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INTEGRATED SOLUTIONS FOR COMBATING GULLY EROSION IN AREAS PRONE TO SOIL PIPING: INNOVATIONS FROM THE DRYLANDS OF NORTHERN ETHIOPIA

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ABSTRACT

Multiple on-site and off-site effects of gully erosion threaten sustainable development, which is especially evident in dryland environments. To control soil erosion by gullying, various soil and water conservation measures have been developed, of which check dams are the most common. Where soil piping occurs, soil and water conservation measures have a limited effect on gully stabilisation, and check dams easily collapse. Therefore, new integrated approaches are needed to control gully erosion induced by soil piping. Here, a subsurface geomembrane dam is proposed as an innovative measure to reduce subsurface flow in soil pipes near gullies. Application of such a dam in Northern Ethiopia resulted in a decrease of gully erosion rates in vertisols and a rising water table in the intergully areas near the gully channel. The consequence of this effect for agriculture near gully channels is the reduction of soil desiccation and, hence, increased crop yields in the intergully areas near the gully channels. In addition, runoff flow diversions into infiltration sites can increase off-site benefits by strengthening economic activities or fasten environmental rehabilitation. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS: crop; dryland; subsurface geomembrane dam; soil and water conservation; vertisol

INTRODUCTION

Gully erosion can be associated with the rapid incision of valley sides or valley floors by the erosive action of flash floods. The devastating effects are especially evident in dryland environments. There, gully erosion contributes 50 to 80% of the overall sediment production (Poesen *et al.*, 2002). In Northern Ethiopia, severe gully erosion was reported in several studies (Virgo & Munro, 1978; Haile & Fetene, 2011), and soil loss by gullying equals 17·6 ton ha^{-1} y^{-1} over the period 1963/1965–1994 (Frankl *et al.*, 2013b).

With the development of extensive and deep gully networks, the hydrologic connectivity of the landscape increases, and large quantities of sediment are exported through the gully and river systems (Poesen *et al.*, 2003). *In situ* agricultural activities are jeopardised, and decreased agricultural production in the proximity of gullies can be expected because of depressed water tables. This is especially apparent at the end of the cropping season when the desiccating effect of the gully on the surrounding land can be observed visually: Near the gully, crops wilt faster (Figure 1). Despite the fact that observations on this process have been reported in literature many years ago (Lowdermilk, 1939; DeBenedetti & Parsons, 1979), very few in-depth studies were actually carried out (for effects on seminatural vegetation, refer to Hagberg, 1995). With fast gully network expansion occurring, infrastructures may be damaged, and costs related to future planning may be much higher than originally budgeted. Downstream effects are also important. Water pollution caused by sediment and urban wastewater threatens human health and decreases agricultural production. As a result of a stronger flash flood regime, rivers—even those that are located many kilometres downstream of the gullies—may respond strongly, and hydrogeomorphic changes may cause infrastructures to be damaged (Billi, 2008).

Soil piping is recognised as an important control of gully development (Valentin *et al.*, 2005). As described by Jones (1971), intense erosion in a soil pipe eventually causes the soil pipe to collapse, by which an open gully is formed. Once initiated, the gully head erodes along the line of till-buried pipes, draining large areas into the gully (Knighton, 1998). The contribution of the soil pipes to the discharge volumes brought to the gully head can hereby be larger than that of surface drainage (Swanson *et al.*, 1989). Moreover, sediment yield from subsurface erosion can be larger than that from surface erosion (Manjoro *et al.*, 2012). Subsequently, deep incision of gullies below the inlets of soil pipes in the gully banks will cause the hydraulic gradient to increase and thereby fasten the development of soil pipes upslope of the headcut (Swanson *et al.*, 1989). In a negative feedback mechanism, soil pipes will thus increase the susceptibility to gully erosion, while, once initiated, gullies will increase the vulnerability of the soils to piping.

Soil piping has been related to gully development in many parts of the world: Ethiopia (Nyssen *et al.*, 2000), Italy

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Figure 1. At the end of the cropping season (late October), the desiccation effect of the gullies on the adjacent intergully areas can be easily observed in the field (south of May Keyih, Ethiopia). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

(Farifteh & Soeters, 1999), South Africa (Rienks *et al.*, 2000) and the UK (Jones, 1971). According to Bocco (1991), soil piping even explains ca 60% of gully development on agricultural land in Europe. However, very few studies investigated the effect of land use conversions or soil and water conservation schemes on soil piping and related gully development. In coastal California, Swanson *et al.* (1989) related the rapid development of gully networks in vertisols by soil piping to the conversion of scrubland into cropland. In Ethiopia, Frankl *et al.* (2012) observed that, in a catchment with soil and water conservation structures, soil piping in vertisols caused headcut retreat rates to be an order of magnitude higher than in other soils. Moreover, where soil piping occurs, flow bypassing of check dams occurs frequently and can even result in the collapse of large gabion check dams during a single rainy season (Figure 2). According to laboratory experiments by Wilson *et al.* (2008), the location of ephemeral gullies closely relates to the network of soil pipes. Such findings indicate that conventional soil and water conservation measures, which focus on minimising surface drainage, are generally ineffective in decreasing soil erosion rates by gullying in areas prone to soil piping (Figure 3).

In response to the latter, this study presents a new integrated approach for gully stabilisation that takes soil piping into account. Special attention is given to the integration of the proposed measures into a larger societal context. Focus is given on dryland environments in a development context, and examples are given from Northern Ethiopia.

MATERIAL AND METHODS

Measuring the Crop Desiccation Effect

To investigate the importance of crop desiccation near gullies in Northern Ethiopia, a study was performed in the catchments east of Hagere Selam (13·64°N, 39·19°E). Fifteen gully segments were selected taking the variability in topography, soils, vegetation cover, and gully size into account. Considering gully size, the average depth and width were 2·7 and 8·7 m, respectively. Perpendicular to the gullies, 65 transects were analysed, parallel with the contour lines and the stone bunds (Nyssen *et al.*, 2007), delineating the farmlands. All investigated transects were located in agricultural lands under wheat, which is the most important crop in this region (Frankl *et al.*, 2013a). The transects crossed farmlands, 5 m upslope from the stone bunds, and had a length of 50 m.

When wheat is drying and ripening, the colour of the crop changes gradually from green to yellow. In order to quantify this effect, vertical photographs were taken by the end of October, whereby the proportion of pixels containing green colour was measured on photographs of the crops (Figure 4A). Along the 65 transects, photographs were taken at distances between 1 and 50 m from the gully bank (at 1, 3, 5, 7, 9, 15, 20, 25, 30, 35, 40, 45 and 50 m). In the intergully area near the gully, there was a greater density of observations because it was expected that the drying effect would be more pronounced in this zone. Photographs were taken top–down from a height of approximately 3 m, using an Olympus µ 300 digital camera, with 3·2 megapixels. The camera was placed at the end of a 1·62 m long rod. As transects were photographed within a couple of minutes in homogeneously managed farmlands, it could be assumed that plant density, date of sowing, phenological plant characteristics, weeding, and light

Figure 2. (A) Because of soil piping in a vertisol lens near the check dam (white arrow), the latter was bypassed in 2011. (B) To counter this, the check dams was re-enforced in early 2012. Soil piping did, however, again caused bypassing of the check dam and the expansion of the gully in the adjacent land (intergully area; May Ba'ati, Ethiopia). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

Figure 3. At the end of the cropping season (late October), the desiccation effect of the gullies on the adjacent intergully areas can be easily observed in the field (south of May Keyih, Ethiopia). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

conditions were similar within transects. For calibration purposes, a reference surface was held above the crop.

The quantitative analysis was performed in Adobe Photoshop, whereby the proportion of pixels was calculated that corresponded to that part of the green colour range that is interpreted as green by human observation, ranging from class 34 to 180 within a total range of green between 0 and 255. For each transect, the proportion of green pixels was plotted for all 13 photographs along the transect, and the linear gradient calculated, indicating the change of colour along the transect. This gradient is a measure for the magnitude of the desiccation effect. As the relative changes along the transects were considered, not the absolute value, the transects could be compared in space and time by the magnitude of the gradient.

In addition, crop yield measurements were performed along 13 transects (generally one transect per gully) through wheat farms, perpendicularly to the gullies. Plots of 2 × 2 m were harvested at 1, 25 and 50 m from the gully edge. The harvest from the sample areas was sun dried and weighed for grain and straw. Twenty-five farmers were interviewed in order to understand their perception on crop desiccation near gullies. Crop growth was also briefly studied from Normalized Difference Vegetative Index (NDVI) values (Asfaha *et al.*, 2014), measured in the end of the growing period with a GreenSeeker.

New Approaches for Gully Erosion Control when Soil Piping Occurs

Reducing gully expansion in soils prone to piping calls for specific measures to tackle soil piping. A new method that was introduced in Northern Ethiopia focuses on the gully heads and consists of inserting a vertical geomembrane dam perpendicular to the gully axis (Figures 5 and 6). The aim is to reduce soil cracking by increasing the local soil moisture conditions and blocking bypass flow in soil pipes near the check dam. Geomembranes of 2 m wide were inserted at depths between 0·3 and 2·3 m below the soil surface, that is, below the plough zone and deeper than the lower limit of soil cracking in the dry season. It is important to have the dam deeper than the gully depth near the gully head. Failing this, the risks of dam undercutting become real. The width of the dam was chosen depending on the local topography and taking run-off flow paths to the gully into account. Generally, in flat terrain, the subsurface dam needs to be wider to ensure that the gully does not develop within lines of buried soil pipes or diverging flow paths that bypass the geomembrane. Here, the total width of the subsurface dams was set at ca 50 m. At the location of the gully head, gabion check dams were constructed to stabilise the gully heads and to fix the geomembrane in the gully. It is important to ensure that the check dam does not extend above the gully shoulder, in order to avoid overflow and new incisions, and that a spillway is constructed that is large enough to drain peak flow discharges. At the lower side of the check dam, an apron is required to limit undercutting by plunge pool erosion. More technical guidelines can be found in Nyssen *et al.* (2004). Near the check dam, the geomembrane was installed at the contact with the gully wall, allowing the check dam to filter sediments from runoff during storm events but preventing the development of soil pipes at the contact zone. When the gully section below the headcut is also eroding over long reaches, the geomembrane dam/check dam can be installed at regular distances. As a rule of thumb, the new structure downslope should be introduced at such a site where the top of the

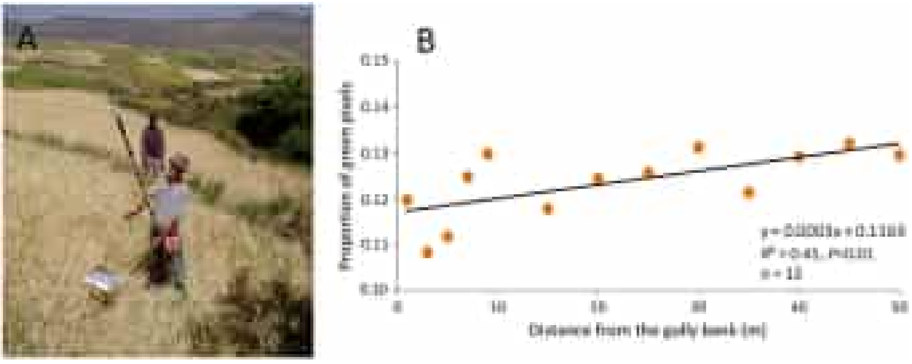

Figure 4. (A) Measuring the crop desiccation effect in the intergully areas by collecting vertical photographs in the field and (B) trends towards more green and more healthy crops away from the gully banks. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

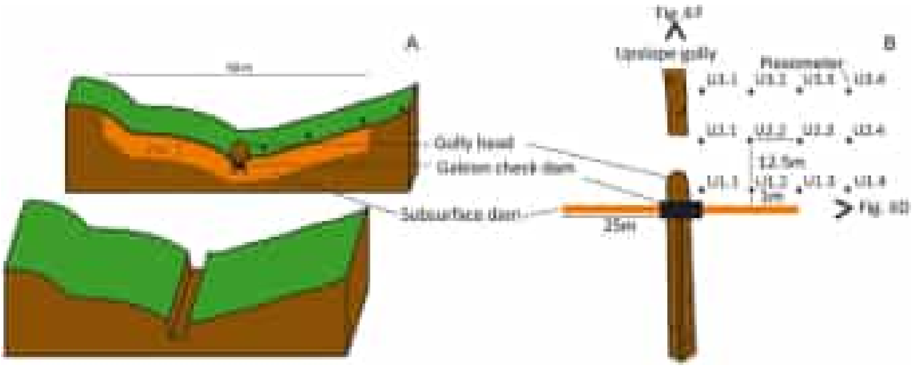

Figure 5. Subsurface geomembrane dam viewed from (A) a schematic block diagram with cross section and (B) plan view. Piezometer locations (U) are indicated by dots. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

new spillway is not lower than the apron of the higher check dam (Nyssen *et al*., 2004).

Subsurface dams were first implemented at a gully head (near Kunale village, 13·65°N, 39.18°E) in 2003. As can be seen on Figure 7, at present, this gully is now fully stabilised and transformed into a grassed waterway. Cropping also occurs in the filled gully. The geomembrane was still in place, and upslope of it, a silted marshy area developed over time. In 2011, a new subsurface geomembrane dam was introduced at a particularly active gully head in May Ba'ati (13·65°N, 39·21°E). With that, ca 2 m deep piezometers were installed in the area upslope of the dam (Figure 5). Groundwater table depth was recorded daily in the piezometers for a period of 2 months in the second half of the rainy season (August–September 2011). Although such a kind of monitoring needs to be performed over longer time periods, and at several sites, some trends could already be revealed.

RESULTS

Crop Desiccation near Gullies

Visual observations as presented in Figure 1 are supported by the interviewing of local farmers. All interviewed farmers

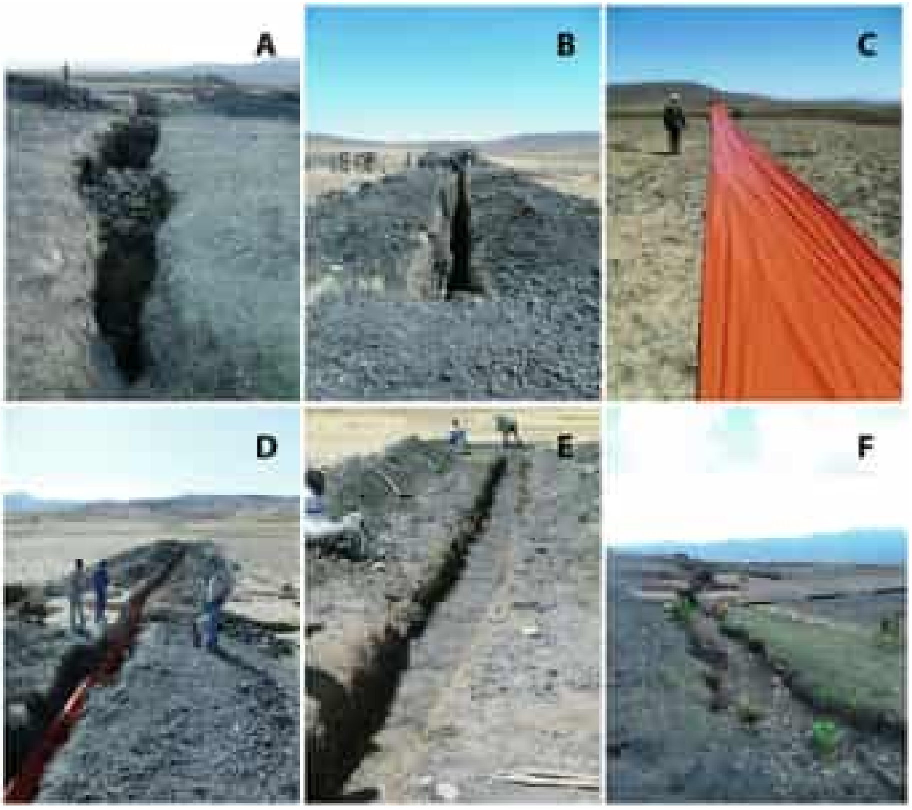

Figure 6. Introducing a subsurface geomembrane dam to stabilise gully heads in a vertisol area in May Ba'ati, Ethiopia. (A) Reinforcement of the headcut with a gabion check dam, (B) digging of a 25 m long and ca 2.3 m deep trench in the intergully area at both sides of the gabion check dam, perpendicular to the gully, (C) the geomembrane (bought from a nearby shop), and (D) introducing the geomembrane into the trench. The upper 0.3 m of the soil profile was not dammed to allow tillage and cropping, (E) filled trench. (F) View on the gully head 1 year after installing the subsurface dam. Upslope from the dashed line, which indicates the position of the subsurface dam, the grass is greener and soil moisture is better as compared with the lower side of the dam. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

Figure 7. After the introduction of the subsurface dam at the gully head in vertisol in Khunale in 2000 (A), the gully was stabilised and filled (B), and the geomembrane dam remained intact. Panel (A) was taken in the dry season and panel (B) in the rainy season. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

stated that they are familiar with faster drying crops near gullies, and 22 of the 25 interviewed farmers also stated that they start harvesting their crops at the edge of the gully and then move away from it. The farming system allows for such precision work, as crops are harvested manually, using sickles. These results are supported by crop yield measurements in the same area. The average of the 13 sampled transects shows a clear gradient in crop yield along the transects perpendicular to the gully. Crop yield was lower at 1 m from the gully bank ($612 \pm 332\,\mathrm{kg\,ha^{-1}}$), compared with the distances of 25 m ($706 \pm 380\,\mathrm{kg\,ha^{-1}}$) and 50 m ($739 \pm 372\,\mathrm{kg\,ha^{-1}}$). The same trend was observed for straw yield. This change in crop yield is most probably caused by a change in soil moisture content as a result of the presence of the gully channel, as a consistent fertility gradient in the soil, with greater fertility away from the gullies is highly improbable.

When harvest time is nearing (end of October), this decreased soil moisture is translated to crops ripening too early, and a clear gradient towards greenness when moving away from the gully was observed (Figure 4B). The average proportion of green pixels over all 65 transects at 1 to 5 m from the gully bank (0·113) was 15% less than in the zone 40 to 50 m from the gully bank (0·130). Site-specific variations are, however, high, as indicated by high standard deviations that range between 0·08 and 0·13.

The Effect of Subsurface Geomembrane Dams

In general terms, small headwater catchments in Northern Ethiopia contain sloping phreatic aquifers that recharge during the rainy season and that dry out during the dry season (Walraevens *et al*., 2009). The build-up of aquifers can be observed in the field, as seasonal springs develop at lower elevations (often at contact zones with the underlying rock) towards the end of the rainy season. Long-term recordings of piezometric levels indicated that water table depths respond strongly to (successive) rainfall events (Walraevens *et al*., 2009). In valley-floor positions, this results in saturated soils with water tables near the surface in the late rainy season. On the valley flanks, however, groundwater depths may remain deep and only show high levels in periods of high rainfall. This is especially true for vertisol areas where subsurface water flow is facilitated by dense networks of soil cracks and pipes (Swanson *et al*., 1989).

Results from the monitoring at the subsurface dam in May Ba'ati show similar patterns to the one described previously. At the headcut of May Ba'ati, located on the lower valley flank, water tables were mostly deep and only rose sharply after rainfall events (Figure 8A–C). However, piezometers closer to the subsurface dams showed water tables that were generally closer to the surface than those more upslope (Figure 8D–E). In addition, the depth of the water tables increased towards the gully channel. These observations indicate (partial) blocking of bypass flow upslope of the subsurface geomembrane dam. On top of that, the proximity of the gully imposed a steep gradient in the water tables. Regarding the effects on vegetation growth 1 year after implementation, the area upslope of the subsurface dam showed greener grass and better soil moisture conditions as compared with the lower side of the dam (Figure 6F). Considering crop growth, healthier denser and taller crop canopies will result in higher NDVI values (Lan *et al*., 2009). Measurements on 9, 18 and 26 September in 2011 showed that, in general, NDVI values were higher further away from the gully and close to the dam, the latter indicating a positive effect of the subsurface dam on crop growth (Moulaert, 2012).

DISCUSSION

Integration of New Measures into a Larger Societal Context

The adoption of soil and water conservation measures in the context of poor dryland countries is dependent on complex socio-economic relations, such as land tenure, education, pressure on the land, institutional control, economic incentives, political stability, social status or long-term planning (Hurni, 1988; Stocking & Murnaghan, 2001; Ananda & Herath, 2003; Bewket, 2007; Tesfaye *et al*., 2013). Given the right context, the sustainability of newly introduced measures to reduce erosion risks is frequently connected to the following: (i) the effect of the measure itself; (ii) the social acceptance and relation to indigenous practices; (iii) cost and feasibility of large-scale implementation and technicality; and (iv) net benefits. When all these factors are met in a satisfactory way, the chances of seeing the introduced measure adopted by local communities become high. Measures that were developed in close interaction with farmers

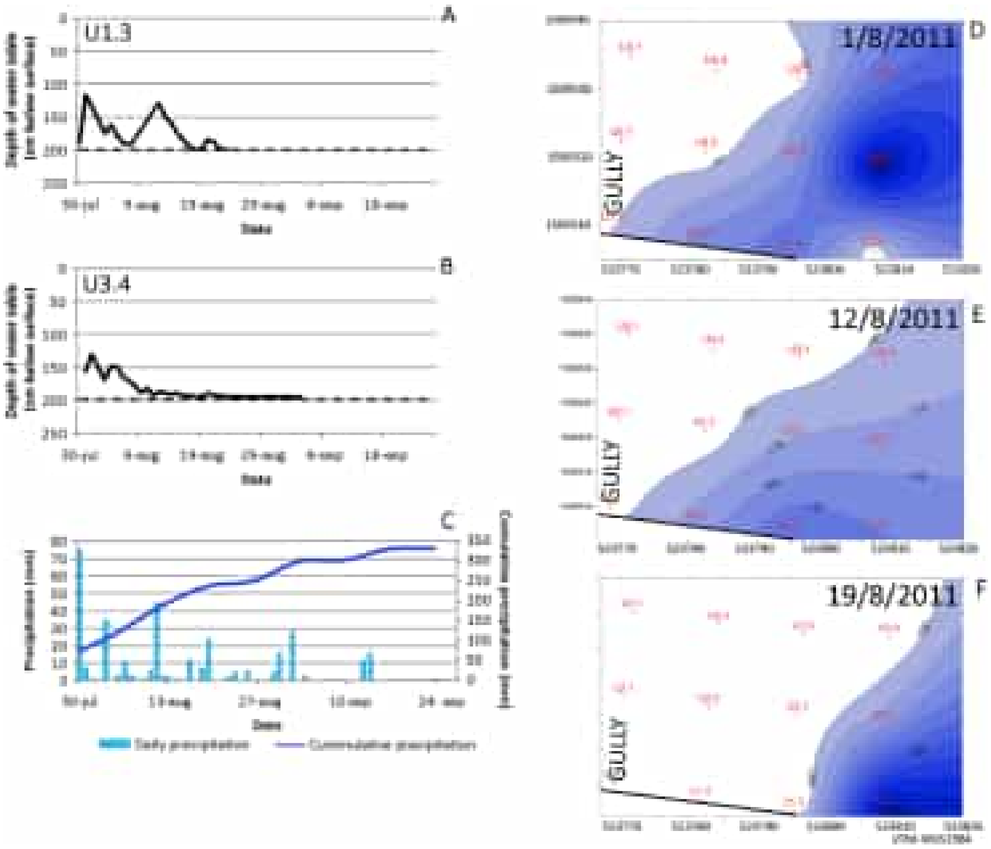

Figure 8. Piezometer readings above the ground surface for (A) U1.3 and (B) U3.4 and (C) precipitation record from a nearby field monitoring station. Groundwater table depth maps for (D) 01/08/2011, (E) 12/08/2011 and (F) 19/08/2011 in relation to the subsurface dam (black line). No colour indicates ground water levels below the 2-m piezometer depth. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

have also a better potential of being adopted (Bewket, 2007; Liniger & Critchley, 2007).

Considering (i), close monitoring of the effects is required over one to several years, in order to observe the impact of variable environmental conditions (Liniger & Critchley, 2007). Rainy seasons in Northern Ethiopia may vary quite a lot in rainfall depth, with alternations between more dry and wet conditions (Jacob *et al*., 2013). Moreover, gully headcuts will especially erode during extreme rainfall events, which do not necessarily occur every year. As shown by Frankl *et al*. (2012), headcut retreat rates in the average rainfall year of 2010 were particularly high at the May Ba'ati gully head. An annual retreat of $1{\cdot}93\,\mathrm{m\,y^{-1}}$ was recorded, which was an outlier in relation to the average of $0{\cdot}34\,\mathrm{m\,y^{-1}}$ for the 24 headcuts in the catchment. In 2011, after the installation of the subsurface dam, the headcut remained in place, and only a large rill developed over a length of 0·62 m upslope of the headcut. The stabilisation of the headcut can, of course, largely be attributed to the constructed check dam. However, the check dam construction remained stable, and bypassing and subsequent collapsing did not occur, even after the particularly strong rains of 2012. The latter caused severe soil piping at check dams in vertisols upslope (with smaller catchment areas) of the geomembrane dam site and, consequently, gully degradation (Figure 2). In addition, four new subsurface dams that were installed in the dry season of 2012–2013 were very efficient during the subsequent rainy season.

Considering (ii), check dams have been widely implemented since many years, and very often, local communities are well aware of their benefits. Many also have good understanding of their technicalities. However, as indicated in this study and by Nyssen *et al*. (2004), check dams frequently collapse or are bypassed in vertisol areas. This strongly discourages farmers to support future implementations of check dams (Bewket & Sterk, 2002). In that regard, the positive effects of subsurface dams on the stability of the check dams can improve the societal perception of the success of gully rehabilitation schemes.

For point (iii), in the context of a low-tech agricultural society and limited financial recourses in general, the cost of the intervention must be kept low (Lapar & Pandey, 1999; Liniger & Critchley, 2007). The geomembrane was purchased from the nearby market. It consists of a thin plastic sheet that serves multiple purposes, like isolating roofs against infiltrating rainfall. Local market prices may vary, but in the period 2010–2012, 50 m of 2 m wide geomembranes could be purchased for ca 2·6 US dollars. The installation of the subsurface dam only requires digging a trench that can be performed from local labour force, that is, farmers from the relevant fields. Like for the construction of check dams and other soil and water conservation structures in Ethiopia, this could be framed into Food for Work programmes.

Net benefits (iv) on the short term are also a prerequisite to adopt an intervention by the society (Hurni, 1988). Environmentally conscious farmers may be interested in reducing soil erosion by gullying and therefore willing to support erosion-control interventions on their fields. However, the direct benefits for their livelihood may not always be so clear, and therefore, locals may not support new interventions (Lapar & Pandey, 1999; Bewket, 2007). As pointed out by Yitbarek *et al*. (2010), this is especially true for gully rehabilitation, as large investments are needed to rehabilitate gullies, with no guarantee of equal returns. The rehabilitation of gullies should therefore, where possible, be designed in such a way that it can maximally benefit the local economy. In a dryland environment, crop production is mainly limited by water stress. Gullies temporally contain water after rainfall events important enough to produce run-off and may hold a permanent flow when draining the water table at the end of the rainy season. However, this water is normally not available for the local society as what often occurs as strong flash floods. Diverting the water from the gully may create a new incision along the diversions. Large fractions of the gully systems are, however, stabilising in Northern Ethiopia (Frankl *et al*., 2011, 2013b), and strong flash floods do not occur any longer in well-managed catchments or only occasionally. As shown in Descheemaeker *et al*. (2009), water flow in such gullies can be diverted into exclosures to enhance vegetation growth or into cropland for irrigation. Moreover, this will reduce run-off discharges in the downslope gully, decreasing the erosivity of the floods. For the exclosures, the additional water can support new economical activities like the establishment of a tree nursery and bee-keeping sites, which can strongly improve the cost–benefit ratio of established exclosures (Figure 9). As indicated by Balana *et al*. (2002), the economic value of exclosures is often low for local societies so that the risk in (re)conversion to agricultural land in the long term remains high. It is critical, however, to ensure that deep percolation of the additional water resources does not initiate landsliding (Moeyersons *et al*., 2008), and thus, drainage to thick colluvial deposits should be avoided.

Figure 9. Gully flow diversion into the exclosure allows the diversification of the local economy by making run-off water available. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

CONCLUSION

Soil piping is a major control of gully development and can strongly reduce the effectiveness of gully rehabilitation measures such as check dams. In dryland environments, dispersive heavy clay soils like vertisols are especially prone to soil piping. In order to enhance the stabilisation of gully heads and increase the stability of check dams, subsurface geomembrane dams were tested in this study as a cheap and low-tech measure in order to block subsurface flow in soil pipes. With the rising of water tables, positive effects can be expected in terms of decreased bypass flow upstream of check dams and in terms of increased crop yields in the intergully areas, as soil desiccation near gullies is decreased. Moreover, the diversion of run-off into adjacent exclosures enhances biomass production, tree growth and biodiversity that can support other economic activities (biomass extraction and bee-keeping).

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