programs (the Rainwater Harvesting Pond Program and the public work component of the PSNP) were practically intertwined. This resulted in a failure as a large majority of the participants merely saw it as a stepping stone to employment in the PSNR (Segers et al., 2008). TANGO (2012) also reports that PSNP and MERET may sometimes operate in same communities and, due to lack of baseline data, this poses challenges to attribute the separate and combined impacts of the projects. Because the primary goal of the previous SWC initiatives is social protection in drought prone areas, land management in the relatively surplus crop producing areas of the southwestern and northwestern parts of the country had been given little policy attention until SLMP was launched in 2008 (Figure 3). However, our recent field observations at selected SLMP sites (Figure 4) in the Upper Blue Nile Basin showed that most of the interventions were not sufficiently implemented as set out in the SLM project objectives.

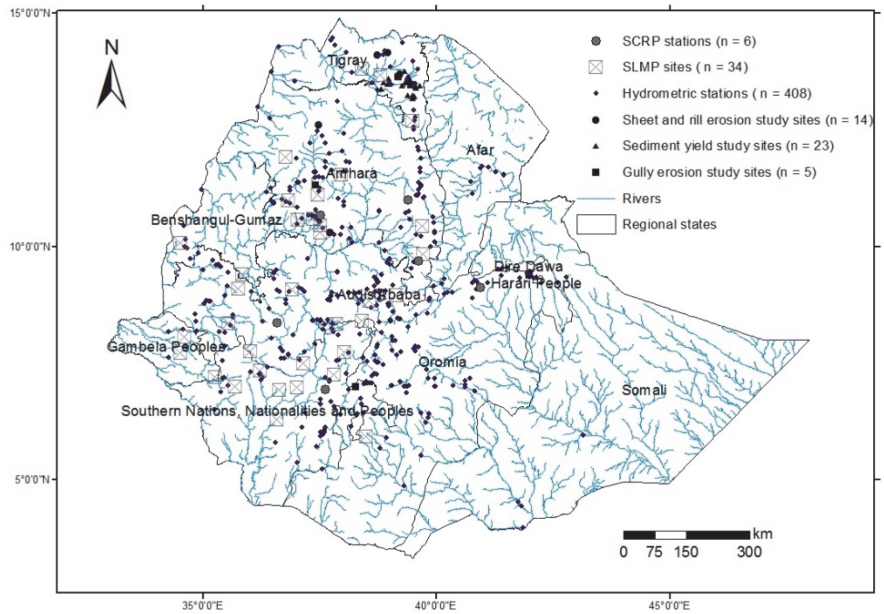

Figure 3. Location of case study sites. The Soil Conservation Research Project (SCRP) stations are part of the 14 sheet and rill erosion sites. The Sustainable Land Management Project (SLMP) project sites were obtained from the SLMP project office in Addis Ababa. The location of the hydrometric stations was obtained from the Ethiopia Ministry of Water Resources.

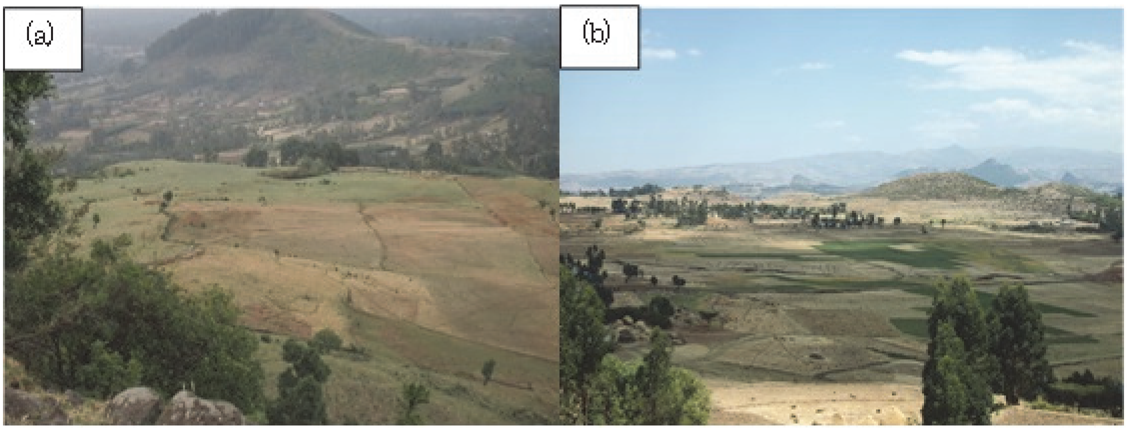

Figure 4. Partial views of the Sustainable Land Management Project (SLMP) watersheds in northwestern Ethiopia: (a) the Kasiri subwatershed of the Guder River in the Fagita Lekoma district and (b) the Maryam Wonz subwatershed of the Gomit River in the Estie Zuria district, both of which are in the upper tributaries of the Blue Nile River Basin. The two subwatersheds were under the SLMP for 5 years (2008–2013). Despite some signs of improvement in terms of vegetation cover as a result of the effect of exclosures and tree planting, structural measures were restricted to gully areas only.

A unique indigenous adaptation strategy to restore the ecology of the community is the mobilization of voluntary uncompensated labor at the community level (i.e. free labor days) (Kumasi and Asenso-Okyere, 2011; Haregeweyn et al., 2012b). The amount of work that each adult between 18 and 60 years old has to provide has recently been increased from 20 to 40 days per year (SLMP, 2013b). Community labor mobilization (Figure 2a) seems to be the best approach to implement large measures within a short period of time at a low cost. These collective actions work to regulate rights for and responsibilities to common-property resources and public goods to manage biophysical processes, negotiate joint investments and technological innovations for enhanced productivity, and regulate benefits (German et al., 2006b; Oström, 1990).

IV Soil and water conservation research in Ethiopia

Clear regional differences exist within Ethiopia in terms of efforts made to understand erosion processes. Out of the 256 published journal articles dealing with various aspects of soil erosion in Ethiopia (Figure 1), ca. 43% were conducted in the Tigray highlands (north Ethiopia). In contrast, in the northwestern and southwestern parts of Ethiopia, where drought risks are low and the productivity of soils is relatively high (Hurni, 1988; Nyssen et al., 2004a), limited attention has been given to both SWC development and research. There is clear evidence, however, of active erosion in regions other than the already highly degraded areas of northeastern Ethiopia. Furthermore, most of the research conducted to date has focused on sheet and rill erosion (Table 1), and gully erosion to a lesser extent (Table 2). Sheet and rill erosion throughout the country, gullying in the highlands, and wind erosion in the Rift Valley and the peripheral lowlands have been identified as the most important present-day geomorphic processes in Ethiopia (Nyssen et al., 2004a). More rarely reported forms of erosion include tillage erosion (Nyssen et al., 2000b, 2007) and landslides (Abebe et al., 2010; Broothaerts et al., 2012).

1 Soil erosion rates at various spatial scales and controlling factors

1.1 Sheet and rill erosion

Few studies have estimated soil loss rates at local, regional or national levels in Ethiopia. Analysis of a compilation of soil loss rates due to sheet and rill erosion at plot and catchment scales indicates that this soil degradation process varies strongly spatially, with a mean soil loss 29.9 t ha^{-1} yr^{-1} (SD = 30.2 t ha^{-1} yr^{-1}, n = 25) (Table 1). The highest rates were observed in Anjeni (110 t ha^{-1} yr^{-1}) and Chemoga (102 t ha^{-1} yr^{-1}) of the Upper Blue Nile Basin. Variation in mean annual rainfall was found to explain 35% of the soil loss variability among the case study sites (Figure 5). Studies in the northern Ethiopian highlands (Nyssen et al., 2005) and the Central Rift Valley of Ethiopia (Meshesha et al., 2014) reported larger erosive power of rainfall as compared to elsewhere in the world. Niang et al. (2014) indicate a likely increase in precipitation and extreme precipitation events throughout the 21st century particularly in the highlands.

The considerable effects of land use on soil loss were reported by Taye et al. (2013), with soil loss rates of 38.7 t ha^{-1} yr^{-1} from rangeland as compared to 7.2 t ha^{-1} yr^{-1} from cropland. They attributed the higher soil loss in rangeland to increased runoff resulting from intensive grazing and soil compaction, whereas soil tillage supports infiltration and causes less runoff and soil loss in croplands. There is also strong variation in soil loss rates within certain land use types located in the same drainage basin, implying the heterogeneous nature and effects of other environmental factors, for which no data are available.

Very few estimates are available about the overall soil loss rates at regional or national scale. FAO (1986) estimated of gross annual soil loss nationwide of 1.9×10^9 t of which 80% originates from croplands. Hurni (1988) estimated a nationwide annual gross soil loss of 1.5×10^9 t, extrapolating data obtained from six SCRP research stations in which the highest loss is from croplands (42 t ha^{-1} yr^{-1}). Sonneveld et al. (2011) provided a tentative nationwide mean annual soil loss map combining the results of different model estimates. They stated that soil loss varies remarkably from 0 t ha^{-1} yr^{-1} in the eastern and southeastern parts of Ethiopia to more than 100 t ha^{-1} yr^{-1} in the northwestern part of the country, but they did not note what causes this huge spatial variation. From the above studies, we can understand that the soil loss estimation at national level is still tentative and inconsistent.

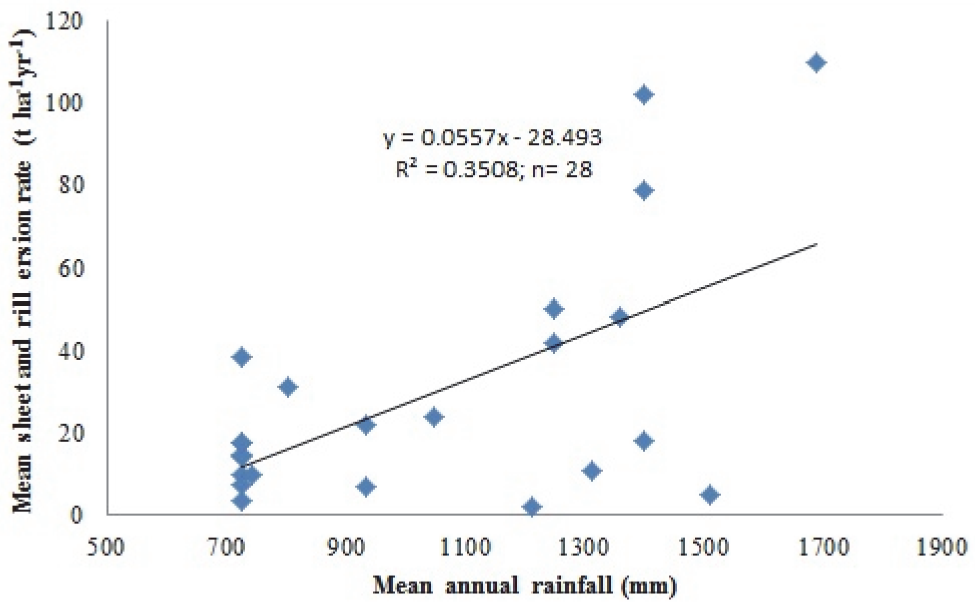

Figure 5. Relationship between mean annual rainfall (mm) and mean soil loss rates (t ha^{-1} yr^{-1}) for 28 case studies sites found across Ethiopia.

Table 1. Sheet and rill erosion rates at various spatial scales under different land use types.

River basin	Study site	Land use	Area	Period	Mean rainfall	Method	Average rate	Source
			(ha)	(years)	(mm)		(t ha^{-1} yr^{-1})	
	National	Cropland	1.1×10^8	7	100–2400	USLE model	42	Hurni (1988)
	National	Mixed	1.1×10^8	10	100–2400	USLE and Expert model	0–100	Sonneveld et al. (2011)
Awash	Maybar	Cropland	0.018	10	1211	Plot experiment	2	Herweg and Ludi (1999)
Blue Nile	Andit Tid	Cropland	0.018	10	1358	Plot experiment	48	Herweg and Ludi (1999)
Blue Nile	Anjeni,	Cropland	0.018	9	1690	Plot experiment	110	Herweg and Ludi (1999)
Blue Nile	Kechemo	Cropland	278–464	2	1300–1500	Rill mapping	18	Bewket and Sterk (2003)
Blue Nile	Erene.	Cropland	278–464	2	1300–1500	Rill mapping + empirical estimate	79	Bewket and Sterk (2003)
Blue Nile	Angereb	Cropland	0.0057	1	1049	Digital photogrammetry	24	Gessesse et al. (2010)
Blue Nile	Chemoga	Mixed	34,600	15	1300–1500	USLE model	102	Bewket and Teferi (2009)
Omo	Gununo	Cropland	0.018	11	1314	Plot experiment	11	Herweg and Ludi (1999)
Omo	Dizi	Cropland	0.018	5	1512	Plot experiment	5	Herweg and Ludi (1999)
Tekeze	MayZeg-zeg	Cropland	0.03–0.39	17	724	Plot experiment	9.9	Nyssen et al. (2009a)
Tekeze	May Zeg-zeg	Cropland	187	4	724	Plot experiment; empirical estimate	14.3	Nyssen et al. (2009b)

Tekeze	Mayleba	Cropland	0.077–0.1	1	724	Plot experiment	7.2	Taye et al. (2013)
Tekeze	May Zeg-zeg	Exclosures	0.03–0.39	7	724	Plot experiment	3.5	Nyssen et al. (2009a)
Tekeze	May Zeg-zeg	Mixed	199	4	724	Watershed	14.8	Nyssen et al. (2008a)
Tekeze	May Zeg-zeg	Rangeland	199	7	724	Hillslope	17.4	Nyssen et al. (2009a)
Tekeze	Enabered	Mixed	2343	6	742	USLE model	9.8	Haregeweyn et al. (2012b)
Tekeze	Aksum	Mixed	Points	750	600–800	Plough marks and patinas	2.1–3.8	Ciampalini et al. (2012)
Tekeze	May Zeg-zeg	Rangeland	0.03–0.39	7	724	Plot experiment	17.4	Nyssen et al. (2009a)
Tekeze	Mayleba	Rangeland	0.077–0.1	1	724	Plot experiment	38.7	Taye et al. (2013)
Wabishebelle	Hunde Lafto,	Cropland	0.018	8	935	Plot experiment	7	Herweg and Ludi (1999)
Wabishebelle	Alemaya	Mixed	5000	1	801	AGNPS model	31	Muleta et al. (2006)
Wabishebelle	Hunde Lafto	Mixed	234	8	935	AGNPS model	22	Haregeweyn and Yohannes (2003)
Average							29.9	
Standard deviation							30.2	

USLE: Universal Soil Loss Equation; PSIAC: Pacific Southwest Interagency; AGNPS: Agricultural Nonpoint Source Pollution model.

Several interacting factors are responsible for the high erosion and land use dynamics in Ethiopia. Bard et al. (2000) studied the environmental history of north Ethiopia with particular reference to the pre-Aksumite to post-Aksumite period (500 BC–900 AD) and concluded that during this period the region underwent effects linked to demographic development, climate change, and changes in vegetation cover, all of which contributed to soil erosion. Pollen and charcoal analysis of sediment cores from two lakes in the highlands of north Ethiopia provide evidence that the vegetation has changed in response to human impacts during the last 3000 years (Darbyshire et al., 2003).

Grepperud (1994) reported a direct relationship between population pressure and land degradation such that, under comparable physical conditions, heavily eroded areas occur in highly populated regions. A shrubland vegetation and environmental data analysis in west Shewa of Central Ethiopia showed that shrubland vegetation may have expanded from lower elevations with drier site characteristics as forests gradually disappeared (Zerihun and Backéus, 1991).

Feoli et al. (2002b) reported that the agricultural system in the Adwa district of north Ethiopia was influenced by elevation, documented by the positive correlation between elevation and human population, livestock densities, and cropland area. A study in the central Rift Valley of Ethiopia by Meshesha et al. (2012) pointed to a marked increase in soil erosion rates from 1973 to 2006, with annual rates of 31 t ha^{-1} in 1973 and 56 t ha^{-1} in 2006. They attributed the increasing soil erosion rates to the conversion of forests or woodlands to croplands.

1.2 Gully erosion In Ethiopia, discontinuous gullies which generally develop on low slope gradients (2 – 9 %; Figure 6) and continuous valley-bottom gullies (ephemeral river channels), formed by intense hydraulic erosion processes typically expanding upslope are identified as the two main types of gullies (Billi and Dramis, 2003).

Figure 6. Evidence of active gully-head and -bank erosion in northwest Ethiopia (maximum depth = 1.5 m).

Possible causes for gully erosion in the study region include human activities such as road construction that lead to a diversion of concentrated runoff to other catchments (Nyssen et al., 2002), disintegration of waterfall tufas (Virgo and Munro, 1977), land use changes (Moges and Holden, 2008; Nyssen et al., 2006; Tebebu et al., 2010), dry spells, and the presence of vertic soil characteristics (Nyssen et al., 2006).

Rates of gully erosion vary with the stage and management condition in the catchment (Figures 2d1 and 2d2; Table 2). Tibebu et al. (2010) estimated an extremely high gully erosion rate of 530 t ha^{-1} yr^{-1} for the Debre-Mawi watershed in northwest Ethiopia (17.4 ha drainage basin size) using semi-structured farmer interviews, remote sensing images, and measurements of current gully volume. This rate was approximately 20 times larger than the measured sheet and rill erosion rates at the same study site. A roughly similar gully erosion rate of 1.7 t m^{-2} (ca. 566 t ha^{-1} yr^{-1}) was reported by Daba et al. (2003) for the Damota catchment in eastern Ethiopia (9 km^2

drainage basin size) on the basis of an analysis of aerial photographs from two different dates (1966 and 1996).

Studies in north Ethiopia show lower gully erosion rates, and the rates have been decreasing in recent years. For example, Nyssen et al. (2006) reported an average gully erosion rate of 6.2 $t\,ha^{-1}\,yr^{-1}$ over a 50-year time span, and this rate has decreased to 1.1 $t\,ha^{-1}\,yr^{-1}$ since 1995. Frankl et al. (2012) reported medium- to long-term (1–47 years) headcut retreat rates to be 10 times higher than short-term ones on the basis of their analysis of archival terrestrial and aerial photographs. Frankl et al. (2011) assessed a region-wide change in gully and river channel morphology in Tigray over the period 1868–2009, using historical photographs and integrating some gully cross-section measurements from 2006 to 2009. They distinguished three hydrological regimes of the catchments: oversized channels stage (1868 to ca. 1965), accelerated channel dynamics stage due to persistent clearance of vegetation (ca. 1965–ca. 2000), and stabilized channels stage as a result of large-scale implementation of SWC measures (ca. 2000–2011). In another study, Frankl et al. (2013) made a study on long-term changes in gully network in the same study region over the period 1964-2010 and the results validate the above findings. They reported that installation of check dams have reduced the cross-sectional areas of the gully channels (through sediment deposition) by an average of 33.5 % compared to untreated gully channels, thereby reducing mean channel depth by one third.

Overall, most of the gully erosion studies conducted in Ethiopia are based on the interpretation of relatively low-resolution aerial photographs or in combination with satellite images and repeated photographs supplemented by data obtained from questionnaires (Table 2). Detailed historical records on gully erosion are lacking.

Moreover, most of the case studies so far are concentrated on the Tekeze Basin, northern Ethiopia, where rainfall depth is relatively limited and where a positive influence of environmental management is clearly evident. The limited case studies from other parts of Ethiopia show that the gully erosion is more severe in those parts of the country, and SWC practices in those areas are also generally limited.

Table 2. Gully erosion rates compiled from different literature sources. Values in m yr^{-1} are linear gully head-cut retreat rates. NA: not available.

Study area	River basin	Area (ha)	Annual rainfall (mm)	Study period (years)	Rate	Remarks	Methods/ data sources	Sources
Tigray	Tekeze	12,300	500–900	32	17.6 t ha^{-1} yr^{-1}	Peak drainage density and volume due to increased erosion rates in the 1980s and 1990s	Small-scale aerial photographs, high-resolution satellite images	Frankl et al. (2013)
		375,000	700	17	4.4 t ha^{-1} yr^{-1}	25% of gullies stabilized due to catchment management	Terrestrial photography, aerial photographs	Frankl et al. (2012)
				47	3.8 m yr^{-1}	NA		
				1	0.34 m yr^{-1}			
		1,000,000	500-900	98	NA	Increased width and depth inherited from a previous period	Repeat photography	Frankl et al. (2011)
				10		Stabilized, large-scale implementation of SWC measures		
Uplands of the Geba catchment		2853	774	51	6.2 t ha^{-1} yr^{-1}	Long term	Field survey and interviews	Nyssen et al. (2006b)
Uplands of the Geba catchment		287	774	12	1.1 t ha^{-1} yr^{-1}	Short term	Field survey and interviews	
May Zeg-zeg		199	774	3	4.1 t ha^{-1} yr^{-1}	Average of short term and long term	Field survey and interviews	Nyssen et al. (2008a)
May Zeg-zeg		187		7	6 t ha^{-1} yr^{-1}	Untreated		
		187		7	2.2 t ha^{-1} yr^{-1}	Treated		
Debre Mawi	Blue Nile	17.4	1240	2	530 t ha^{-1} yr^{-1}	Untreated	QuickBird imagery, field survey and interviews	Tebebu et al. (2010)
Umbulo	Omo	2372	1067	12	11-30 t ha^{-1} yr^{-1}	Untreated	Field survey and interviews	Moges and Holden (2008)
Hararghie	Wabishebelle	900	827	31	566 t ha^{-1} yr^{-1}	Untreated	Aerial photo	Daba et al. (2003)

1.3 Sediment yield

Africa generally has a poor spatial distribution of hydrometric stations, and the few available ones are compromised by a short length of records, data discontinuities, and poor data quality (Vanmaercke et al. 2014). Similarly, data on SY, defined as the total sediment outflow from a catchment measurable at a point of a reference and for a specified period of time, are rarely available for Ethiopian rivers (Figure 3; (Haregeweyn et al. 2015b). The few available studies rather show significant SY variability and high associated impacts. An analysis of sediment discharge data for 10 medium-sized catchments (121–4590 km^2 drainage basin size) in sub-basins of the Giba River, located in Tigray, revealed SY values ranging from 5 to 66 $t\ ha^{-1}\ yr^{-1}$(Vanmaercke et al., 2010). Reservoir sediment surveys conducted for 14 micro-dam watersheds in northern Ethiopia show a large spatial variation among the catchments, ranging from 2 to 19 $t\ ha^{-1}\ yr^{-1}$, which also ranged in drainage basin size from 0.71 to 67 km^2 (Haregeweyn, 2006; 2012a). Such high SY values have drastic consequences for the life expectancy of many reservoirs in the Ethiopian highlands (Haregeweyn et al., 2006).

The poor availability and reliability of SY data for Ethiopian rivers remains a major bottleneck for a better understanding of the dynamics and drivers of SY variability in the region (Haregeweyn et al., 2015b). Sonneveld et al. (2011) also stressed that the application of better soil erosion models in Ethiopia is restricted by data paucity. On the other hand, sediment yield analyses made at regional scale relying heavily on soil loss rates measured at plot scale could lead to wrong conclusions due to the strong dependence of erosion process rates on spatial scale (de Vente and Poesen, 2005; Nyssen et al., 2008a). Moreover, despite the significant contributions of gully erosion to the overall sediment budget (Haregeweyn et al., 2013; Nyssen et al., 2004a; Poesen et al., 2003), previous studies have not accounted for this process so far.

Overall, information on the sediment budget, that is, a detailed account of the sources and deposition of sediments as it travels from its point of origin to its eventual exit from a drainage basin (Reid and Dunne, 1996), is missing. This requires the development of long-term and representative soil loss and related databases. Haregeweyn et al. (2015b) emphasized the need for the maintenance and monitoring of existing hydrometric stations in addition to the establishment of new ones, which are needed to reflect the different eco-hydrological environments in Ethiopia.

2 Effectiveness of SWC measures

2.1 Technical effectiveness

The influence of human activities on the landscape has traditionally been damaging, but this trend seems to have reversed recently in some parts of the country. Studies in northern Ethiopian confirm the “More People–Less Erosion” hypothesis (Tiffen et al., 1994). Land management in Tigray has led to significant improvements in terms of soil structure, rain infiltration, crop yield, biomass production, groundwater recharge, and prevention of flood hazard (Nyssen et al., 2008b). Studies on land use and land cover change over the past few decades document a trend towards the increased removal of remnant vegetation, but the trend has slowed and even reversed in some areas of northern Ethiopia because of the government’s set-aside policy (Nyssen et al., 2004c). In other studies, Nyssen et al. (2009c, 2014) found a significant increase in woody vegetation and SWC structures in areas with higher population densities, especially during the last two decades. Riverbeds also have become stabilized as a result of decreased runoff following the implementation of SWC interventions (Frankl et al., 2011, 2012, 2013; Nyssen et al., 2006).

However, the impacts of specific SWC measures have repeatedly been subject to debate among researchers. Some authors state that SWC efforts do not lead to the desired effects, or are even counterproductive (Hengsdijk et al., 2005; Keeley and Scoones, 2000). However an analysis of case studies throughout Ethiopia shows the positive effects of SWC measures at various spatial scales (plot, hillslope, and small and medium watersheds) (Table 3). The major measures evaluated are stone bunds, trenches with or without bunds, *fanya juu* terraces, exclosures, and watershed management and conservation tillage.

The results show a mean seasonal runoff reduction of 40%, with large spatial variability, ranging from 4% in Andit Tid (northwest Ethiopia) to 62% in Gununo (South Ethiopia). Similarly, soil loss was reduced by an average of 65%, but again with large regional variations (35–89%). Studies on the effectiveness of minimum tillage in croplands in three different sites in Tigray showed runoff and soil loss reductions in the range of 39–61% and 12–17%, respectively (Table 3).

Few studies on the effectiveness of integrated SWC measures at the watershed scale also document the notable impact of SWC measures on runoff reduction (18–88%) and soil loss reduction (14–78%). At the larger basin scale, a sediment management model of the Blue Nile Basin using the SWAT model by Betrie et al. (2011) showed that the implementation of grass strips reduced the SY at the outlet of the Upper Blue Nile Basin by 44%, and the implementation of stone bunds reduced it by 41% and reforestation by 11%. However, the authors admit that precise interpretation of the quantitative results may not be appropriate because some erosion processes, such as e.g. gully and channel bank erosion, are not well represented in their model (Betrie et al., 2011). Case studies on exclosures implemented in degraded hillslope areas show that they are highly effective in the reducing mean runoff (71%) and soil loss (69%) (Table 3).

The effectiveness of SWC measures is, however, influenced by the moisture regime and by the age of the structures. Kato et al. (2011) reported that soil bunds, stone bunds, and grass strips are more effective under low rainfall regimes, whereas grass waterways are more suited to use under high rainfall regimes. Hurni et al. (2005) indicated that SWC efforts in the Ethiopian highlands will work to a more limited extent in humid areas compared to the semi-arid areas. Taye et al. (2015) studied the evolution of the effectiveness of stone bunds and trenches for the reduction of runoff and soil loss in the semi-arid Ethiopian highlands and concluded that these measures are only fully effective in the first year of their construction. Own detailed analysis of their data showed that the effectiveness of unmaintained structures decreases to 80% of the original value in the second year, 50% in the third year, and nearly 0% in the fourth year after implementation.

Most of the above evaluated technologies are biased towards physical structures and their effects on reducing soil loss, rather than enhancing and increasing agricultural production. Other associated impacts such as land productivity (nutrient cycling) or climate regulation through carbon sequestration have not been well studied in Ethiopia. As a consequence, studies of the effectiveness of indigenous SWC measures as compared to the introduced measures are rare. Moreover, most of the evaluations were concentrated in north Ethiopia (Tigray), whereas high runoff rates and more active erosion are believed to be occurring in the central and northwestern parts of the country, where poor land management practices and erosive rainfall are evident (Hurni, 1988;

Nyssen et al., 2004a). There is also a lack of data and adoptable methodologies to assess the impacts at the watershed level. In real-world landscape situations, it is not only important to select the most efficient erosion control measures, but also to determine their optimum location in the catchment. Hence, there is a need for research that shows a more integrated evaluation of the impacts at the watershed scale (Mekonnen et al., 2014).

Table 3. Effectiveness of SWC measures in reducing runoff and soil loss at various spatial scales. RLR, runoff loss reduction; SLR, soil loss reduction; NA, not available.

Land use (spatial scale)	Study area	Area (ha)	Time (Year)	RLR (%)	SLR (%)	Type pf SWC treatment	Source
Rangeland (plot)	Mayleba (Tigray)	0.077–0.1	1	60	83	Stone bunds, trenches with and without bunds	Taye et al. (2013)
Cropland (plot)	Mayleba (Tigray)	0.077–0.1	1	46	63	Stone bunds with and without trenches	Taye et al. (2013)
Cropland (plot)	Hunde Lafto (Harerghie)	0.018	8	48	61	Stone bunds and *fanya juu* terraces	Herweg and Ludi (1999)
Cropland (plot)	Maybar (Wello)	0.018	8	27	35	Stone bunds and *Fanya juu*	Herweg and Ludi (1999)
Cropland (plot)	Andit Tid (Shewa)	0.018	10	4	52	Stone bunds and *Fanya juu*	Herweg and Ludi (1999)
Cropland (plot)	Anjeni (Gojjam)	0.018	7	33	67	Stone bunds and *Fanya juu*	Herweg and Ludi (1999)
Cropland (plot)	Gununo (Gamogofa)	0.018	11	62	91	Stone bunds and *Fanya juu*	Herweg and Ludi (1999)
Cropland (plot)	Dizi (Illibabur)	0.018	5	50	89	Stone bunds and *Fanya juu*	Herweg and Ludi (1999)
Cropland	Galena (Shewa)	0.021	3	28	47	Graded soil bund	Adimassu et al. (2014)
Average				**40**	**65**		
Mixed (micro watershed)	Different parts of Tigray	202 plots	3-21		68	Stone/soil bunds combined with exclosures	Gebremichael et al. (2005); Nyssen et al. (2007, 2008a)
Mixed (micro watershed)	May Zeg-zeg (Tigray)	187	4	81	78	Stone/soil bunds in croplands, exclosures and check dams in gullies	Nyssen et al. (2009b, 2010)
xed (micro watershed)	Enabered (Tigray)	2343	6	18	76	Stone/soil bunds in croplands, exclosures and check dams in gullies	Haregeweyn et al. (2012)
Mixed (medium watershed)	Central Rift Valley	1.6×10^6	33	NA	39	Stone/soil bunds in crop lands and exclosures	Meshesha et al. (2012)
Mixed (large watershed)	Upper Blue Nile Basin	18×10^6	12	NA	11-44	Buffer strips, stone bunds, afforestation	Betrie et al. (2011)
Mixed	Adwa (Tigray)	37×10^4	NA	NA	77	Reallocation of crops according to their capacity, a multi-criteria and multi-objective decision analysis	Dragan et al. (2003)
Mixed	Gobo Deguàt (Tigray)	369	1	NA	14	Afforestation	Hengsdijk et al. (2005)

Average			**NA**	**55**	**61**		
Exclosures (plot)	May Bàati (Tigray)	0.001	2	71		Exclosures	Descheemaeker et al. (2006a)
Exclosures (hillslope)	May Bàati (Tigray)	1–3	3-20	NA	79	Exclosures	Descheemaeker et al. (2006b)
Exclosures (hillslope)	Tigray	5–41	7	NA	59	Exclosures	Mekuria et al. (2007)
Average			**NA**	**71**	**69**		
Cropland (plot)	May Zeg-zeg (Tigray)	0.007	7	39	17	Minimum tillage	Lanckriet et al. (2012)
Cropland (plot)	May Zeg-zeg (Tigray)	0.007	7	52	15	Minimum tillage	Araya et al. (2011)
Cropland (plot)	Adigudom (Tigray)	0.0095	1	61	12	Permanent raised beds with furrows	Gebreegziabher et al. (2009)
Average			**NA**	**51**	**15**		

2.2 Profitability of SWC measures

There are even more diverging opinions about the profitability of SWC, mainly influenced by the specific type of measure, type of agro-ecology, and the assumptions made in the cost-benefit analyses. A performance assessment of *fanya juu* terraces, soil/stone bunds, grass strips, and double ditches was conducted in seven research sites in different agro-ecological settings by Herweg and Ludi (1999); the results indicated the measures did not bring a net increase in crop yield and biomass production. In a case study of Anjeni in the northwestern Ethiopian highlands, Kassie et al. (2011) stated that *fanya juu* terraces cannot be characterized as a "win–win" measure to reduce soil erosion because of the lower net value of crop income for plots with *fanya juu* terraces as compared to those without them. By contrast, another case study from the Anjeni site by Adgo et al. (2013) reported that SWC measures have long-term benefits to smallholder farmers. An assessment of the effects of stone bunds on crop yields and farm profitability based on on-farm research in Tigray, northern Ethiopia, by Gebremedhin et al. (1999) showed that investment in stone bunds yielded a 50% rate of return. However, another study in the same region on plots with stone bunds of different ages (from 3 to 21 years old) reported that the cost of building stone bunds is nearly the same as the value of the induced crop yield increase, despite an average increase in grain yield of 53% (Nyssen et al., 2007). The repeated occurrence of apparently contradictory results indicates the poor validity of the outcomes of profitability calculations of implementing SWC measures.

The profitability of specific SWC measures is also affected by the type of agro-ecology. A comparative study of the impact of stone bunds on the value of crop production in low and high rainfall areas of the Ethiopian highlands by Kassie et al. (2008) reported that plots in semi-arid areas with stone bunds are more productive than those without them, whereas this relationship is not evident in semi-humid areas. Accordingly, Nyssen et al. (2004a) reported that investments in SWC in high rainfall areas might not be profitable at the farm level, although the societal benefits are positive. Kato et al. (2011) also stressed that SWC investments perform differently in different regions of Ethiopia and underlined the importance of the selection of appropriate combinations of technologies and careful geographical targeting when promoting and scaling up SWC technologies for adaptation to climate change.

There appears to be a lack of general consensus among researchers on the methodological approach to be employed when analyzing the economic impacts of SWC interventions. Teshome et al. (2013) determined the economic efficiency of three different types of SWC technologies (soil bunds, stone bunds, and *fanya juu* terraces) in the watersheds of Debre Mewi and Anjeni in the northwestern Ethiopian highlands. They reported great variation in the estimates of profitability for the SWC measures and that the use of different underlying assumptions changed the cost–benefit analysis results considerably. Bekele (2005) confirmed that, although adopting a conservation strategy results in higher grain yields and net returns as compared to not adopting one, the normalized second order stochastic dominance analysis results do not support positive net return to farmers.

Conservation investments often have long pay-back periods and reduce short-term household incomes. The yield penalty resulting from the reduced planting area and high investment costs both contribute to this; hence, policies focusing on minimizing the area-loss effect and subsidizing the initial investment costs have been shown to improve farmers' incentives to use SWC measures to conserve the soil (Shiferaw and Holden, 2001). To expand and sustain SWC programs, Ethiopian land management initiatives could seek to benefit from global carbon markets while at the same time reducing poverty and restoring local agro-ecosystems. The Humbo Natural Regeneration Project in the Southern Nations region (Brown et al., 2011) can serve as a good example. It was the first forestry (afforestation/reforestation) project in Africa to be registered under the Clean Development Mechanism, and it generated substantial knowledge on carbon sequestration at the national level.

A lack of empirical data on crop responses to soil erosion has hindered policy-relevant research. Traditionally, most of the analyses conducted on the economic benefits of SWC measures only consider the impact on crop yield, but studies should also address externalities such as changes in ecosystem services, water availability, erosion and sedimentation control, plant nutrient enrichment, and carbon sequestration for climate regulation (Descheemaeker et al., 2006a, 2006b; Mekuria et al., 2011a, 2011b). Prato (1999) emphasized that the conventional economic approach of using a cost–benefit analysis is unsuited to evaluate the efficiency of preserving and restoring of ecological services (UNEP, 2003). In addition to the methodological difficulties encountered when applying contingent valuation and conducting a cost–benefit analysis, problems also arise when the non-market values of ecological services are estimated independently from the viewpoint of ecosystem planning and management. A cost–benefit analysis thus requires the integration of quantifiable data such as the costs for SWC measure implementation and crop yield, but it also requires the integration of data about environmental conditions and landscape sensitivity.

3 Factors controlling farmers' decisions to implement SWC measures

Farmers' decisions to adopt SWC measures in Ethiopia reveal a host of barriers. These challenges include among others labor availability, limited capital, lack of or limited incentives and benefits, land tenure policy, technology choices, technical support, and community participation.

The high labor demand required for the implementation of SWC measures was found to be an important bottleneck in several case studies (Bekele and Drake, 2003; Bewket, 2007; Gebremedhin and Swinton, 2003; Tefera and Sterk, 2010). Although lack of capital inhibits farmers from paying cash for SWC measures (Adimassu et al., 2013; Asrat et al., 2004; Shiferaw and Holden, 1999; Tefera and Sterk, 2010), many farmers are willing to contribute a substantial amount of free labor as a gesture for their support for conservation programs (Asrat et al., 2004).

Incentives such as participation in FFW programs (Gebremedhin and Switon, 2003), the provision of loans for purchasing fertilizers (Daba, 2003), and programs supporting initial SWC investment (Bekele and Drake, 2003) were found to positively influence farmers' adoption of SWC measures. However, some programs have had conflicting results because large majority of farmers do participate in conservation works as they see it only as an entry point to employment in other development programs (e.g. Segers et al., 2008).

Land tenure insecurity arising from the government's ownership of land is also reported to discourage farmers from implementing SWC technologies (Bewket, 2007; Gebremedhin and Swinton, 2003). Quantification on the economic impacts of the recent Land Certification Program in Ethiopia (involving the use of non-alienable use-right certificates) on the other hand revealed that the program increases land-related investment (Deininger et al., 2011; Holden et al., 2009).

Several studies note the application of inappropriate technology relative to local conditions as a reason for the low adoption rate or the unsustained use of SWC measures (Adimassu et al., 2013; Amsalu and de Graaff, 2006, 2007; Bewket, 2007; Bewket and Sterk, 2002; Duguma and Hager, 2011). Some farmers either perceive the structures as ineffective (Bewket and Sterk, 2002) or have developed negative attitudes towards externally recommended measures (Amsalu and de Graaff, 2006). In addition, the lack of technologies that provide quick returns to subsistence-constrained farmers also seems to deter investments in land resources (Shiferaw and Holden, 1999). In order to enhance the sustained use of the measures, conservation interventions should focus not only on the biophysical performance of the measures but also on the economic benefits (Amsalu and de Graaff, 2007; Duguma and Hager, 2011; Shiferaw and Holden, 1999; Tefera and Sterk, 2010).

A lack of technical support from development agents and other development officers is another factor that negatively influences farmers' cooperation in adopting conservation measures (Bekele and Drake, 2003; Dessie et al., 2012; Tefera and Sterk, 2010; Tesfamichael et al., 2013). EARO (1998) argued that extension services for natural resources management have been marginalized. Moreover, insufficient attention has been given to indigenous practices and the farmers' level of competence in solving their own problems, which is usually underestimated and deemphasized in the design of land management practices (Haile et al., 2006).

The various land management approaches that have been tried in SWC programs have largely been on "command-and-control" policies that have yielded limited success

(Shiferaw and Holden, 2000). Keeley and Scoones (2000) question Ethiopian environmental rehabilitation policy and its supposed “participatory” approach. However, Nyssen et al. (2004c) argued that natural resources conservation in Ethiopia is directed towards an integration of food self-sufficiency with conservation/restoration of the environment, and it frequently uses a participatory approach.

Taken as a whole, these results suggest the need for designing and implementing appropriate policies and programs that will influence farmers’ behavior towards the implementation of SWC measures in their agricultural practices. Leadership training and the reinforcement of stakeholder feedback as a fundamental activity could lead to an increased willingness of the landowners to take on new responsibilities (Liu et al., 2008). The importance of linking extension services to informal networks to enhance adoption of sustainable natural resource management practices has been emphasized by Tesfamichael et al. (2013). Social learning could foster the adoption of SWC measures through positively influencing interactions among the actors and creating opportunities to apply both indigenous and scientific knowledge (Dessie et al., 2012).

Consequently, the requirement is to design plans for SWC conservation measures that enable policymakers to create projects that will be accepted by local farmers (Asrat et al., 2004; Okumu et al., 2004) and that will also ensure land conservation and sustain local food production (Holden et al., 2004; Shiferaw and Holden, 2000).

V Summary of main findings

Soil erosion still remains a significant problem in large parts of Ethiopia, and it could get worse in the future because of the forecasted increase in population and the occurrence of extreme precipitation events throughout the 21st century (Niang et al., 2014). Many of the SWC programs have mainly targeted social protection to frequently drought affected areas in northern and northeastern Ethiopia, whereas natural resources conservation itself was not given sufficient policy attention. Moreover, the extent and areal coverage of available SWC measures remain unknown.

The few tested SWC measures were found to be more effective in runoff and erosion reduction in semi-arid areas than in humid areas. Other possible impacts such as improvement in land productivity (vegetation improvement and nutrient cycling), flood and sedimentation control, and climate regulation remain under researched.

Divergent opinions exist with regard to the profitability of SWC, which are mainly influenced by the approach used and the assumptions made in cost–benefit analyses. A cost–benefit analysis requires the integration of quantifiable data such as the costs for SWC measure implementation and the value of crop yield, but it also requires the integration of data about environmental conditions. The current practice of evaluating SWC initiatives only in terms of social protection needs to be expanded to address land conservation on an equal criterion. To expand and sustain SWC programs, attracting benefits from carbon markets shall be explored. There should be a clear boundary between essentially unrelated rural development programs or farmers may not have the incentive to make the conservation programs succeed. Integration of indigenous SWC practices and modern scientific technologies by engaging the community though all stages of the planning and implementation process remains important.

Overall, the poor availability and reliability of soil erosion data, lack of adoptable methods combined with the high heterogeneity of environmental factors remain major bottlenecks for soil erosion studies in the region. Moreover, a clear institutional arrangement and coordination between the extension and research efforts for appropriate land management efforts is lacking. Therefore, a full-fledged institution responsible for overseeing the research and extension aspects of land management programs remains an important but unrealized goal. To enhance the agricultural research–extension linkages, policy changes, institutional reorganization, and the strengthening of institutions will be required.

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