Z. Geomorph. N. F.	**52**	3	291–315	Berlin · Stuttgart	September 2008

Effects of region-wide soil and water conservation in semi-arid areas: the case of northern Ethiopia

by

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with 11 figures and 5 tables

Summary. Studies on the impacts of environmental rehabilitation in semi-arid areas are often conducted over limited space and time scales, and do typically not include detailed biophysical components. This study makes a multi-scale assessment over a time span of 30 years of environmental rehabilitation in one of the world's most degraded areas: the Tigray highlands of Northern Ethiopia. The study shows that in Tigray sheet and rill erosion rates have decreased by approximately 68 %, infiltration and spring discharge are enhanced and vegetation cover has improved. These impacts are evidenced and quantified by a comprehensive comparison of the current landscape with a coverage of 30-year old photographs and substantiated by field investigations. The positive changes in ecosystem service supply that result from these conservation activities in the Tigray highlands are an issue of global concern.

1 *Introduction*

Semi-arid areas of the world (UNEP 1994) are often marginalized in terms of investments in natural resource management and agricultural production (Reij & Steeds 2003). "It is like pouring water on a stone" is a popular saying in the better endowed parts of the country when talking about Ethiopia's peripheral drylands. The overall productivity of such areas is often perceived to be so dramatically damaged by human impact that recovery is deemed impossible (Thomas 1993, Rasmussen et al. 2001). However, several impact studies have demonstrated that investments in drylands do pay off in economic terms (Boyd & Turton 2000, Reij & Steeds 2003, Holden et al. 2005). Such case studies are often limited in space, time and scope; they may include better endowed regions (Anon. 1998, Holden et al. 2005) and/or high-investment and nearby-monitored NGO-type of interventions. One might therefore ponder to what extent these reports on recovery are representative of wider areas. Such impact studies typically do not include detailed botanical, hydrological and geomorphic components (Rohde & Hilhorst 2001). Here, we present a study that makes a multi-scale assessment of the results of 30 years of environmental rehabilitation of a whole region in one of the world's most degraded areas: the Tigray highlands in Northern Ethiopia (fig. 1).

DOI: 10.1127/0372-8854/2008/0052-0291 0372-8854/08/0291 $ 6.25

Despite the catastrophic impact of dry years on the degraded environment (Casenave & Valentin 1992, Valentin 1996), no tendency of decreasing rainfall can be observed in the Ethiopian highlands (Hulme 1992, Conway 2000), or for the rainfall station of Mekelle, located in the centre of the study area (fig. 2). Causes of current land degradation by sheet, rill and gully erosion are to be found in the unsustainable use of natural resources and in changing land use and land cover, which result from human impact on the environment (Nyssen et al. 2004a).

There is geomorphologic (Hurni 1985, Moeyersons et al. 2006) and palynological evidence (Bonnefille & Hamilton 1986) that deforestation and the associated

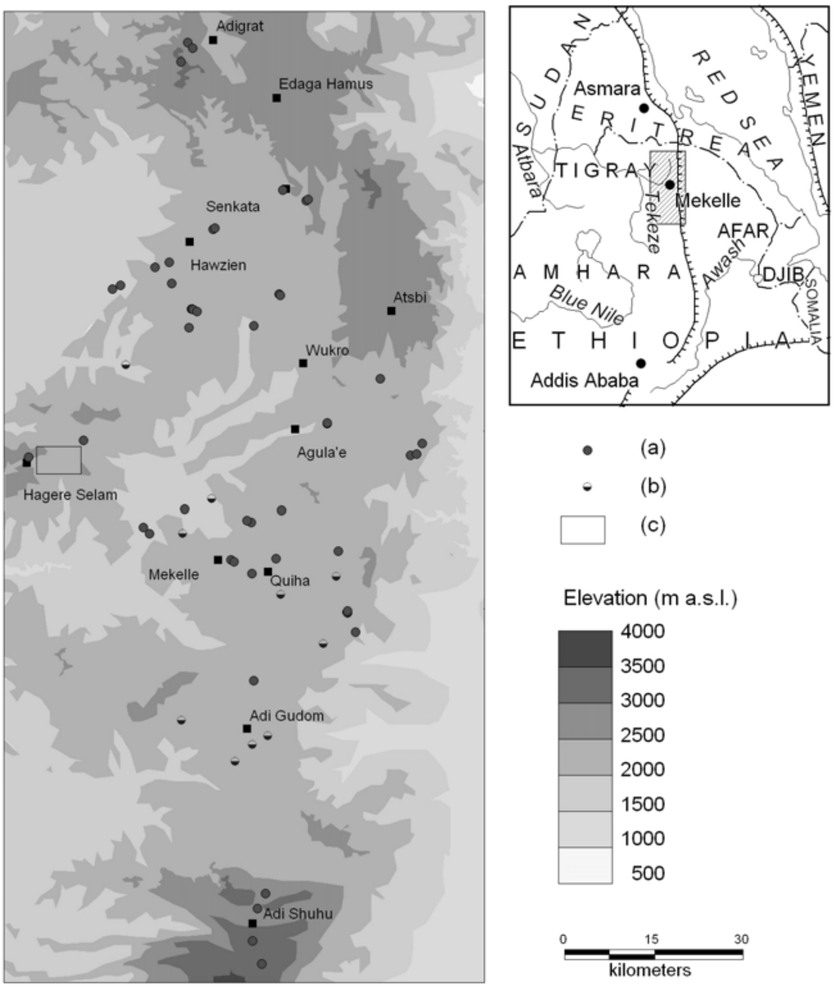

Fig. 1. Location of monitoring sites used for (a) region-wide repeat photography (10^{10} m^2; 30 yr), (b) studies on sediment deposition from catchments into reservoirs (10^6–10^7 m^2; 10 yr), and (c) investigations on stone bunds, exclosures and gullies in Dogu'a Tembien (10^2–10^6 m^2; 1–10 yr).

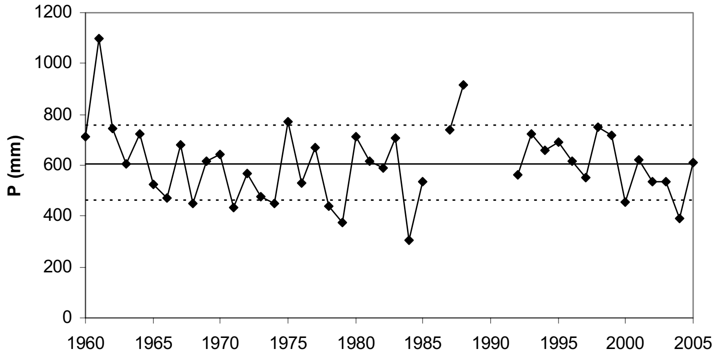

Fig. 2. Annual rainfall in Mekelle/Quiha since 1960, with indication of average ± 1 standard deviation. Missing data are related to the civil war in the 1980s. Source of data: National Meteorological Services Agency, Addis Ababa.

soil erosion in the Ethiopian highlands is by no means recent. However, modern population growth is assumed to have accelerated soil erosion due to a progressive change in land cover with the main purpose of increasing food production within a subsistence farming system (Wøien 1995, Kebrom & Hedlund 2000). As land resources are pushed to their limits, ruptures in the fragile equilibrium contribute to catastrophes such as the 1984 famine.

As a response to such situations, huge efforts are currently made in Tigray (Northern Ethiopia) at a regional scale (10^5 km^2) to control soil erosion, for instance through the construction of stone bunds and the rehabilitation of steep slopes (Descheemaeker et al. 2006a, b, Nyssen et al. 2007). The impacts of these erosion control measures are subject to debate: some authors state that these efforts do not lead to the desired effect, or are even counterproductive (Keeley & Scoones 2000, Hengsdijk et al. 2005).

This paper assesses changes in ecosystem functionality in the Ethiopian highlands based on observations deduced from the comparison of 51 historical photographs taken in 1975 (HTS 1976, Virgo & Munro 1978) with the current status. These comparisons are linked to results of more than ten years of field research (on-farm and at catchment scale). The combination of a variety of methods allows for a holistic analysis of observed environmental changes in Tigray between 1975 and 2006 incorporating details on the effectiveness of conservation measures in this marginal semi-arid area, which is representative for mountain dryland environments elsewhere.

2 *Study area*

The study area lies on the western flank of the Rift Valley in the north of Ethiopia between 12°50′ and 14°20′N, 39° and 40°E, extending over an area of some 10^4 km^2 (fig. 1). Major rocks are Precambrian metavolcanics and metasediments, Mesozoic sandstone and limestone and Tertiary basalt. Erosion, in response to the Miocene and Plio-Pleistocene tectonic uplifts (order of 2,500 m), resulted in the formation of tab-

Table 1. Average yearly rain depth (P_y) and degradation coefficient (C_f) for Mekelle, in the periods preceding the taking of repeated photographs

	P_y (mm)		C_f (eq. 1)	
	1975	2006	1975	2006
Preceding year	451	610	70	162
5 preceding years	514	538	88	111
10 preceding years	532	578	95	115

ular, stepped landforms (between 2,000 and 2,800 m a. s. l.), reflecting the subhorizontal geological structure. Intervening mountain ranges rise locally to 3,000 m a. s. l. These high elevations result in a more temperate climate than would normally be associated with the latitude (Virgo & Munro 1978). Average yearly rainfall ranges between 500 and 900 mm yr^{-1}, with a unimodal pattern, except in the southern part of the study area where a second (smaller) rainy season locally allows growing two successive crops within one year (Nyssen et al. 2005).

Since our research involved the use of repeated photographs to analyze soil erosion phenomena, rainfall as well as rain seasonality of the Mekelle/Quiha meteorological station were examined for the period encompassed by the photographs. Soil erosion, especially under natural conditions, in a specific area, is dependent on annual and seasonal rain, as, e. g., expressed by Fournier's (1962) degradation coefficient (C_f, mm):

$$C_f = p^2/P_y \quad (1)$$

where: p = monthly precipitation (mm) during the wettest month;

P_y = yearly precipitation (mm).

The recent period was slightly wetter, but also had a slightly higher degradation coefficient than the early 1970s (table 1).

The dominant land use is small-scale rainfed subsistence agriculture, for which the main constraints are inadequate soil water and excessive soil erosion (Virgo & Munro 1978). Since the 1980s a land tenure regime has been introduced leading to an approximate equalization in size of landholdings between households: "there is no single household or other kind of social group capable of concentrating land in large amounts" (Hendrie 1999).

3 *Materials and methods*

3.1 *Repeat photography methods*

Repeated photograph interpretation is used for many purposes and can take on many different forms (Hall 2001). It has been used for landscape rephotography covering up to 100 years of change (Progulske & Sowel 1974, Skovlin & Thomas 1995, Rohde & Hilhorst 2001, Grove & Rackham 2001), or for sampling change in vegetation (Johnson 1984, Nader et al. 1995, Boerma 1999).

The methodology of ground-based repeat photography (JOHNSON 1984, NIEVERGELT 1998, BOERMA 1999, HALL 2001, HERWEG & STEINER 2001, LÄTT 2004) has been used for this analysis. As the name implies, repeat photography means retaking photographs from the same spot and of the same subject several times; it requires precise repositioning of the camera and composition of the subject (HALL 2001), which in our case meant rephotographing a distant landscape.

Photographs of the environment in Tigray, taken in 1975 (HTS 1976, VIRGO & MUNRO 1978) have been obtained. Fifty-one landscapes photographed in early 1975 (dry season) have been revisited in the same season in 2006 and a new set of photographs prepared. They cover the wide range of agro-ecologies and environments present in the study area (fig. 1, table 2). It can be assumed that the location of the interpreted landscapes is random. In no way, the original photographers could foresee which specific landscape changes would take place over a period of thirty years, including two revolutions, a long civil war and two famine epochs.

The relocation of the historical photographs was based on rough indications by the original photographers, knowledge of landforms on various rocks, and a dozen-year long geomorphologic research experience in the study area. The camera position was furthermore obtained by identification of unique landscape features such as mountain peaks, drainage lines, and their relative position. Finally, the exact camera position and orientation was then obtained by lining up near and distant objects in a triangulation system. Not all photographs could however be repeated; particular problems concerned the growth of eucalyptus trees which were an obstacle to re-photogaphy, as well as the absence of identifiable objects.

The photographs used in the analysis were made by NEIL MUNRO (48 photographs; 1975), RUTH TRUMMER (3; 1972), JAN NYSSEN (46; 2001 and 2006); FIKIR ALEMAYEHU (1; 2005), ANNELIES BEEL (1; 2005) and JOZEF NAUDTS (3; 2006). The 1975 photographs were made with a Praktica Exa-1a camera (slide film) and the 2006 by a digital Kodak© Easyshare CX4230 camera.

For this study, the photographs were shown to JOZEF DECKERS, DICK GROVE, MITIKU HAILE, NEIL MUNRO, JAN NYSSEN and JEAN POESEN, all of whom have long-standing geomorphologic experience in Ethiopia (GROVE & GOUDIE 1971, GROVE et al. 1975, HTS 1976, VIRGO & MUNRO 1978, NYSSEN et al. 2004a, 2007). Couples of

Table 2. Number of analyzed landscapes by elevation class and rock type (the major agro-ecological variables in the study area)

Lithology	Elevation (m a. s. l.)			
	1500–2000	2000–2500	2500–3000	3000–3500
Basalt and dolerite	1	2	5	2
Limestone	2	20		
Sandstone	1	8	2	
Granite		4		
Precambrian	2	2		

photographs were presented on PowerPoint®, without indicating locations and the relative position of the new and old photographs was randomized. Only photocouples, taken at exactly the same place, in the same season and under the same angle were considered. This fact was demonstrated in the PowerPoint® presentation, by indicating identical objects. The immediate foreground is dependent on the exact position of the photographer. To avoid bias, it was masked for the analysis, unless it had clear reference points. The dataset of repeated photographs can be obtained from the corresponding author upon request (www.geoweb.ugent.be/download/TLP_3_Photomonitoring.pdf).

3.2 *Landscape analysis*

The repeated photograph interpretation involved comparing on-the-ground conditions of 2006 to photographs depicting the 1975 conditions, whereby scores were assigned by the experts to both situations.

For every couple of repeated photographs, the experts interpreted various indicators (table 4), in such a way that they could select only those indicators that they thought would be relevant. For these relevant indicators, they compared both photographs.

The evaluation was then converted into numerical scores:

–2: the situation has strongly deteriorated
–1: deteriorated
0: unchanged situation
1: improved
2: the situation has strongly improved

Fig. 3. Selection of homogenous land units in a landscape. Amentile, SE of Mekelle. The level farmland is established on alluvium deposited behind a freshwater tufa dam.

Given that the scoring method used ordinal variables, the median score per indicator was calculated for every photo-couple, provided that at least four of the six experts thought the indicator relevant for the photo-couple. Averages of the median scores were then calculated for each indicator, for the whole set of repeated photographs. The deviation of the median from zero (no change) was tested with the t-test (Diem 1963).

3.3 *Detailed analysis*

Whenever possible, homogenous parts of the photographs were taken for detailed analysis (fig. 3). Here, a quantitative evaluation was made of the changes in soil loss rates through sheet and rill erosion, using the Universal Soil Loss Equation (USLE) (Wischmeier & Smith 1978) and assuming that only the vegetation cover (C-factor) and the support practices (P-factor) have changed over the last 30 years.

The experts assessed ground cover and conservation practices at both epochs. These observations were converted into numerical values. For the semi-natural vegetation cover, USLE calibrations for Ethiopia (Hurni 1985) allowed to develop the equation:

$$C = 0.25\ e^{-0.0529\ V} \qquad (2)$$

where: C = USLE'S C-cover factor (dimensionless);

V = vegetation cover (%) as assessed by the experts.

For cropland, an average C value of 0.15 was taken (Hurni 1985).

From data reported (Desta et al. 2005), the overall USLE's P-factor (i. e. the support practice factor indicating reduced soil erosion rates due to farming practices and conservation measures) for stone bunds was estimated at 0.32, which may be considered as a medium-term value (up to 20 years) for stone bunds on farmers' fields in the Ethiopian highlands (Nyssen et al. 2007). Soil bunds with trenches, generally constructed on relatively level land, were assumed to have the same effectiveness. From this medium term value, and taking into account an additional effect of contour plowing (generalized on arable land), P-values for different conditions of bunds on arable and non arable land could be interpolated (table 3).

In case a landscape comprised more than one land unit, these were interpreted separately (fig. 3), and the arithmetical averages of the assessed C and P values were attributed to the landscape.

Table 3. Conversion of stone and soil bund status into USLE's P-factor

Quality of stone and soil bunds	P for non-arable land	P for arable land
None	1	0.90
Remains	0.8	0.72
Poor	0.6	0.54
Moderate	0.4	0.36
Good	0.2	0.18

Given

$$A_{75} = R\ K\ S\ L\ C_{75}\ P_{75} \quad (3)$$

and

$$A_{06} = R\ K\ S\ L\ C_{06}\ P_{06} \quad (4)$$

(A estimated soil loss, R rain erosivity factor, K soil erodibility factor, SL slope factor, C cover factor, P support practice factor; 75 stands for the situation in 1975 and 06 stands for the situation in 2006), we could calculate the estimated change in soil loss by sheet and rill erosion ($A_{\%}$), expressing the rate of 2006 as a percentage of that in 1975:

$$A_{\%} = (A_{06}/A_{75}) \times 100 = (100 \times C_{06} \times P_{06})/(C_{75} \times P_{75}). \quad (5)$$

4 *Results*

4.1 *Average landscape changes since 1975*

When evaluating the repeated landscape photographs (taken in the dry season of 1975 and 2006) for various indicators (table 3), the experts found a significant improvement of the situation with respect to visible erosion phenomena, vegetation cover on non arable land as well as grass and shrubs between cultivated farm plots. Whereas the population of Ethiopia has increased from 34 to 77 million between 1975 and 2006 (ESA 2004) (fig. 4), land management (figs. 4, 5) but also overall vegetation cover (fig. 6) have improved in the study area. These changes are not climate-driven (fig. 2, table 1) but the result of human intervention as is demonstrated on fig. 5.

Though only visible on part of the repeated photographs, the conditions have also improved with respect to cultivation of steep slopes and stone bunds in farmland (fig. 5).

It was in the years following the 1975 photoset, that large environmental programs were undertaken in Ethiopia by the then Derg government (1975–1990), in a rather top-down way (Keeley & Scoones 2000). In most of Tigray, collective terracing activities started a decade later, in the period of civil war against the Derg regime, and still continue at a vast scale today. Many people are now accustomed to see land covered with soil conservation structures in Northern Ethiopia – our study shows the contrast with 30 years ago. In nearby areas where such activities are not organized (such as the Simien Mountains) (Nievergelt 1998) a similar improvement cannot be found.

In Tigray, environmental rehabilitation is at the top of the agenda of the regional government. The inspiration came from a baseline study during which the 1975 photographs were taken (HTS 1976). The 1992 Symposium on Environmental Degradation held at Mekelle established the base for a new land rehabilitation approach (Aseffa et al. 1992), which stresses the necessary partnership between technicians ('with the necessary knowledge, as equal partners and not as patrons') and peasant farmers, 'through a natural extension of the present experience with participation'. Farmer-based approaches, developed in the liberated areas during the struggle against

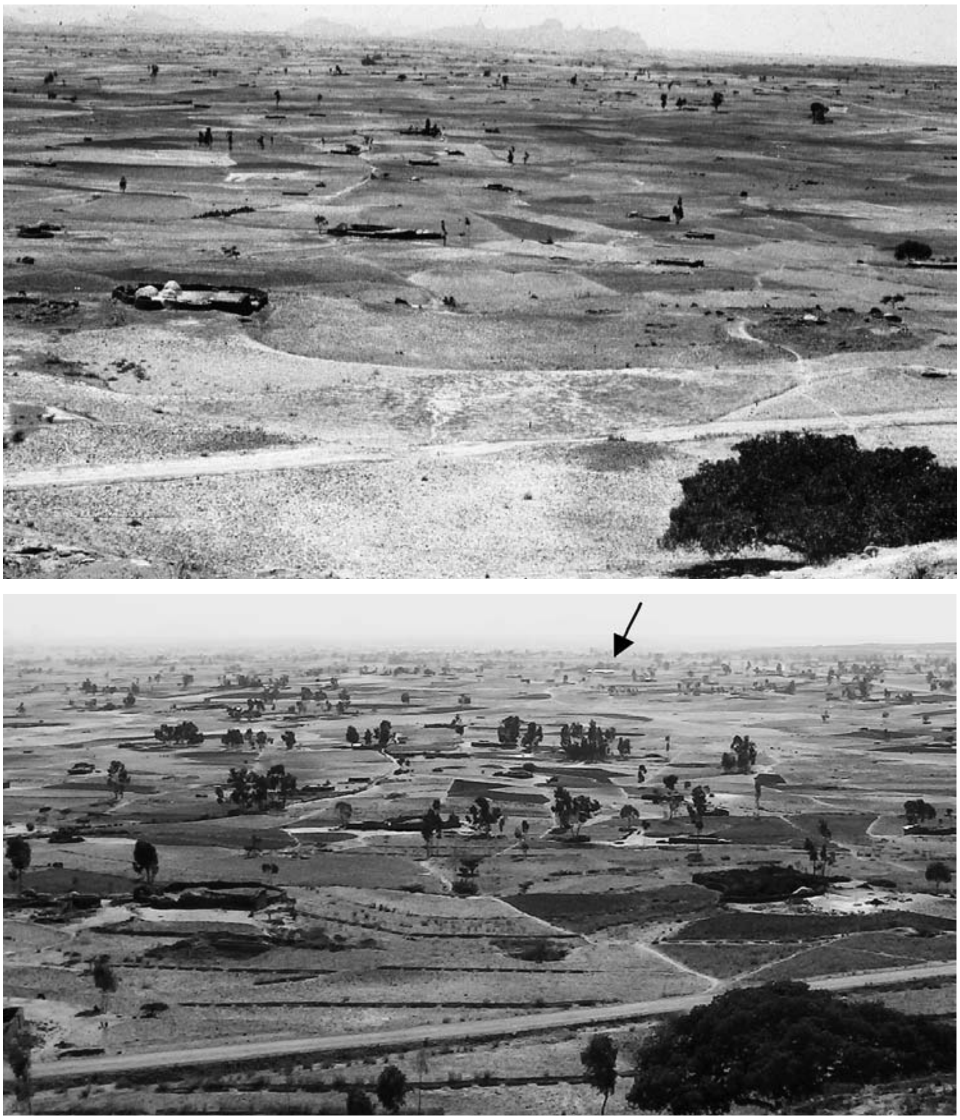

Fig. 4. Where, in 1975 (top), clear evidence of sediment deposition is visible in Tahtay Senkata (lower middle of the photograph), this process has been halted now because of soil bunds constructed along contours. Increased spring discharge allows the Tsenkaniet dam, built recently in the lower part of this catchment (arrow) to hold water year-round. The increase in number of houses evidences population growth.

Fig. 5. This landscape in Makhano, south-east of Senkata, represents the average situation with regard to land management changes between 1975 (top) and 2006 (bottom). Besides high density and quality of stone bunds along the contour, vegetation cover is also improved. The rangeland which covered all the non-arable land in 1975 has now been partly converted into exclosures, which has created a typical source-sink system, i. e. soil and runoff water lost from the upper slopes will be trapped in the exclosure and the infiltrated water will contribute to groundwater recharge. The traditionally protected church woodland (right centre of the photograph) has not changed, indicating that there are no significant changes in rainfall and that improvements elsewhere are socially rather than climate driven.

Table 4. Interpretation of landscape change in the study area (n = 51)

Visible soil erosion indicators	n	score	change
Gully erosion	16	−0.1 ns	Slightly deteriorated
Overall assessment of erosion	50	0.4 ***	Slightly improved
Land cover and protective measures			
Vegetation cover on non arable land	48	0.7 ***	Improved
Grass, herbs and shrubs on non arable land	40	0.7 ***	Improved
Grass and shrubs between cultivated farm plots	20	0.9 ***	Improved
Cultivation of the steepest slopes	10	0.7 **	Improved
Stone/soil bunds in farmland	11	1.0 ***	Improved
Overall assessment			
Vegetation cover	51	0.8 ***	Improved
Land management	50	0.7 ***	Improved

n = number of landscape sites where the phenomenon was observed by at least 4 of the 6 experts; score = average of the median scores given to all the interpreted landscapes, ranging from −2 (strong deterioration) to +2 (strong improvement), with level of significance for the deviation from a test value zero (no change) (*** significant at 0.01 level; ** significant at 0.05 level; ns not significant); change = comparison of the situation in 2006 with that in 1975.

the Derg regime in the 1980s include the integration of local and external technologies without losing the best of local practices and traditions (Berhane & Mitiku 2001, Nyssen et al. 2004b). Maintaining and enhancing farmers' participation is obviously a continuous challenge (Mitiku et al. 2006).

4.2 *Variability in landscape changes*

The average scores (table 4) cover variable and sometimes extreme situations. At most sites, soil erosion has slightly decreased, but in a few cases, it has decreased strongly, or even increased. The average situation with respect to gullies, however, tends to show deeper channel incision than in 1975, despite a relatively rapid environmental recovery. With respect to overall vegetation cover (fig. 7a), some exceptionally extreme cases of degradation exist (fig. 8). It appears that the traditional management of Des'a forest through bylaws (Zenebe 1999) has not been sufficient to prevent it from regressing. Landscapes with deteriorated vegetation cover in 2006 invariably correspond to places where there is/was still a good tree cover (rift escarpment, some remnant forests around churches) and where the need for conservation seems to be less felt by population and authorities. In all other cases, the vegetation cover has improved slightly to strongly (figs. 5, 6, 7a, 9).

Similarly, overall land management has improved over 85 % of the study area (fig. 8b). We refer to some representative landscapes, where the land management has improved slightly to strongly (figs. 4, 5, 6).

Fig. 6. The northern slopes of Mt. Tsibet (extreme south of the study area) represent the average change with regard to vegetation cover between 1975 (top) and 2006 (bottom). The church forest (at right) is an old remnant forest, but in 2006 (bottom) other parts of the slopes have been converted into exclosure.

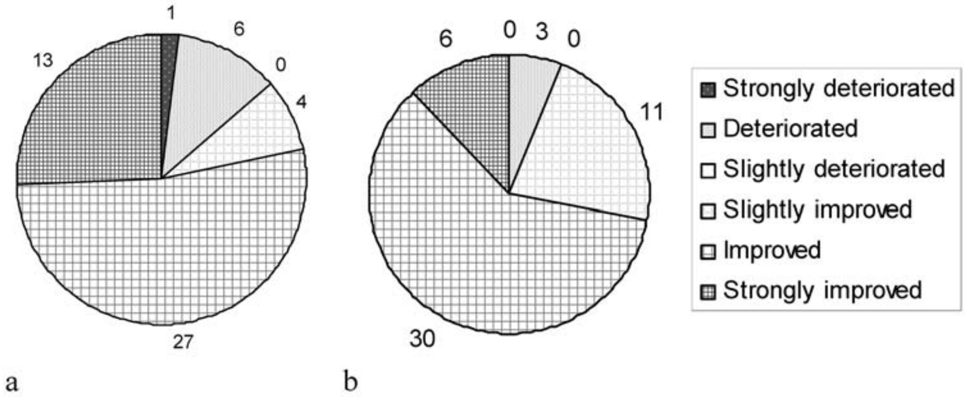

Fig. 7. Changes of (a) vegetation cover and (b) land management in Tigray (1975–2006). Figures indicate the number of monitoring sites analyzed by the expert panel.

4.3 *Quantitative assessment of changes in soil loss*

From a detailed analysis of land units within 45 landscapes, it appears that, on average, soil loss by sheet and rill erosion in 2006 is estimated at only 68 % of its rate in 1975 (table 5). This is due to a substantial improvement in ground cover by vegetation (USLE's C-factor) and in conservation practices (USLE's P-factor), particularly stone bund building (figs. 4, 5).

The P-factor remains relatively high (0.72 on a scale where 0 represents perfect conservation and 1 total absence of conservation practices), as large areas are either not yet treated by physical conservation structures, or because the latter are weak in several places.

This average situation hides quite remarkable variations (fig. 10). Four analyzed sites show absence of conservation practices (P) and very strong decrease of vegetation cover (C-factor). These are the areas with ongoing deforestation, such as those around Des'a Forest (fig. 9).

At the ca. 40 other sites, the C and P factors are either stable or have decreased. These correspond to the most common situation in Tigray, where degraded areas are under rehabilitation. In these 40 sites, soil loss has decreased on average to 64 % of the 1975 rate.

5 *Discussion*

5.1 *Key factors in increased ecosystem functionality*

Observations on decreased soil erosion rates, despite strongly increased population density, become sound when considering the large-scale implementation of soil and water conservation (SWC) practices that has taken place over the last two decades. In the early 1980s a start was made with closing strongly degraded areas. In the generally stepped topography of the study area, exclosures, which mostly cover the steep slopes, form 50 to 150 m wide and 200 to 2000 m long vegetation strips, parallel to

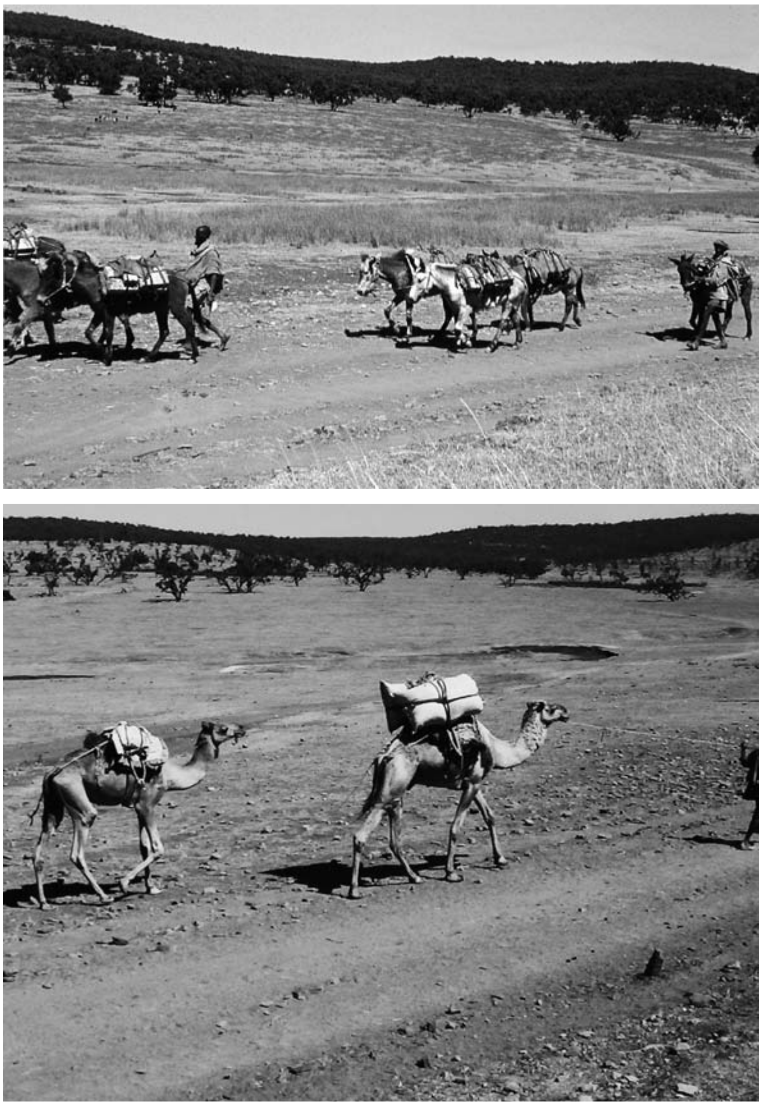

Fig. 8. As an exception to the general trend, all repeated photographs of Des'a forest (such as this one near Agero) show ongoing deforestation between 1975 (top) and 2006 (bottom). Due to prohibitions on wood transport the forest has however not been cleared totally and individual *Olea* and *Juniperus* trees survive along the fringes. A gully has developed in 2006 as the consequence of enhanced runoff conditions due to decreased vegetation cover.

Table 5. Average change of explanatory factors of sheet and rill erosion (n = 45)

	1975	2006	change
Average USLE C-factor (vegetation cover)	0.121 (± 0.055)	0.096 (± 0.048)	79 %
Average USLE P-factor (conservation practices)	0.838 (± 0.181)	0.720 (± 0.231)	86 %
C x P	0.102 (± 0.052)	0.069 (± 0.037)	$A_{\%}$ = 68 %

$A_{\%}$ = rate of sheet and rill erosion in 2006 as a percentage of the 1975 situation

the contour lines (Descheemaeker et al. 2006a, b, c). In the protected exclosures (figs. 5, 6), the recovery process invariably starts with a rapid increase in diversity and cover of herbaceous species, while after 3–5 years shrub and tree species gain importance and start to suppress the herb layer (Aerts et al. 2004; Tefera et al. 2005). Age of closing goes hand in hand with an increase in vegetation cover and density as well as with an improvement in soil fertility (Descheemaeker et al. 2000c). The establishment of exclosures enhances infiltration and biomass production. The impact of these interventions on land rehabilitation is discussed below.

5.2 *Stone bunds conserve soil and water*

Physical structures like stone bunds have been built in all land use types (fig. 4), whereas trenches were established in pasture and shrub lands (fig. 5), check dams in gullies. Given the semi-arid environment, the structures are designed to conserve both soil and runoff.

Based on measurements on 202 field parcels (Nyssen et al. 2007), stone bunds reduce soil loss on average to 32 % of the pre-existing situation. Truncation of the soil profile at the lower side of the bund does not lead to the expected soil fertility decrease, mainly because the dominant soil types of cropland (Regosols, Vertisols and Vertic Cambisols) do not have pronounced vertical fertility gradients. Negative effects of runoff concentration or crop burial by sediment deposition due to bunds were only found along 1.5 % of the studied bunds. On these field parcels with stone bunds, there is a 53 % average increase in grain yield of in the lower part of the plot, as compared to the central and upper parts. Taking into account the space occupied by the bunds, stone bunds led in 2002 to a mean crop yield increase from 0.58 to 0.65 t ha^{-1}. Additional positive off-site effects are runoff and flood regulation. From technical, ecological and economic points of view, the extensive use of stone bunds, involving people's participation, is a positive operation (Desta et al. 2005, Vancampenhout et al. 2006, Nyssen et al. 2007). Bekele & Holden (1999) and Boyd & Slaymaker (2000) have demonstrated that given the ecosystem services (*sensu* Robertson & Swinton 2005) rendered by the farmers through stone bund building, current subsidies and incentives are justifiable.

Fig. 9. The gully of May Baredom (SE of Mekelle) has expanded strongly, but gully banks were more stable in 2006 (bottom) than in 1975 (top). Intense gully formation took place in the intermediate period (most probably at the very period when the 1975 photograph was taken and in the drought-prone 1980s). The current gully stabilization is related to improved vegetation cover in the catchment (see changes on the hills at the back of the photographs).

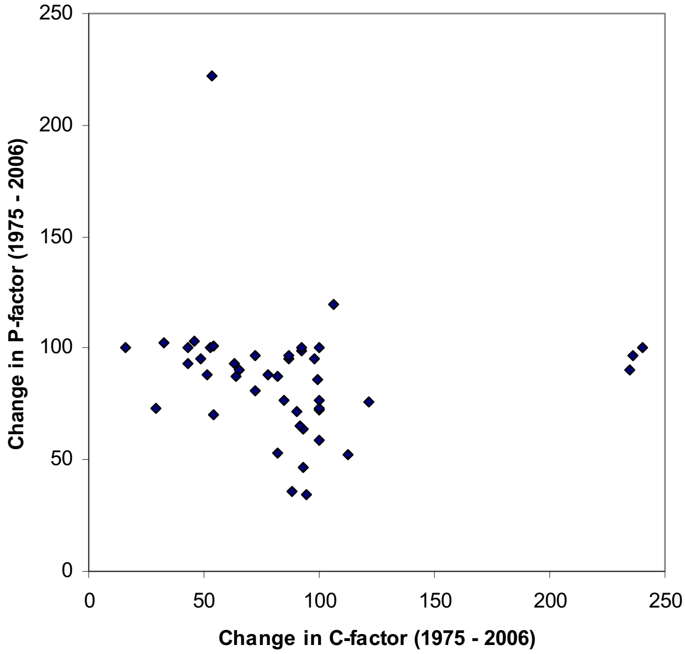

Fig. 10. Change of USLE's C and P factors in 45 analyzed landscapes (100 C_{06}/C_{75}; 100 P_{06}/P_{75}).

5.3 *Exclosures and woody biomass production*

Household energy in Tigray is for 81 % produced from firewood and for 17 % from crop residue and dung (CSA 2007). Fuel of rural households consists for 76 % of collected firewood, whereas urban households cook and heat for 74 % with purchased firewood and charcoal. The "exclosure" policy is another cornerstone in the dynamics whereby both population and vegetation density have increased. "Exclosure" means areas set aside, where agriculture and grazing are forbidden so that the regeneration of the natural vegetation is enhanced. In the Tigray highlands, vegetation regrowth in exclosures (figs. 5, 6) has become an important measure to combat land degradation and to increase biomass production; in several districts they cover up to 15 % of the land (Descheemaeker et al. 2006a, b).

Runoff production in exclosures, measured using runoff plots (Descheemaeker et al. 2006b), is significantly reduced when a degraded area is allowed to rehabilitate after closure. Though runoff depth is significantly correlated with event variables such as rain depth, rainfall intensity, storm duration and soil water content, total vegetation cover is the most important variable explaining about 80 % of the variation in runoff coefficients. Runoff was found to be negligible when the vegetation cover exceeds 65 % (Descheemaeker et al. 2006b).

Soil water fluxes in exclosures are determined both by the rainfall regime and by extra water input through run-on from upslope (Descheemaeker et al. 2008). Increased vegetation density in exclosures results in increased infiltration and higher

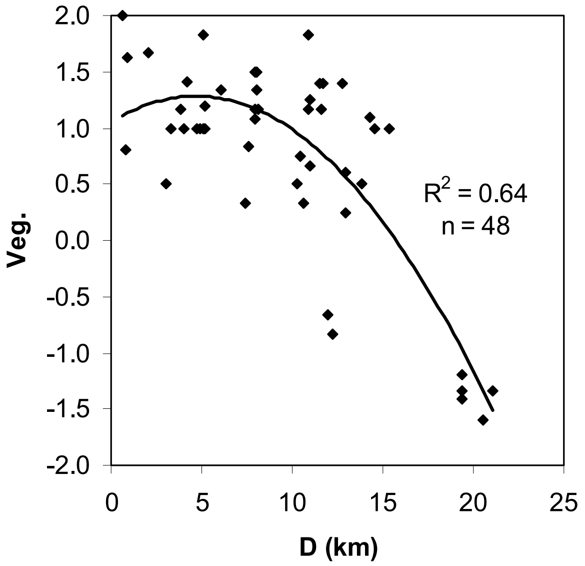

Fig. 11. Average expert rating of change in total vegetation cover on non arable land (Veg., ranging between "strongly improved" (+2) and "strongly deteriorated" (−2)) in function of the distance to the nearest town (D, km). Whereas most monitored landscapes have undergone a (slight to strong) positive change in vegetation cover, there has been a partial shift of degradation of vegetation to more remote areas, typically a daily donkey action radius away from the towns.

transpiration, which in its turn triggers vegetation restoration through increased biomass production. With vegetation restoration, water use for biomass production also becomes more efficient. Through water balance simulations (Descheemaeker et al. 2008), it was demonstrated that at a catchment scale, expanding the area under exclosure leads to decreased runoff and increased infiltration and evapotranspiration. The parallel increase in deep percolation is attributed to the presence of source-sink systems. The source areas produce runoff, which infiltrates in the sink areas (the exclosures) (fig. 5). Vegetation restoration is responsible for the high infiltration capacity of the exclosures, but as transpiration is not increased at the same rate, the surplus infiltration drains beyond the root zone and contributes to groundwater recharge. This explains the earlier reported phenomenon (Nyssen et al. 2002) of improved spring discharge in lower parts of the landscape after degraded areas were turned into exclosures in Tigray.

Besides effects on enhanced infiltration, decreased downstream sediment deposition and flooding, exclosures provide ecosystem services such as growth of grass and trees, increase in wildlife and biodiversity, climate regulation, drought mitigation and carbon sequestration.

Our very diverse photoset (table 2) shows an overall improvement of vegetation cover, also in the degraded customary firewood production areas such as Geba valley and parts of the rift escarpment (fig. 3). Firewood is still available due to better biomass production and to the use of bark, leaves and branches of the now widely spread eucalypts (as can bee seen on most repeated photographs). Wood production for urban consumption (22.5 % of the Tigray population lives in towns (CSA 2007)) takes place at a distance (fig. 11) and contributes to deforestation of areas like Des'a forest. Better protection and management of these remnant forests, enhancement of access to alternative sources of urban energy and changes in cooking habits (Asmerom 1991; Bereket et al. 2002) should be top priorities to sustain the current positive trends.

5.4 *Gully erosion and rehabilitation*

As mentioned earlier, repeated photographs show that locally gullies are larger than in 1975 (figs. 8, 9); this evolution seems not in phase with the generally observed improved environment. Whereas some gullies in the Tigray highlands started as a direct consequence of deforestation (fig. 8), the general trend in gully evolution is somewhat more complex. In a detailed case study (Nyssen et al. 2006a), gullying started around 1965 after gradual environmental changes, including removal of vegetation from cropland and eucalyptus plantation in the valley bottom. Rill-like incisions grew into a gully, which increased rapidly in the drier period between 1977 and 1990. The estimated evolution of gully volumes in nearby areas shows patterns similar to those of the studied gully. Average gully erosion rate at catchment scale over the last 50 years is 6.2 t ha^{-1} yr^{-1} (Nyssen et al. 2006a). In critical periods, such as during the drought of the 1980s, gully volumes increased rapidly, both as a consequence of the expansion of existing gullies and of the incision of new gullies. On the other hand, since 1995, no new gullies have developed in the Dogu'a Tembien study area. Specific short-term gully erosion rates are now on average 1.1 t ha^{-1} yr^{-1} (Nyssen et al. 2006a).

Rapid gully development in the study area is some 50 years old and is mainly caused by human-induced environmental degradation. Under the present-day conditions of 'normal' rain and catchment-wide runoff trapping (especially behind stone bunds and in exclosures), gully erosion rates have strongly decreased.

The current size of the gullies is mainly explained by the fact that they were incised during the degradation of the 1980s (Nyssen et al. 2006a), whereas the environmental recovery programs of the last two decades could not heal their scars yet (fig. 9). Other repeated photographs also show that in 1975 active gullying was ongoing as can be deduced from bank collapse, whereas in 2006 gullies, though larger, have stabilized with some vegetation growing on their banks.

5.5 *A cross-check: reservoir sedimentation rates*

The results of the repeat photography study are in full accordance with recent studies whereby volumes of sediment trapped in 5–10 yr old reservoirs (with a drainage area of 1 to 24 km^2) were measured (Nigussie et al. 2005), and related to environmental characteristics, including the watershed management activities undertaken over the last decades. Average area-specific sediment yield (SSY) is 10.5 (± 4.9) t ha^{-1} yr^{-1} (n = 10) (Nigussie et al. 2005), which is much less than the 16.8–32.8 t ha^{-1} yr^{-1} measured in the 1975 studies (HTS 1976, Virgo & Munro 1978). Despite the fact that the 1975 data concern merely two rivers (catchments of 115 and 153 km^2) which were monitored during only one year, the difference with current rates is large enough to conclude for a significant decrease in SSY, which corresponds to the results of the repeat photography study.

The calibration of a Factorial Scoring Model for SSY and reservoir sedimentation rates in Tigray (Nigussie et al. 2005) helped to identify the controlling factors of SSY; the density of physical conservation structures in the catchments was the major factor explaining the great variability in SSY. Stratigraphic analysis of the reservoir sediment, through observations on the continuity and characteristics of the layering and relating it to the age of the dam, indicates that the annual inflow of sediment suddenly decreased after physical conservation measures were implemented in the catchment (Nigussie et al. 2006).

6 *Conclusions*

The recent active intervention by authorities and farmers to conserve the natural resources in Tigray has led to demonstrated significant improvements in terms of soil conservation, infiltration, crop yield, biomass production, groundwater recharge and prevention of flood hazard. Results from detailed *in situ* studies are corroborated by analyses of landscape changes, which show that the status of natural resources has improved (and locally strongly improved) since 1975. The increased ecosystem functionality is due both to improved vegetation cover and to the implementation of physical conservation structures. The USLE application indicates that currently, average soil loss by sheet and rill erosion is at around 68 % of its 1975 rate. These decreasing rates are substantiated by comparisons between SSY in 1975 and 2003.

Exceptional degradation, however, is still ongoing around Des'a forest and some other remnant forests. Like elsewhere in Tigray, conservation of vegetation cover should be strongly implemented here. A system for sustainable forest exploitation must be established. On average, gullies have expanded slightly since 1975; but these incisions date probably back to the 1980s.

This study invalidates hypotheses on (a) irreversibility of land degradation in Tigray and *a fortiori* in less marginal semi-arid areas; and (b) futility of SWC programs. The study furthermore demonstrates that (a) land management has become an inherent part of the farming system in Tigray, (b) it is possible to reverse environmental degradation in semi-arid areas through an active, farmer-centered SWC policy (Stocking 2003), (c) keeping small-scale farmers on their land by providing adequate levels of subsidies (Robertson & Swinton 2005, Pimbert et al. 2006) is an effective way to sustain the agricultural system of semi-arid areas in the long term and to provide ecosystem services to the society, and (d) the 'More People – Less Erosion' hypothesis (Tiffen et al. 1994) is also valid in other, semi-arid areas. In a highly degraded environment, with high pressure on the land, no alternatives are left open but to improve land husbandry.

The challenges to be met include (a) *in situ* SWC of farmland (Nyssen et al. 2006b), (b) shifting to stall feeding of livestock and ecologically sound grazing management of rangelands, (c) involving local communities in decision making about resource management (Robertson & Swinton 2005, Bekele et al. 2005, Segers et al. 2006) and (d) active development of a policy for sustainable urban energy consumption.

Acknowledgements

This research was carried out in the framework of the Zala-Daget project ("Fighting desertification in the Tigray Highlands: lessons to be learnt from successes and failures of soil erosion control techniques"), a collaborative project between Mekelle University, Relief Society of Tigray (Ethiopia) and K. U. Leuven and Africamuseum (Belgium), funded by the Belgian authorities through VLIR. JN was employed by K. U. Leuven with standing place at Mekelle University during fieldwork and write-up of the manuscript. Many individuals and institutions contributed to this research. The authors particularly acknowledge the Tigrayan farmers whose hard work in an adverse environment allows environmental recovery. Their endeavour was an inspiring source for us scientists. We thank John Thornes (King's College, London) and Michael Stocking (University of East Anglia, Norwich) for critical reading of the manuscript and constructive suggestions.

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