Gully Development in the Tigray Highlands

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Abstract
In the Tigray highlands, gully development is linked to poverty-driven unsustainable use of the land in a vulnerable semi-arid and mountainous environment, where intense rainfalls challenge the physical integrity of the landscape. Over the last two centuries, three major phases in the hydrological regime of the region could be distinguished. In the first phase, between 1868 (or earlier) and ca. 1965, the relatively stable gully channels showed an oversized morphology inherited from a previous period when external forcing of environmental conditions caused significant channel development. In the second phase (ca. 1965–ca. 2000), increased aridity and a continued vegetation clearance accelerated dynamics of the gully system. A sharp increase in gully headcut retreat rates, network densities and volumes could be quantified for that period. With the widespread implementation of soil and water conservation measures, erosion rates decreased, which announced the start of the third hydrogeomorphic phase since ca. 2000. In 2010, about one-fourth of the gully channels were stabilized. These hydrogeomorphic developments correspond to a gully *cut*-and-*fill* cycle in the second half of the twentieth century and suggest that a pre-1868 cut cycle took place.

Keywords
Gully • Headcut retreat • Repeat photography • Vertisol

10.1 Introduction

In dryland environments, water availability and biomass production are often restricted and confined to a short rainy season. As a result, the carrying capacity of the ecosystem is rapidly exceeded by human exploitation of natural resources, especially in sub-Saharan countries like Ethiopia, with fast demographic expansion and deficient exploitation techniques (Kassas 1995). Furthermore, the resilience of the land is often reduced by recurring droughts and severe land degradation, which threatens sustainable development in these fragile environments.

The Tigray Rural Development Study (TRDS; HTS 1976), which investigated the state of the environment in the 1970s, concluded that land degradation was severe in the Tigray highlands and that natural resources were put to their limits (Virgo and Munro 1978). Almost a decade later, the devastating effects of drought and desertification were brought to a global audience with the drought that stroke the region in 1984–1985. In a context of civil war, region-wide crop failures led to massive famine and starvation. As shown on historical photographs (Fig. 10.1), severe gully erosion destroyed valuable land, jeopardizing in situ and downstream agricultural production, increasing the costs of transport and infrastructure construction and producing flash floods of polluted water which threatened human health.

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Fig. 10.1 Active gully channel networks in a barren landscape of Tigray highland (*Photographs* by Jean Poesen—*top*, and Piotr Migoń—*middle* and *bottom*)

Several studies reported significant gully erosion in Ethiopia and especially addressed the Tigray highlands (Fig. 10.1; Virgo and Munro 1978; Berakhi and Brancaccio 1993; Nyssen et al. 2000, 2002, 2004, 2006; Billi and Dramis 2003; Munro et al. 2008; Reubens et al. 2009; Frankl et al. 2011, 2012, 2013b, c, d). Among the first, Virgo and Munro (1978) assessed the status of soils and landscapes in northern Ethiopia, documenting numerous cases of severe gully erosion. The importance of gully erosion in Vertisols, which are susceptible to soil piping, was discussed by Nyssen et al. (2000). Berakhi and Brancaccio (1993) and Nyssen et al. (2006) studied the effect of road building on gully erosion risk, and Nyssen et al. (2004) investigated the usefulness of check dams to control gullies. Nyssen et al. (2006) analysed the development of four gully systems in the Tigray highlands by developing a field method which is based on how local people remember the evolution of specific gullies. A similar approach was used by Moges and Holden (2008) who studied gully development in southern Ethiopia. A small gully network in eastern Ethiopia was studied by Daba et al. (2003), using a time series of digital elevation models derived from small-scale aerial photographs. An analysis of the development of gully headcuts, their cross sections, networks and volumes at regional scale in Tigray highlands was carried out by Frankl et al. (2011, 2012, 2013b, c, d). By using repeated terrestrial photography, aerial photographs and satellite images, these authors could define distinct phases in gully erosion development since the late nineteenth century. Nigussie Haregeweyn et al. (2005, 2008) linked the presence of gullies to the rate of reservoir sedimentation (catchment sediment yield).

10.2 Gullies and Gully Erosion

In the Oxford Dictionary of Earth Sciences (2008), a gully is defined as a "feature of water erosion that develops from the run-off of a violent torrent that bites deeply into topsoil and soft sediments". Gully erosion can thus be associated with the rapid incision of valley sides or valley floors by the erosive action of flash floods. This is also apparent from the definition of Poesen et al. (2003) who proposed that gully erosion is an "erosion process whereby runoff water accumulates and often recurs in narrow channels and, over short periods, removes the soil from this narrow area to considerable depths", a definition that is widely used in scientific literature. Gully erosion is thus the result of disruptions in a previous stage of equilibrium that cause changes in the run-off volumes and sediment delivered to a certain place in the landscape (Graf 1988; Knighton 1998). Causes of incision by concentrated overland flow are numerous and can be grouped into six categories (Schumm 2005): geologic, geomorphic, climatic, hydrologic, animal and human causes. Examples that are most relevant for the case of the Tigray highlands are uplift, base level lowering, mass movements, increased aridity or humidity, increased mean run-off discharge and/or peak discharge, decreased sediment load, animal grazing and tracking, flow diversion, urbanization and infrastructure construction. As the geomorphic development of gullies is related to alternating conditions, they are also referred to as non-regime channels (Schumm 2005).

In order to efficiently transfer water and sediment via run-off downslope, the shape and size of gullies mainly adjust to peak flow discharge properties (Knighton 1998). Channel shape and size may be spatially and temporally very variable, depending on local environmental characteristics (e.g. soil, vegetation), and the time that is needed to accommodate changes in run-off discharge and sediment load, i.e. reaction and relaxation times (Knighton 1998).

Frankl et al. (2013c) characterized gully cross-sectional characteristics in the Tigray highlands by surveying 811 gully cross sections in various environments, reflecting contrasts in lithology, topography, soil, land use and climate. Gully top width (TW) varied between 0.35 and 31.90 m, with a median of 6.34 m. Gully depth (D) varied between 0.20 and 12.77 m, with a median of 2.15 m, and bottom width (BW) ranged between 0.10 and 19.50 m, with a median of 3.00 m. The median cross-sectional area (CSA) was 10.1 m^2 and ranged between 0.15 and 236.5 m^2. As the boxplots show (Fig. 10.2a), the distributions are right-skewed and the variability of the observations, as indicated by interquartile range, is higher for *TW* (5.20) and *BW* (2.70) than for *D* (1.79). The median *TW–D* ratio was 2.7, while the median *BW–TW* ratio was 0.5. Note that for *TW/D* and *BW/TW*, median and mean do not differ much as the distributions are nearly normal. As shown in Fig. 10.2b, plotting *D* over *TW* shows wide scatter around a linear relation purged through the origin (0, 0).

Catchment area is the most important factor explaining the variability in *TW*, *D* and *CSA*, as it reflects the volume of water that drains to a certain point in the landscape. However, the large variability in soil management and environmental characteristics causes the gully shape and size to be locally very variable. As shown by Frankl et al. (2013c), besides the catchment area, lithology and the presence of check dams are the most important explanatory factors to account for gully morphology in the Tigray highlands. Gully cross sections in shale-derived deposits are on average 36.7 % larger than those in deposits derived from volcanics. This is mainly related to the higher erodibility of shale-derived materials and to the presence of travertine dams. Degradation and breaching of the latter

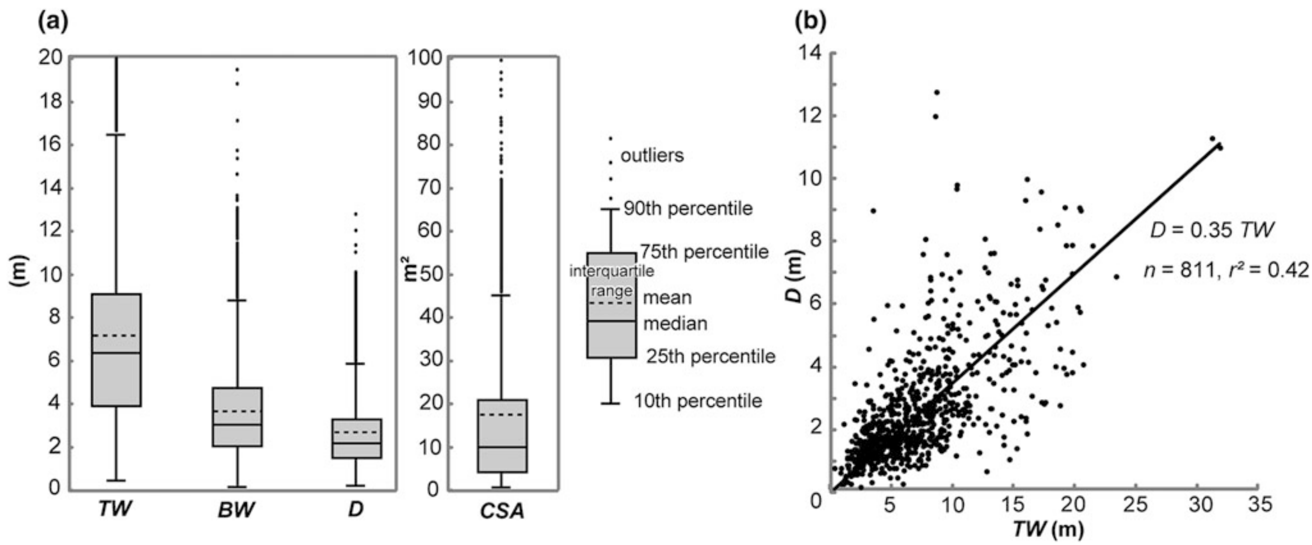

Fig. 10.2 Cross-sectional characteristics of gullies in Tigray highlands (Frankl et al. 2013c). **a** Boxplots for gully top width (*TW*), bottom width (*BW*), depth (*D*) and cross-sectional area (*CSA*) for 811 sections. Outliers larger than 20 m and 100 m^2 are not displayed, **b** plotting gully depth (*D*) over gully top width (*TW*) shows a linear relation. Based on Frankl et al. (2013c)

Fig. 10.3 The deeply incised travertine dam at May Mekdan and gully network upslope (*Photograph* of 2010 by Amaury Frankl; 13.58°N, 39.56°E)

(Moeyersons et al. 2006; Fig. 10.3) triggers regressive erosion and exposure of thick, fine-textured soils locked upslope of the dams. Check dams, which are successfully implemented in low-active gully sections, cause the gully depth to decrease by circa one-third. This makes moderately active gully cross sections with check dams on average 33.5 % smaller than those of very active gullies without check dams.

10.3 Evidence of Past Dynamics

10.3.1 Early Evidence of Gullying

The oldest terrestrial photographs known for the highlands of Tigray are those taken during the British military expedition to former Abyssinia in 1867–1868, with the objective to

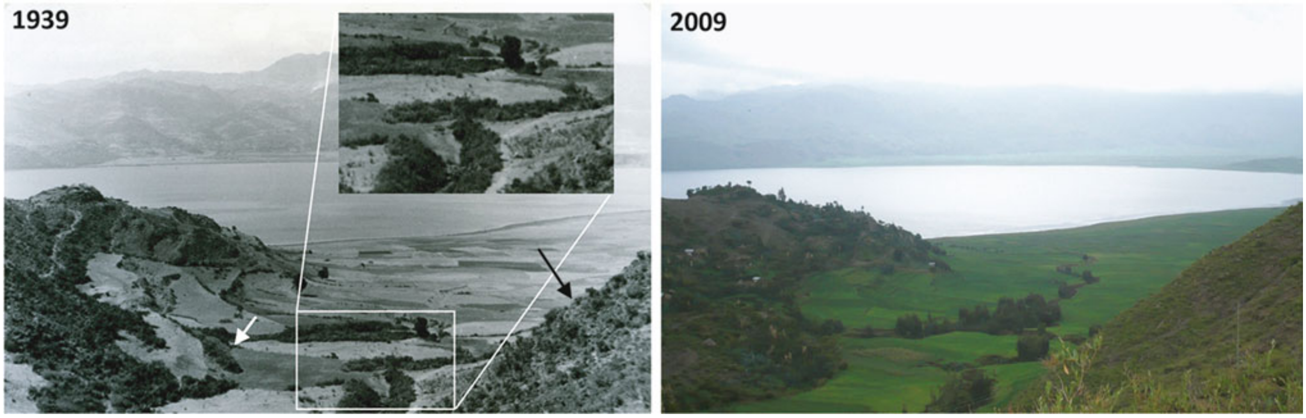

Fig. 10.4 The gully draining the valley in 1939 (*left*) is low-active (smooth cross section, vegetated) and has been partially converted to cropland (*zoom*). Although wood harvesting and agricultural exploitation in 1939 severely affected the environment, shrub cover on the arable land (*white arrow*) and on the surrounding hills (*black arrow*) of this small catchment draining to Lake Ashenge is still relatively high. By 2009, the gully had extended downstream by 294 m (*right*). It is freshly incised (=high-active section) and remains active despite the recent soil and water conservation efforts. Original photograph (*left*): Maugini (Istituto Agronomico per l'Oltremare, Firenze, I). Repeat photograph by Amaury Frankl 12.56°N, 39.25°E. Based on Frankl et al. (2011)

release a number of Europeans who had been imprisoned by Emperor Tewodros (Sharf et al. 2003). Such historical photographs are often the only records available on the environmental status for the period 1868–1963 (Fig. 10.4), after which aerial photographs were produced for the area (Nyssen et al. 2010). Aerial photographs taken during the Italian occupation of Ethiopia in 1935–1941 have recently been discovered but were not yet analysed. In order to compare the previous and current situations, historical terrestrial photographs were repeated in the field according to the technique of repeat photography by Hall (2001). Qualitative and quantitative analyses of time-lapsed photographs revealed that in the late nineteenth and early twentieth centuries, gullies were common features of the northern Ethiopian landscape (Frankl et al. 2011). However, most gullies seen on historical photographs from that period show smooth and vegetated cross sections (Fig. 10.4). As their size and morphology suggest, the gullies were not in equilibrium with the prevailing conditions but were rather inherited from a previous period when external forcing of environmental conditions caused significant geomorphic change (Nyssen et al. 2009; Frankl et al. 2011). Most probably, such ancient gully incision cycles occurred during the frequent droughts of the nineteenth century, as reported by Pankhurst (1995), leading to famine and great mortality. These calamities would have increased the environmental vulnerability to human interference and, hence, also the run-off response of the land.

10.3.1.1 1960s–1990s Cut Cycle

The study of time-lapsed terrestrial photographs and aerial photographs indicates that the recent gully incision phase in Tigray highlands started around 1965, with a marked increase in gully drainage densities and volumes (Frankl et al. 2013b). In 1963–1965, gully drainage density (D_{total}) and area-specific gully volume (V_{a}) were still relatively low, i.e. 1.86 km km^{-2} and 32.23 × 10^{3} m^{3} km^{-2}, respectively (Fig. 10.5a–c). 48 % of the gully network was high-active. From a largely low-dynamic gully system in the 1960s, network expansion and increased erosion rates in the 1980s and 1990s caused the drainage density and volume to peak in 1994. D_{total} was then 2.52 km km^{-2} and V_{a} 60 × 10^{3} m^{3} km^{-2}, with 93 % of the gully network being highly active (Fig. 10.5a–c). This corresponds to a soil losses by gully erosion (*SLg*) of 17.6 ton ha^{-1} year^{-1} over the period 1963–1994. The terrestrial photographs from that period show gullies which were very active, having clear-cut walls and transporting considerable amounts of debris (Fig. 10.1). The average incision rate of gully cross sections was 0.04 m year^{-1}, and maximum incision rates of 0.13 m year^{-1} were observed in Vertisol areas (Frankl et al. 2011). At the upper gully margins, headcuts incised upslope, while at the lower ends, debris fans were deposited and incised subsequently. Long- to medium-term linear headcut retreat rates (R_{l}) were on average 3.8 ± 4.7 m year^{-1} (Frankl et al. 2012). This gully *cut* cycle, that started in the mid-1960s, lasted until ca. 2000, after which a new gully *fill* cycle was initiated.

10.4 Rehabilitation in the Twenty First Century?

As a result of huge efforts in environmental rehabilitation undertaken since the 1970s, denudation rates decreased in the highlands of Tigray—although remained fairly high in absolute terms—reducing the importance of gully erosion. Mean run-off discharge as well as sediment load and flash

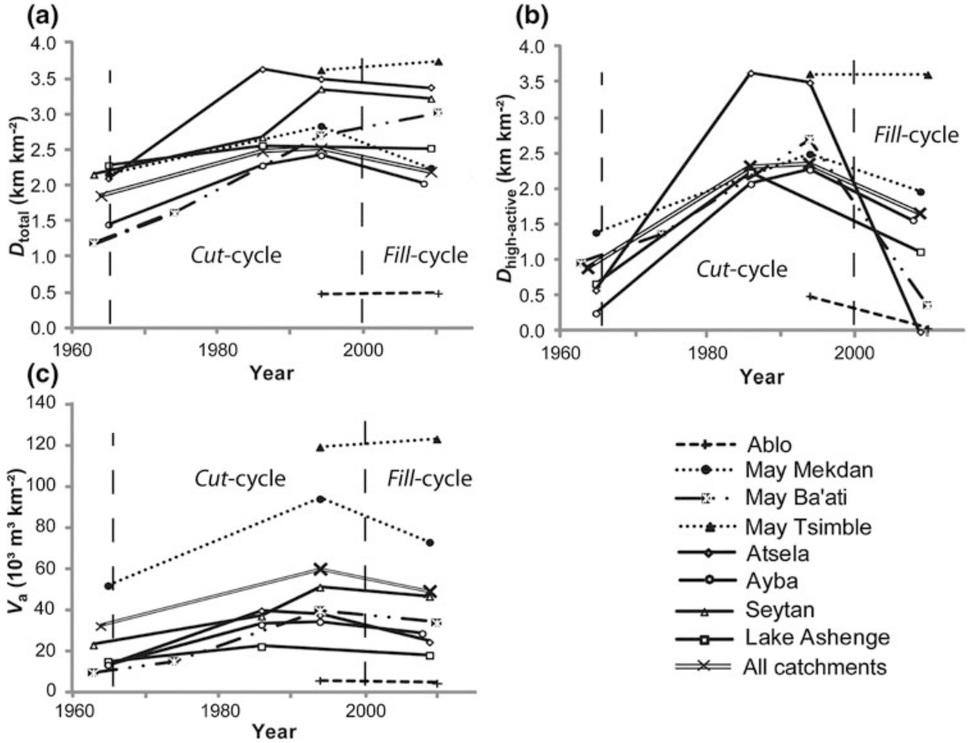

Fig. 10.5 Gully *cut*-and-*fill* cycle during the period 1963–2010 as expressed by trends in total drainage density (D_{total}) (**a**), drainage density of the high-active gullies ($D_{\text{high-active}}$) (**b**) and area-specific volume development (V_a) (**c**). Based on Frankl et al. (2013b)

flood peaks decreased (cf. Moeyersons 1989, 1990), causing gullies to become less active and to fill in partially, especially when check dams were installed (Frankl et al. 2013b; Fig. 10.6a). When proper land management was applied, gullies could even be transformed into a green linear oasis which contributes to the ecological restoration of the degraded area. Moreover, their resilience against the effects of drought or land use changes on run-off response of the land increased. Lower ends of gully channels became non-active and even migrated upslope.

This gully *fill* cycle is well evidenced by the analysis of aerial photographs and more recent satellite images (Frankl et al. 2013b). This analysis indicates that average D_{total} and V_a decreased to 2.20 km km^{-2} and 48.96 × 10^3 m^3 km^{-2}, respectively (Fig. 10.5a–c). Even more important is the decrease in average $D_{\text{high-active}}$ to 1.65 km km^{-2}, indicating that 25 % of the gully network had become low-active. These findings are also supported by repeat-photography studies, indicating that in 2006–2009, about 23 % (n = 8) of the channel cross sections were stabilized and had cross-sectional characteristics similar to those of the pre-1963 gullies (Frankl et al. 2011). Among the other 31 gullies and river sections studied from repeat photography, 44 % were highly active, whereas 23 % were in a transitional stage. Strong channel degradation can be the result of a clear-water effect, which causes the gullies in the valley bottoms to incise. This can be facilitated by the presence of thick, erodible alluvio-colluvial deposits in valley bottom position. However, strong degradation can also be the result of local factors, such as different slope/channel coupling, and connectivity or catchment scale, with large catchments having longer reaction times than small catchments. The reduced gully erosion rate is also apparent from the headcut retreat rates studied by Frankl et al. (2012). Present-day linear headcut retreat rates (R_l) are much smaller than those typical for the medium to longterm, with an average R_l of 0.34 ± 0.49 m year^{-1}. However, gullying in Vertisols remains very active as gully development is largely controlled by soil piping. In Vertisols, present-day headcut retreat rates up to 1.93 m year^{-1} were recorded and large gabion (wire net structures, filled with rocks) check dams, which are cost- and labour-intensive, were sometimes bypassed in one rainy season, forcing the gully to expand laterally into the adjacent land (Fig. 10.6b).

10.5 Factors Controlling Gully Erosion

10.5.1 Hydrogeomorphic Phases and the Role of Land Use and Precipitation

From ca. 1868 to 1965, in a first hydrogeomorphic phase, gullies were mostly low-active, displaying smooth (vegetated) cross sections. This indicates that environmental

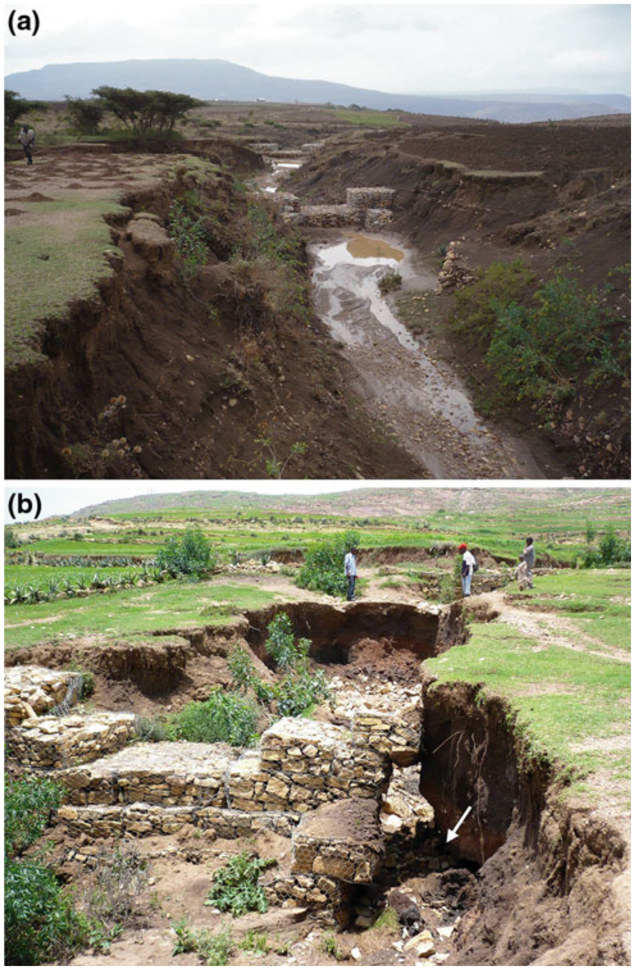

Fig. 10.6 Effectiveness of check dams as a measure to control gully erosion. **a** Siltation behind gabion check dams caused the gully channel to fill in by approximately one-third of its depth in a catchment where slope run-off response decreased thanks to the implementation of soil and water conservation measures. Notice also on the left gully bank soil pits that are dug to plant trees, **b** at another location, the presence of a Vertisol lens in the lower soil profile (*white arrow*) caused the gabion check dam to be bypassed in one rainy season, forcing the gully flow to erode the adjacent land. Photographs taken in 2009 (**a**) and 2011 (**b**) by Amaury Frankl 13.65°N, 39.21°E

vulnerability did not yet reach a critical point for large-scale channel expansion and degradation to occur. After 1965, a marked transition from low- to high-active gullies took place in a second hydrogeomorphic phase. This is most probably related to arid pulses that occurred in the 1970s and 1980s. A similar phenomenon was observed in Senegal (Poesen et al. 2003). Such phases alter biomass production and increase human pressure on land and vegetation. In order to secure food production, farmers were forced to cultivate steeper land and overgrazing removed most of vegetation from the hillslopes. Analyses of region-wide land use and cover on the basis of Landsat imagery by de Mûelenaere et al. (2013) in the 1970s and 1980s confirmed that in 1984/1986, the area covered by bare soil was extensive and that the area covered by cropland peaked. From the analysis of land use and land cover on old terrestrial photographs, Meire et al. (2013) also indicated a minimum in vegetation cover in the period 1940s–1990s. Frankl et al. (2013a) showed that the length of the crop growth period decreases with increasing drought in the Tigray highlands, making croplands very vulnerable to high-intensity rainfall during the summer rainy season.

Since ca. 2000, the large-scale implementation of soil and water conservation measures started to yield positive effects on the environmental rehabilitation and on the stabilization of gullies. Several studies indeed indicate that vegetation cover and land management strongly improved in recent decades (e.g. Gebremedhin et al. 2004; Munro et al. 2008; Alemayehu et al. 2009; Mekuria et al. 2009; Nyssen et al. 2009; de Mûelenaere et al. 2013; Meire et al. 2013). As a reaction to severe land degradation that stroke northern Ethiopia in the 1970s and 1980s, environmental rehabilitation programs were launched with the aim of increasing land resilience to the effects of droughts. Biophysical conservation measures that were implemented include the following: (1) the establishment of exclosures in critical steep-sloped zones (Descheemaeker et al. 2006); (2) the introduction of stone bunds (Nyssen et al. 2008) and soil trenches; and (3) the construction of check dams in gullies (Fig. 10.6a; Nyssen et al. 2004). At present, exclosures cover 10–15 % of the land surface and stone bunds are found at an average density of 57 km km^{-2} (Schumacher 2012). This led to greening of the landscape in which the surface covered by bushland, forest or *Eucalyptus* plantation strongly increased. This greening is partly the result of the introduction of *Eucalyptus* trees to support the growing need of construction wood in decades where population is remarkably increasing. At a national level, population size almost doubled, from 40 million in 1980 (Maddison 2006) to 88.4 million in 2013 (FAOSTAT 2013). In Tigray, population size increased from 3.1 in 1994 to 4.3 million in 2007, representing 6 % of the total Ethiopian population (CSA 2008), whereas population density increased from 63 to 86 persons km^{-2}.

10.5.2 Check Dams as Soil and Water Conservation

In addition to soil and water conservation measures implemented in the gully catchments (e.g. stone bunds, soil trenches), the construction of loose rock or gabion check dams in gullies is a widely used conservation measure in the highlands of Tigray. Technically, the aim is to transform the long, uniform and steep longitudinal profile of the gully bed into successive, nearly horizontal steps (Ayres and Scoates 1939; Hurni 1986) by trapping sediment behind the dams.

The success of their implementation relies on the availability of loose rocks in the immediate surroundings and the free labour programs, making such dams installation community-based and cost-effective (Gebremedhin and Swinton 2003). However, check dams commonly collapse. As indicated by Nyssen et al. (2004), 39 % of loose rock dams collapse after two years which is a phenomenon strongly linked to the drainage area and slope gradient of the soil surface next to the gully, the product of these factors being a measure of run-off energy. In Vertisol areas, where soil piping occurs, flow bypassing of check dams is commonly observed and can even result in the collapse of large gabion check dams during a single rainy season (Nyssen et al. 2004; Frankl et al. 2012; Fig. 10.6b). It is therefore very important that the technical instructions (BoANR 1997; Hurni 1986; Nyssen et al. 2004) are followed when implementing new gully control structures and that maintenance is organized regularly. Moreover, Vertisol areas with piping require specific measures to prevent flow bypassing. More research is also necessary on the extent to which check dams delay run-off response and enhance infiltration.

10.5.3 Direct Human Intervention

By engineering the landscape through road and drainage canal construction, humans may cause important modifications to natural run-off pathways. As shown by Nyssen et al. (2002), a 6.5-km-long new road segment resulted in the development of 16 new gullies (total volume of 10,034 m^3) and the stabilization of five small gullies (with a total volume of 100 m^3). In these newly developed gullies, linear headcut retreat rates (R_l) were up to 10 times greater than those recorded in the gullies with no changes in their catchment area, with average R_l for the period 1994–2010 being 21.3 m $year^{-1}$. Distances between culverts are commonly large, and therefore, sites that received run-off from a relatively small drainage area before road construction may experience important increases in run-off because of the catchment area increase. In order to avoid new gully heads developing after building mountain roads, appropriate engineering works (e.g. flow energy dissipaters and/or splitters) should be undertaken during road construction.

10.5.4 Solutions for Vertisols

Soil piping is recognized as an important reason for the development of gullies (Valentin et al. 2005). In Vertisols, this is related to their periodic shrinking and swelling. In a dry Vertisol, shrinking results in the development of wide cracks, which can be as much as two metres deep. Run-off water subsequently infiltrates into the subsoil (bypass flow) and drains underground. Intense subsurface erosion of the dry, dispersive clays results in the development of soil pipes, which, once collapsed, may turn into gullies (Fig. 10.6b). When a Vertisol gets wet, swelling causes cracks to close and the Vertisol becomes almost impermeable. Consequently, run-off production is very high, and large run-off volumes drain through pipes to the gully heads (Nyssen et al. 2000; Frankl et al. 2012). Reducing gully expansion in Vertisols calls for specific measures to reduce the rates of soil piping. As proposed by Frankl et al. (2012), introducing a subsurface geomembrane dam at gully heads can increase the water storage upslope of the dam and thus reduce soil piping. This has been successfully demonstrated at May Ba'ati village (13.65°N, 39.21°E).

10.6 Conclusions

Fast land degradation may occur when improper land management is applied. Most dramatic is the development of extensive and deep gully networks, which in the highlands of Tigray produce large volumes of sediment that are transported through the gully and (ephemeral) river systems since the 1960s. However, local communities have proven that this trend can be reversed. At a regional scale, since ca. 2000, gully networks are increasingly being stabilized and the landscape is re-greening. These results have to be understood within a socio-economic context of strong population growth and a low-level technological development, where most people rely on land resources for their livelihood and where the fragility of the country's economy is frequently emphasized, for example when climatic shocks such as drought cause severe food shortages and famine. Socio-economic developments and their relation to land degradation should therefore be monitored closely. With a population size which is likely to double by 2050, Ethiopia faces immense challenges. The key is to rehabilitate the land, as a resource base for food security and ecosystem services, and to strengthen and diversify the rural economy in order to make local communities less dependent on land resources. Such challenges are embraced by many local, national and international programmes and should remain high on the agenda.

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