https://doi.org/10.5194/egusphere-2024-1125
Preprint. Discussion started: 24 April 2024

Gully rehabilitation in Southern Ethiopia – value and impacts for farmers.

Wolde Mekuria[1], Euan Phimister[2,5], Getahun Yakob[3], Desalegn Tegegne[1], Awdenegest Moges[4], Yitna Tesfaye[4], Dagmawi Melaku[1], Charlene Gerber[5], Paul D. Hallett[6], Jo U. Smith[6]

1 International Water Management Institute (IWMI), Nile Basin and East Africa Office, P. O. Box 5, Addis Ababa, Ethiopia.
2 Business School, University of Aberdeen, Aberdeen AB24 3FX, UK.
3 Southern Agricultural Research Institute, P.O. Box 6, Hawassa, Southern Nation Nationality People Regional State, Ethiopia
4 Hawassa University, P. O. Box 5, Hawassa, Ethiopia.
5 Stellenbosch Business School, Stellenbosch University, Cape Town, South Africa.
6 School of Biological Sciences, University of Aberdeen, Aberdeen AB24 3UU, UK.

Correspondence to: Wolde Mekuria (w.bori@cgiar.org)

Abstract. Gully erosion can be combatted in severely affected regions like sub-Saharan Africa by a range of low-cost interventions that are accessible to affected farmers. However, for successful implementation, biophysical evidence of the effectiveness of interventions needs to be combined with buy-in and input from local communities. Working with farmers in a watershed in Southern Ethiopia, we investigated (a) the effectiveness of low-cost gully rehabilitation measures to reduce soil loss and upward expansion of gully heads, (b) how farmers and communities view gully interventions, and (c) whether demonstrating gully interventions in-context changes farmers' knowledge and perceptions of their capacity to act. On-farm field experiments, key informant interviews, focus group discussions and household surveys were used to collect and analyze data. Three gully treatments were explored, all with riprap, one also with grass planting, and one with grass planting and check-dam integration. Over a period of 26 months these low-cost practices ceased measurable gully head expansion, whereas untreated gullies had a mean upward expansion of 671 cm resulting in a calculated soil loss of 11.0 tonnes. Farmers viewed these gully rehabilitation measures positively, apart from the high cost of input materials and technical requirements of gabion check-dams. Ongoing rehabilitation activities and on-farm trials influenced knowledge and understanding of similar gully treatments among survey respondents. On-farm experiments and field day demonstrations empowered farmers to act, addressing pessimism from some respondents about their capacity to do so.

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1 Introduction

Land degradation caused by gully erosion is one of the most persistent and complex global environmental problems (Poesen et al. 2003; Menendez-Duarte et al. 2007), resulting in a significant loss of key environmental services (SDG Report 2019). For example, gully erosion contributed up to 70% of soil loss in each of the Loess Plateau of China (Cheng et al. 2007), the northwestern highlands of Ethiopia (Dagnew et al. 2017) and selected areas of the United States (Bernard et al. 2010). Multiple environmental (Tebebu et al. 2010; Conforti et al. 2011; Conoscenti et al. 2013), and anthropogenic factors (Moges and Holden, 2009; Jahantigh and Pessarakli 2011; Asmamaw et al. 2012; Asres et al. 2016; Alem 2022) contribute to the initiation and development of gullies and gully erosion in a landscape.

Although gully erosion is a global problem and occurs in all geographical areas (Menendez-Duarte et al. 2007), Africa is the worst-hit continent (Were et al. 2023). Around 20 to 25% of the land area of Sub-Saharan Africa (SSA) is severely affected by gully erosion (FAO 2001). An assessment of gully erosion in Tigray in northern Ethiopia, found that it accounted for 28% of the average total soil loss of 14.8 t ha^{-1} y^{-1} measured over a 4-year period (Nyessen et al. 2008). In southern Ethiopia, measurements of soil erosion within gullies ranged from 11 to 30 t ha^{-1} yr^{-1} (Belayneh et al. 2024). The economic costs of soil loss due to gully erosion are high; for Kenya, this was estimated to be equal to total agricultural exports (Cohen et al. 2006). These costs are experienced mostly by rural communities, particularly poorer households, who generate much of their income from the land (Mekuria et al. 2023). Severe gully erosion affects the livelihoods of rural communities in several ways, including the degradation of croplands (Yitbarek et al. 2012; Yazie et al.2021), land fragmentation (Frankl et al. 2011), reduced livestock carrying capacity of rangelands (Adimas et al. 2021; Alem 2022), limitation of movement (Worku and Tripathi 2015) and death (Moges and Holden, 2008) of both humans and livestock , and increased siltation of freshwater ecosystems and destruction of water infrastructure (Degife et al. 2021).

Across the different countries of the world, there are several development initiatives aimed at controlling gully erosion (Simpson 2010). However, one of the biggest challenges in controlling gully erosion is that once the soil has degraded and gullies have formed, complex measures are required to stop their expansion. The rehabilitation of big gullies usually takes several decades and requires huge financial resources (Poesen et al. 2003; Nasri et al. 2008; Perroy et al. 2010). Available technologies need to be contextualized to a specific site to be effective, considering costs, labour and available resources in addition to the physical challenge (Blake et al. 2018; Shi et al. 2019; Wen et al. 2021; Bai et al. 2023). In poorer countries the challenge is greater. Ethiopia is an example, where gully erosion is severe and has profound environmental and economic implications (Yitbarek et al. 2012; Erkossa et al. 2015).

In response to these problems, gully erosion controlling measures have been implemented in Ethiopia as part of the national soil and water conservation initiatives since the 1980s (Haregeweyne et al. 2015). These initiatives include Food-for-Work (FFW) (1973–2002), Managing Environmental Resources to Enable Transition to more Sustainable Livelihoods (MERET, 2003–2015), Productive Safety Net Programs (PSNP, 2005–present), Community Mass Mobilization through free-labor days

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(1998–present), the National Sustainable Land Management Project (SLMP, 2008–2018) and Climate Action Through Landscape Management (2019 – present). Despite decades of interventions, the problem has, in fact, worsened rather than improving, and more communities are being affected than ever before (Steenmans 2017; Belayneh et al. 2020). This suggests the need for context specific measures and understanding of the right time to implement gully rehabilitation (Kropacek et al. 2016). Rabinovich et al. (2022) demonstrated that providing better knowledge and understanding can increase farmers' intention to adopt measures to prevent soil erosion.

Previous soil and water conservation interventions show that farmers and communities are more likely to adopt and maintain measures when scientific and local knowledge and circumstances are well integrated (Amsalu and de Graaff 2006; Haregeweyn et al. 2015). Ethiopian farmers are aware of the importance of gullies on soil erosion but addressing their impacts has typically arisen from participation in communal land development activities rather than measures which a farmer might take on their own land (Menginstu and Assefa 2020). For individual farmers, soil and water conservation measures can be perceived as requiring too much labour to be implemented on their own land (Bewket 2007).

To counter this, a number of field experiments in Ethiopia have explored whether low-cost interventions, accessible to individuals or small groups of farmers on their own land, are effective in preventing and rehabilitating gullies at an early stage of their development. Barvels and Fensholt (2021) suggested that vegetative measures are effective rehabilitating gullies in the Highlands of Ethiopia. Similarly, studies by Belay and Bewket (2012) and Addisie et al. (2018) indicated that integrated measures (i.e. both physical and biological measures) were most effective in controlling gully erosion and converting gullies into productive land. Addisie et al. (2018) reported that re-grading gully heads and banks, and adding stone riprap at the gully heads were effective ways to stop the upward expansion of gully heads and control the expansion of gullies.

A link between farmers' perceptions and their willingness to adopt effective gully erosion mitigation strategies will draw together socioeconomic drivers with biophysical evidence. Therefore, the key contribution of this study arises from the combination of such on-farm field experiments with a range of quantitative and qualitative analyses to explore how farmers and communities view gully interventions and whether demonstrating farm field experiments in-context changes their knowledge and perceived capacity to act.

Similar practices are deployed globally to tackle gully erosion, but in the global south, low-cost options that can be established by communities are far more common. An example is Halaba district in southern Ethiopia, which is particularly prone to gully erosion, and contains simple indicators such as networks of small and medium gullies as well as big gullies are common (Mekuria et al. 2023). We use this region as a case study to interpret both biophysical and socioeconomic drivers of gully rehabilitation measures, but the research has wider applicability to other regions and fills a major knowledge gap bridging impacts on people and the environment. We first investigated the effectiveness of low-cost gully rehabilitation measures to reduce the upward expansion of gully heads and soil loss using a series of on-farm field experiments. The understanding of the community and individuals of gully management practices was then explored. Key informant interviews provided base

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information to assess the drivers, pressures, state, impact and responses for gully erosion in the communities, while focus group discussions were used to assess the benefits and costs of multiple gully rehabilitation measures from the perspective of the local communities. Finally, household survey information from similar areas with and without the on-farm field experiments was used to evaluate whether the field experiments and the dissemination activities within the community's changed knowledge, perceived capacity and ability and intention to take measures to address gullies. By including farmers in our investigation of gully mitigation strategies, our goal was to identify policies and practices that would be the most effective, acceptable and practical to implement.

2 Methods

2.1 Study area

This study was conducted in Aba-Bora watershed, Halaba, Southern Ethiopia (Figure 1). Selected characteristics of the watershed are summarized in Table 1 (Mekuria et al. 2023). Households in the Aba-Bora watershed make their livelihood mainly from a subsistence mixed crop-livestock farming system (Mekuria et al. 2023). A number of households also engage in off-farm and non-farm activities. However, agriculture and crop sales income in particular, account for over 80% of household incomes, with the remaining coming from external sources (Mekuria et al. 2023).

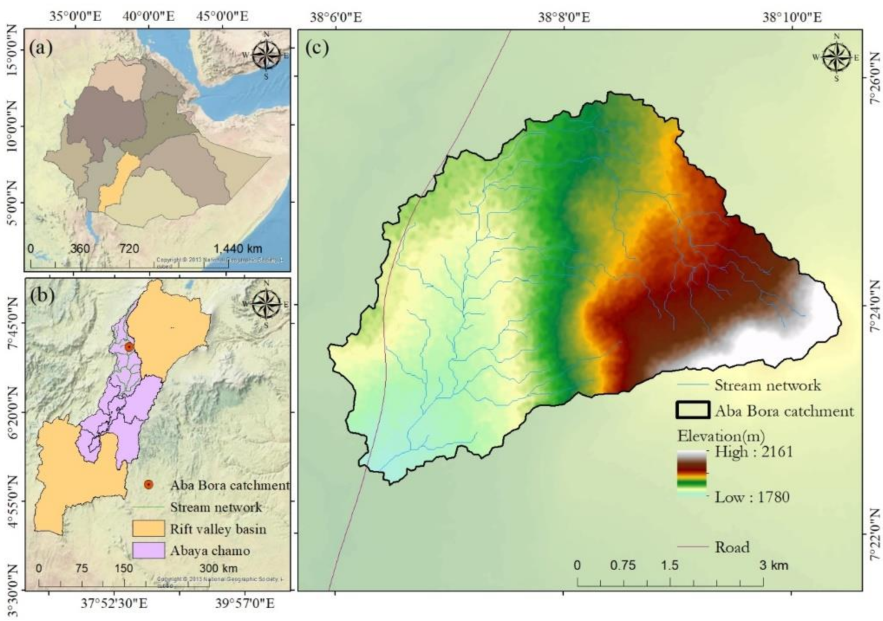

Figure 1: Location map of the study area, Aba-Bora watershed, Halaba, Southern Ethiopia. *Source: Authors' creation*

Declining soil fertility, severe soil erosion, reduced access to surface and groundwater, and poor water quality are the main socio-economic and environmental challenges in the studied watershed (Sinore and Umer 2021). In particular, gully erosion (Figure 2) is one of the main causes of land degradation, manifested by deep gullies that are being exacerbated by increased deforestation in the upstream areas (Mekuria et al. 2023), soils susceptible to soil erosion (Yakob et al. 2022) and a shift from

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livestock to crop-based agriculture (Byg et al. 2017). The lack of low-cost gully rehabilitation technologies and the awareness of local communities for addressing gullies at the early stage of gully initiation and formation also contributed to the expansion of gullies (Addisie et al. 2017).

Table 1. Selected characteristics of Aba-Bora watershed (Mekuria et al. 2023).

Site characteristics	Values
Area (km^2)	28.91
Elevation (m)	From 1780 to 2161
Dominant land use and land cover	Croplands
Rainfall distribution	Bimodal
Duration of long rainy season	July – September
Duration of short rainy season	March - May
Monthly rainfall during long rainy season (mm)	Ranges from 100 to 146
Monthly rainfall during short rainy season (mm)	Ranges from 20 to 143
Annual rainfall (mm)	Ranges from 752 to 1272
Mean annual temperature (ºC)	Ranges from 19 to 22
Average Education (Years in School)	2.182
Average Family size	6.472
Average landholding (Timad)**	3.843
Tropical Livestock Units	2.985

***Note**: Timad is equivalent to 0.25 ha of land.*

2.2 Study design

To gather and analyze data, the study employed both quantitative and qualitative methods, including on-farm field experiments, key informant interviews, focus group discussions and household surveys. The on-farm field experiment was established in 2021 to investigate the effectiveness of low-cost gully rehabilitation measures to reduce the upward expansion of gully heads and associated soil loss. In this study, low-cost gully rehabilitation measures refer to interventions that can be implemented with farmers capacity or with limited external support.

Nine paired gullies (i.e. treated and untreated) with depths less than 3 m were selected (Table 2). The study considered three low-cost gully rehabilitation measures as treatments (Figure 2) and each of the treatment was replicated three times. The treatments were (1) regrading the gully head (45º) by establishing stone riprap (Riprap treatment); (2) regrading the gully head and gully bank by establishing stone riprap at the gully head and planting grasses on the gully banks (Riprap-grass planting integration treatment); and (3) regrading the gully head and gully bank by establishing stone riprap at the gully head, planting grasses on the gully banks and constructing small sandbag check-dams (Riprap-grass planting-check-dam integration treatment).

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Table 2. Dimensions of treated and control gullies.

	Replication one		Replication two		Replication three	
	Treated	Control	Treated	Control	Treated	Control
Treatment one						
Average depth (m)	2.7	2.7	1.2	1.2	1.3	0.8
Average width (m)	5.8	5.3	2.8	3.8	2.5	2.1
Average length (m)	27.0	23.0	16.0	18.0	25.0	27.0
Coordinates						
x	38.134535	38.184920	38.132695	38.133720	38.132406	38.132295
y	7.383361	7.323133	7.381327	7.383768	7.3839	7.384105
z	1856	1868	1853	1866	1856	1860
Treatment two						
Average depth (m)	2.2	0.8	2.1	1.5	1.1	0.7
Average width (m)	4.3	1.8	5.3	5.0	2.1	1.2
Average length (m)	26.5	34.0	20.2	17.0	22.0	14.0
Coordinates						
x	38.132318	38.132303	38.133043	38.132303	38.132540	38.132470
y	7.382736	7.382705	7.382736	7.382736	7.384143	7.384105
z	1847	1845	1864	1845	1850	1862
Treatment three						
Average depth (m)	1.7	1.9	1.3	0.8	2.8	3.5
Average width (m)	4.6	4.5	3.4	3.3	4.6	4.5
Average length (m)	24.6	26.0	32.6	28.0	25.4	15.0
Coordinates						
x	38.13575	38.13575			38.133720	38.133658
y	7.38	7.38			7.383768	7.383731
z	1875	1876			1866	1854

According to Yakob et al. (2024, unpublished), the soil in the study area exhibits a high clay content in the subsoil than in the topsoil, an argic subsoil horizon, and a high base saturation in the 50–100 cm depth. Accordingly, the soil in the study area is classified as Luvisols. Selected characteristics of the soil in the study area are summarized in Table 3.

Table 3. Physicochemical properties of soils in the study area.

Horizon	**Depth (cm)**	%Sand	%Clay	%Silt	Textural class	pH	CEC Meq / 100 g soil	%OC	P mg/kg	Na mg/kg
A	0-26	38	28	34	Clay loam	6.82	43.52	4.44	4.26	141.18
Bt1	26-43	14	44	42	Silty clay	7.18	43.74	3.83	3.95	316.63
E	43-110	46	24	30	Loam	7.75	42.22	2.59	3.01	558.31
Bt2	110-132	18	44	38	Clay	7.38	51.63	2.14	5.52	580.18
E'	132-180	18	28	54	Silty clay loam	7.70	51.48	2.01	3.55	538.46
Bt3	180-200+	14	36	50	Silty clay loam	7.37	49.51	1.85	4.45	473.30

In order to promote knowledge and understanding of the experiments in the community and as part of the joint evaluation of field experiments, a field day was organized in the treated kebele in November 2022 in collaboration with the Southern

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Agricultural Research Institute (SARI) and woreda and zonal agricultural offices. The field day focused on the demonstration of gully head treatments and gully bank stabilization, as well as incentives used to support the sustainable management of land resources. More than 55 participants comprise of farmers, extension agents, experts from district, zonal and regional levels agricultural offices, and local administrative bodies attended the field day to observe ongoing natural resource management activities and share ideas.

Figure 2. Severe gully erosion in Aba-Bora and low-cost mitigation options *Picture credit @Wolde Mekuria*

Key informant interviews were conducted to understand the system and assess the drivers, pressures, state, impact and response (DPSIR) to gully erosion and develop the conceptual DPSIR framework of the interventions for gully erosion and formation. DPSIR was adopted as it has been widely deployed to provide a causal framework to link environmental and social processes (Kristensen 2004). Twenty-five key informants consisting of 8 local practitioners (district and zonal agricultural offices), 10 knowledgeable farmers, 2 NGOs, 2 cooperatives and 2 civil societies/community-based organizations and 1 local administrative body were selected.

Two focus group discussions (separate men and women) were conducted to assess the costs and benefits of five gully rehabilitation measures from the perspective of local communities. The assessed gully rehabilitation measures included those evaluated in the field experiments and commonly implemented in the study area. These were gully-head treatment, gully reshaping and planting grasses, loose rock check-dams, vegetation log check-dams and gabion check-dams. During the focus

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group discussions, the selected gully rehabilitation measures were first discussed (i.e. the practices were presented using understandable descriptions in the local language and confirmed by the participants). Second, the advantages and disadvantages of each gully rehabilitation measure were identified from the perspective of the local communities. Third, the participants were asked to rate the importance of each identified advantage and disadvantage (i.e. giving 3 points for the most important, 2 for the intermediate and 1 for the least important one). Fourth, the participants assigned an overall rating for each practice or intervention (i.e. rating each practice or intervention as positive, negative, or neutral).

Two household surveys were conducted in 2021 and 2023 in the Aba-Bora and nearby Guder watersheds in localities (kebeles[1]) where land was judged to be highly degraded with big gullies present. This included the kebele where the on-farm field experiment took place. In 2021, data were collected from 522 households (including 123 from the kebele where the on-farm field experiment took place). In 2023, a follow-up survey collected data from 500 households, of which 451 could be identified as the same respondents (including 114 where the on-farm field experiment took place). The sample represented a random sample of households drawn from lists provided by each kebele administration after stratification based on wealth and gender status. The data were collected during February and March in each of 2021 and 2023 using a team of enumerators employing tablets, with the questionnaires available in both English and the local language Amharic.

2.3 Data collection and analyses

Following the establishment of the treatments, we monitored the upward expansion of gully heads in the treated and control gullies at different intervals, after 4, 9, 12, 17 and 26 months. To monitor the upward expansion of gully heads, first we installed pegs at 1 and 2 meters from the gully head in both treated and control gullies. Then, we selected a permanent reference point and measured the distance from the reference point to the second peg. We did this to relocate the position of second peg in case it is removed due to the upward expansion of gully heads with time. In addition, we measured the depth and width of the upward expanded part of gullies at the end of the project period (i.e. 26 months after the establishment of treatments) to estimate the amount of soil loss during the period of investigation. Erosion further down the gully was not accounted for in our study.

We used semi-structured questionnaires and checklists to gather data from survey participants, key informants and participants of focus group discussions. The key discussion points with key informants included causes and severity of gully erosion, existing gully rehabilitation measures, effectiveness of responses to address gully erosion, management, and allocation of natural resources and on the key changes following the implementation of gully rehabilitation measures. Data gathered through focus group discussions included costs and benefits of gully rehabilitation measures, an evaluation by communities of the importance of gully rehabilitation measures (i.e. ranking of costs and benefits of assessed measures), and farmers priorities for gully rehabilitation technologies.

[1] Kebeles are typically localities containing around 500 households, with an administrative centre around which agricultural extension is typically organized.

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The qualitative data collected through key informant interviews and focus group discussions were analyzed using content analysis (Hsieh and Sannon 2005; Bernard 2006; Elo and Kyngas 2008). For qualitative analyses, we developed a coding scheme based on the main thematic areas, including items such as drivers of gully erosion and formation, pressure on the natural resources, response of gully erosion, impacts of gully rehabilitation measures, and decision-making processes. Deductive coding was then employed using codes such as severity of gully erosion, types of drivers and impacts, and types of interventions. During the coding process, more codes were added when new issues emerged from the textual data. In addition, codes were merged, removed, or modified to avoid repetition and resolve disagreements between codes.

The 2021 and 2023 household surveys included a series of questions exploring respondents' knowledge, attitudes and behaviour with respect to land degradation and gullies. The 2023 survey included several more specific questions on gullies, drawing on the nature of the on-farm experiments. The data from respondents in the kebele where on-farm experiments took place (the "treated") were used to compare to those without farm experiments (the "non-treated") to explore the potential impact of the on -farm experiment. Where identical questions were asked in both 2021 and 2023 surveys, the impact of the on-farm experiment was examined using a panel difference in difference approach, controlling for individual fixed effects and a common trend (Glewwe and Todd, 2022). The more specific questions on gullies, asked in 2023 only, were analysed using a simple comparison between the one treated and non-treated kebeles.

3 Results and discussion

3.1 Gully head upward expansion and soil loss

The results indicated that all treated gullies displayed zero upward expansion irrespective of the types of gully treatment, whereas increasing upward expansion of gully heads was observed in the untreated gullies (Figure 3). For example, the mean upward expansion of gully heads in the untreated gullies varied between 15 and 23 cm after four months of establishment of treatments. These values ranged from 78 to 463 cm after 18 months and then varied between 467 and 1080 cm after 26 months since the establishment of treatments (Figure 3). Over a period of 26 months, the mean upward expansion of untreated gullies increased from 19 to 671 cm. Assuming a bulk density of 1.2 – 1.5 g cm^{-3}, the estimated soil loss due to the upward expansion of gully heads in the untreated gullies ranged from 2.8 to 20.2 tonnes, with a mean value of 11.0 tonnes. This calculated value was zero in the treated gullies, reflecting the effectiveness of interventions in halting the upward expansion of gully heads and reducing soil loss.

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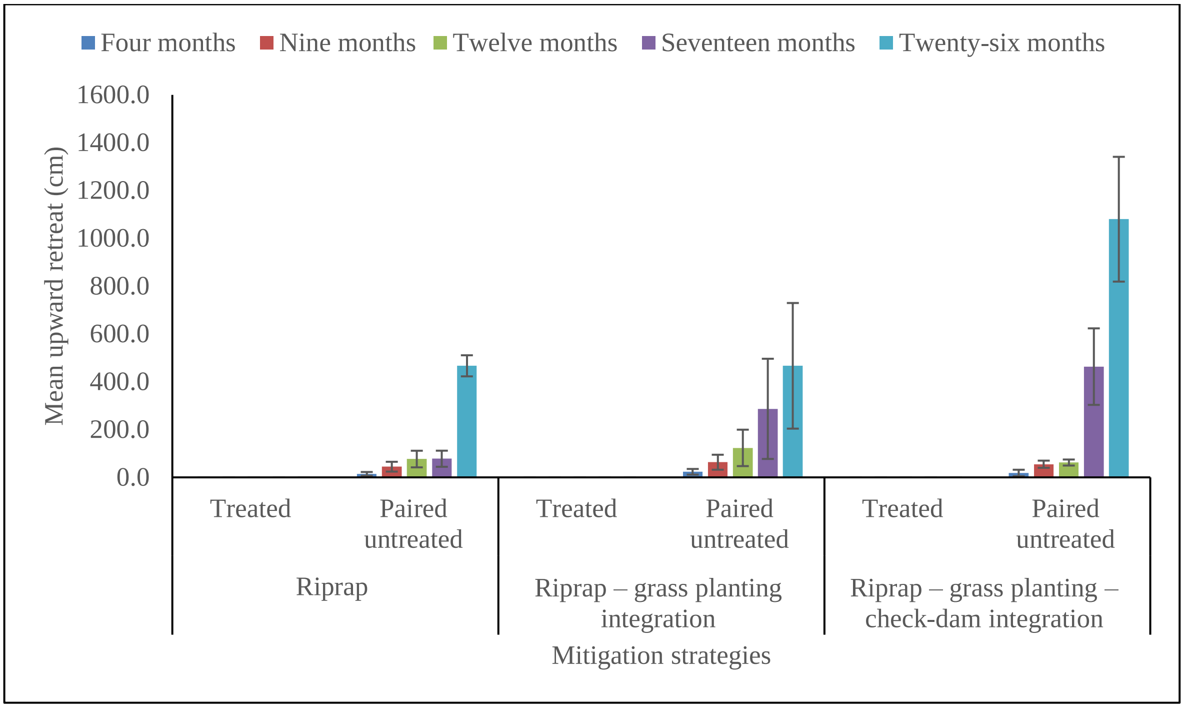

Figure 3: The mean upward expansion of gully heads in the treated and control gullies. Each treatment had separate control gullies as described in the study design. This was done because the gullies were spatially distributed, and a single control cannot work. The values for the upward expansion of gully heads for treated one was zero.

3.2 The drivers, pressures, state, impact and response for gully erosion and formation

All respondents indicated that gullies usually initiated in the upstream areas and took the form of rill erosion. Over time the rills got longer and deeper in the mid- and foot-slope landscape positions to form gullies. The density and depth of gullies increased from mid-slope positions, but only in a few locations, to foot-slope position, suggesting that gullies are unevenly distributed within the watershed. The key informants identified multiple human induced, natural and climatic drivers of gully erosion and formation (Figure 4). About 80% of the respondents characterized the severity of gully erosion as very severe, while the remaining 20% of the respondents characterized gully erosion as severe, causing environmental, social and economic impacts. The identified impacts suggest that gully erosion has both long- and short-term negative impacts that affect the livelihood of local communities (Figure 4). The respondents also mentioned multiple initiatives implemented in the watershed to address gully erosion. These initiatives covered multiple dimensions; capacity building, providing technical support and implementing diverse interventions or measures (Figure 4). The commonly implemented gully rehabilitation measures included check-dams (loose rock, sandbags and gabion check-dams), biological measures such as planting multipurpose tree species and grasses on gully banks, and gully head treatments.

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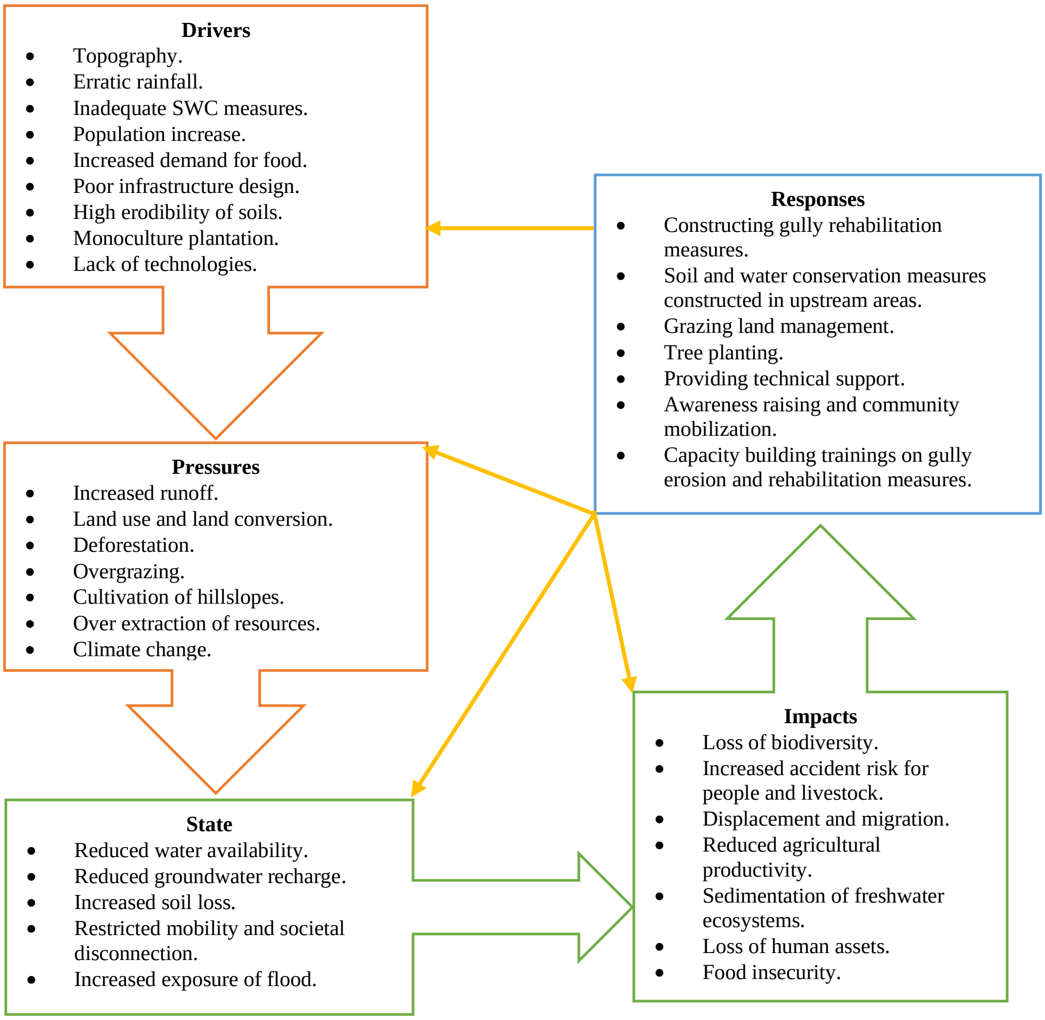

Figure 4: Conceptual drivers, pressures, state, impact and response framework for gully erosion and formation.

The majority (90%) of key informants indicated that the implemented gully rehabilitation activities were successful, though not adequate compared with the severity of the problem. These respondents further elaborated that the rehabilitations measures reduced soil erosion and converted degraded lands to productive lands. Particularly, gully rehabilitation measures supported the restoration of degraded lands in several ways, including through reducing expansion and upward expansion of gullies, reducing runoff and soil loss and promoting changes in cultivated and grazing land management (Figure 5). The key role of gully rehabilitation measures in reducing runoff and soil loss was attributed to the capacity of the measures to reduce the speed of runoff, retain soils and facilitate the growth of grasses in the retained soil. The contribution of check-dams to cultivated and

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grazing land management was mainly through converting degraded areas into productive land or reducing degradation (i.e. increasing access to land) and improving the production of livestock feed and crops. Furthermore, key informants suggested that gully rehabilitation measures enabled farmers to diversify their crops to grow cereal, vegetables and fruit. This was mainly attributed to reduced soil loss that resulted in enhanced soil nutrient retention and sometimes the accumulation of sediments at the back of check-dams. One of the key informants elaborated this as:

> *"Farmers who migrated have started to come back and grow cash crops such as khat, vegetables and maize due to the improvement of soil fertility. Particularly, this is observed at the downstream areas of each treated gullies*".

In relation to the contribution of gully rehabilitation measures to livestock production, one of the key informants stated:

> "*Decades ago, households used to have more than 30 livestock on average, however, the expansion of overgrazing and shortage of livestock feed forced them to reduce the number of livestock. Following the recent community-based watershed development activities, including gully rehabilitation works, the number of livestock per household is increasing due to increased production and availability of livestock feed from restored areas and gullies*".

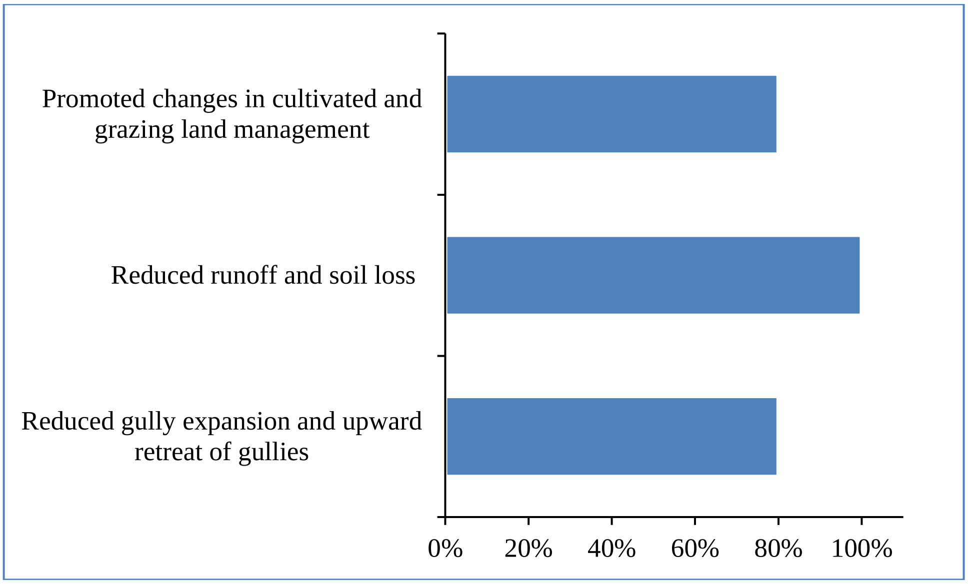

Figure 5: Mechanisms by which gully rehabilitation measures restore degraded lands. Numbers indicate the proportion of key informants that mentioned the specific mechanisms. The sum of numbers is greater than 100%, as a respondent can mention multiple ways.

The ongoing rehabilitation activities were also key to establishing community awareness about the negative consequences of gully erosion and the need for collective action to control gully erosion. The respondents mentioned that providing continuous technical support was key to enhancing the effective implementation and sustainability of gully rehabilitation measures, particularly biological measures. However, a few (10%) of the respondents stressed that it was hard to judge the success of interventions compared to the challenges of gully erosion.

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The results of key informant interviews suggested that gully erosion can be addressed by individual or collective actions. Particularly, the respondents mentioned that small gullies (having less than 3 m depth) can be rehabilitated using locally available materials and capacities. However, once the gullies get large and deep, it is beyond the capacity of local communities to rehabilitate them. The decisions on the planning, design and implementation of gully rehabilitation measures combined both bottom – up and top – down approaches. At the local or kebele level, a community watershed team was the key decision-maker, dictating interventions areas, types of interventions, and the labor and material contributions of communities. However, there were also cases where the regional bureau and zonal departments allocated a quota (e.g. types and quantity of interventions) to each district and kebele. The regional and zonal departments and NGOs were also involved in providing technical, material and financial support.

Community level decisions in relation to gully rehabilitation measures are usually related to the contribution of free labor and locally available materials. Our survey found this extended beyond building materials, such as stone and wood, to equipment and tools required for construction. In line with this, the community watershed team closely worked with kebele and district level experts to decide on community mobilization. This determined who participated, the types of interventions and the use of material and labor. There were also household-level decisions that could be implemented by individual households, such as taking measures to prevent runoff from entering their houses and farmlands. These practices were usually done through constructing wooden or vegetation check-dams, water harvesting structures and bunds (on and around their farmlands), and homestead plantations. The key informants also indicated that there were some individuals who were aware of gully erosion and so took their own actions around the homestead (e.g. planting trees, gully head treatment).

The results indicated that there were some local level strategies used to implement and sustain interventions. This included the use of informal platforms such as Idir (self-support groups), Iqub (voluntary cooperatives) and bylaws, and working closely with formal institutions to enforce laws and protect interventions from free-riders. Incentive mechanisms for landless young people and women were also among the strategies to effectively manage gully rehabilitation measures. Furthermore, the use of locally available materials, and involving elders and religious institutions in awareness creation campaign, were among the strategies to sustainably implement gully rehabilitation measures.

The key informants mentioned multiple sources of information. A majority (40 - 60%) of the respondents indicated that the key sources of information were the ongoing gully rehabilitation activities, personal experience and observation. The key limitation of gully rehabilitation measures constructed using locally available materials was the short lifespan of physical interventions, such as sandbags or log check-dams, but when they were combined with vegetation, the longevity of the intervention improved. Our findings suggest that most of the gully rehabilitation measures were well received by the communities, with the only concern being a temporary loss of access to their land or resources during construction. Out scaling or wider implementation of gully rehabilitation measures was constrained by shortage of personal working equipment (mentioned by 30% of the respondents), limited access to inputs and raw materials (30%), increasing prices of inputs (e.g. gabion wires, 60%), high labor demand (10%), technical requirement (30%) and limited sources of finance (10%).

3.3 Costs and benefits of gully rehabilitation measures from the perspective of local communities

Participants of focus group discussions representing men and women identified 24 benefits (or advantages) and 17 costs (or disadvantages) of five gully rehabilitation measures assessed in Aba-Bora watershed (Supplementary materials 1 and 2). Across both focus groups, the number of benefits identified for most of the gully rehabilitation measures were higher than the costs (Figure 6). There were gender differences in perceived costs and benefits. While female groups identified equal numbers of costs and benefits for loose rock check-dam, male groups felt the benefits were greater than the costs. An opposite trend between genders was observed for gabion check-dam (Figure 6). Both women and men groups identified more benefits for gully reshaping and planting, indicating that there was a consensus among the two groups regarding the benefits of this intervention. Both groups identified comparable numbers of benefits and costs.

The benefits were diverse (Supplementary material 1) and covered both environmental (e.g. conservation and increased access to water, improved soil fertility, and reduced runoff and soil erosion), economic (e.g. increased agricultural production, reduced farmland loss and increased availability of livestock feed) and social (e.g. movement of people and livestock, reduced damage by flood, and knowledge exchange) categories. Of the 24 identified benefit factors, women were the only respondents to identify (i) the use of locally available materials, (ii) conserving and increasing access to water, and (iii) increased access to productive land. On the other hand, the male group listed eight benefits that were not identified by female groups. These were (i) increased income, (ii) increased access to diverse food, (iii) improved appearance of the landscape, (iv) reduction in damage caused by floods, (v) regulation of micro-climate, (vi) ease of constructing the interventions, (vii) durability of the interventions, and (viii) serving as a learning site (Supplementary material 1). The participants also identified several costs of the assessed interventions or practices that were environmental (e.g. lack of effectiveness in reducing soil erosion and runoff), economic (e.g. high labor demand, cost, shortage of local available inputs), or social (e.g. demand in skilled manpower, technical support) (Supplementary material 2).

Across both groups, the number of environmental benefits identified by the participants were larger than the respective environmental costs (Figure 7). Whereas female groups identified more social costs than benefits, male groups had an opposite opinion (Figure 7). Across both groups, the benefits of the assessed gully rehabilitation measures related more to the environmental and economic benefits, whereas the costs related more to economic and social costs (Figure 7).

The results suggested that the benefits outweighed the costs for most of the interventions, as the mean ratings of the importance values of benefits were greater than the values of costs (Figure 6). The ratings of the importance of benefits assigned by female groups across all the interventions varied between 2.3 and 2.5 (i.e. the rating is out of 3, and 3 represents high importance, 2 – medium and 1-low importance), with a mean value of 2.4, while the ratings of the costs ranged from 1.8 to 2.5, with a mean value of 2.0. The ratings of benefits assigned by male groups varied between 2.2 and 2.8, with a mean value of 2.5, while the ratings of the costs ranged from 2.4 to 2.9, with a mean value of 2.6.

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Apart from gabion check-dams, all other gully rehabilitation measures assessed were evaluated as positive (Table 4). The local communities considered environmental and economic factors more than social factors in their overall assessment of the gully rehabilitation measures (Table 4). This suggested that generating short-term economic benefits was key to sustaining the assessed gully rehabilitation measures, but that associated tangible benefits and ecosystem services were appreciated. The negative overall assessment of gabion check-dams by the local communities was mainly attributed to the high cost of input materials and its technical requirement, which were often beyond the capacity of local communities or farmers.

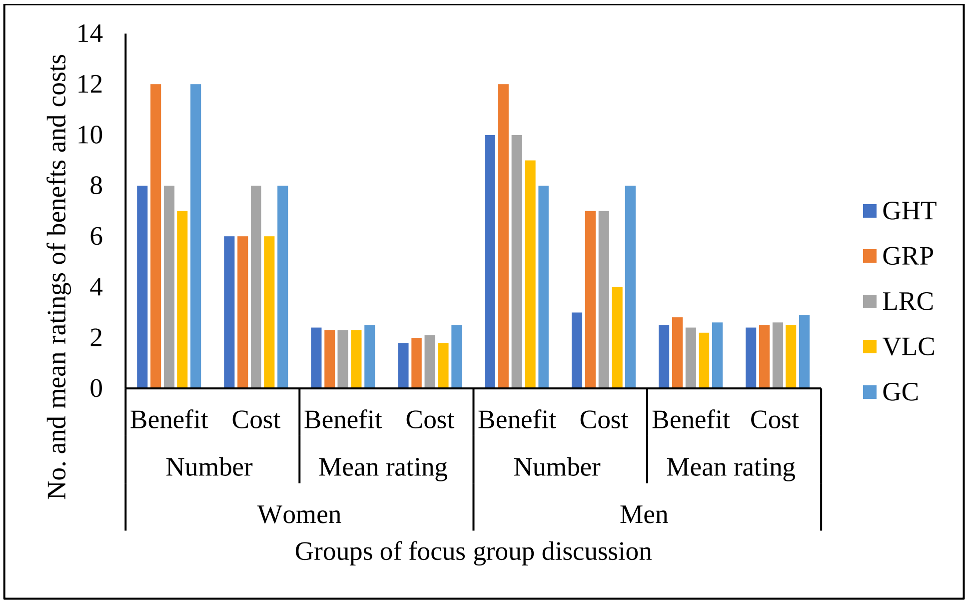

Figure 6: The number and ratings of the importance of benefit and cost factors in the perspective of the local communities. GHT – gully head treatment, GRP – gully reshaping and planting, LRC – loose rock check-dam, VLC – vegetation log check-dam, GC – Gabion check-dam.

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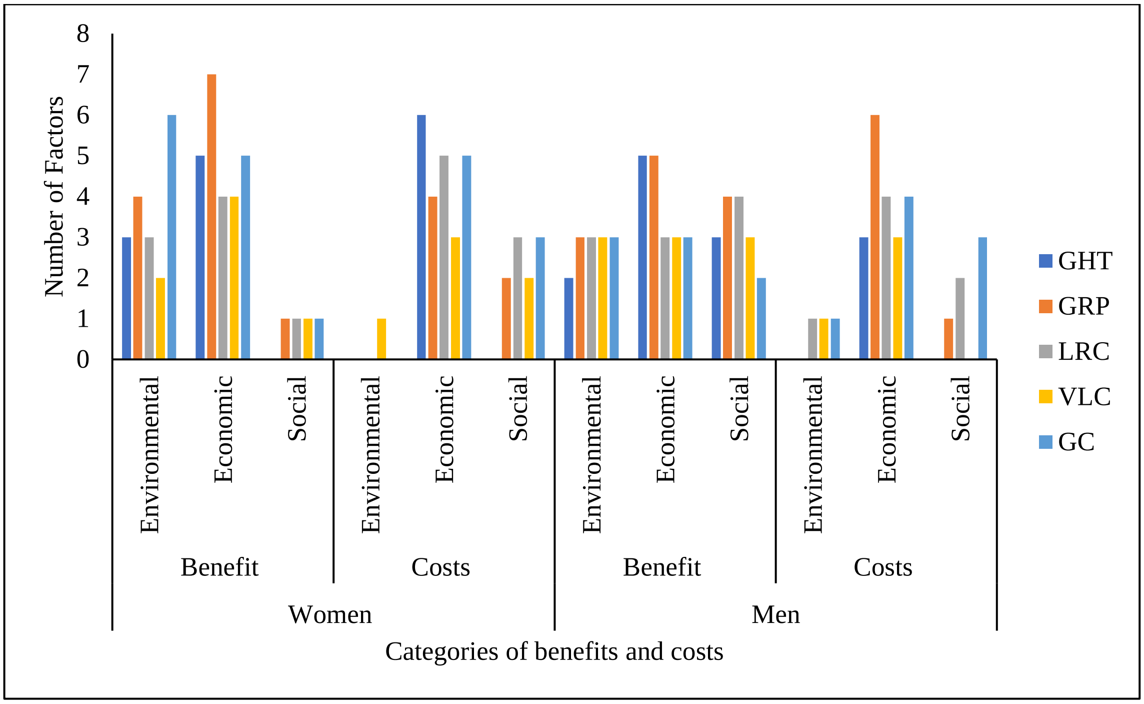

Figure 7: The number of benefit and cost factors under each of the categories of benefits and costs.

360 **Table 4**. Local communities' overall assessment of gully rehabilitation measures.

Gully rehabilitation measures	Overall assessment	Reasons
	Women	
Gully head treatment	Positive	Good water retention and soil conservation.
Gully reshaping and planting	Positive	Good for increased access to grass for livestock.
Loose rock check-dam	Positive	Good performance and has the advantage of water collection.
Vegetation log check-dam	Positive	Easy to construct.
Gabion check-dam	Negative	Because of the high cost of materials and the technical requirement, which is beyond the capacity of the local communities.
	Men	
Gully head treatment	Positive	Practical and relatively easy to construct.
Gully reshaping and planting	Positive	Additional benefit from grass (for livestock).
Loose rock check-dam	Positive	Good performance and longer lifespan compared to VLC.
Vegetation log check-dam	Positive	Easiest to construct and with locally available materials.
Gabion check-dam	Negative	Because of the high cost of input materials and its technical requirement, which is beyond the capacity of local communities.

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3.4 Local communities' knowledge, attitudes and behaviour

Knowledge and awareness of gullies by the >500 respondents are summarised in Table 5. The data describes typical attitudes about land degradation and the respondents' views on the extent that gullies have advanced between experimental locations with and without interventions in place. To a general question about the extent of land degradation and gully erosion, there was no evidence of a change in attitudes before and after the experiments took place. There was some evidence that in the treatment areas there were some changes in the perceptions of the extent and most important types of soil erosion and where gully erosion occurs, with a greater perception that main impacts are focussed on farmland.

Table 5. Impact of on-farm field experiment - Difference in Difference Estimates

	Treated-Non-treated	Standard Error
Do you think there is a land degradation problem in your community? (1- Yes, 0 – No)	-0.207	(0.120)
Compared to your past experience, how do you see land degradation in general now? (1-Increasing, 2-Same, 3-Decreasing)	0.013	(0.069)
What is the most important form of land degradation?		
Soil erosion on farmland (1- Yes, 0 – No)	0.275	(0.026)**
Soil erosion on communal grazing land (1- Yes, 0 – No)	-0.108	(0.127)
Gully erosion (1- Yes, 0 – No)	-0.174	(0.054)**
Depletion of soil quality [SOM and nutrient depletion] (1- Yes, 0 – No)	0.002	(0.076)
Compared to your past experience, how do you see gully formation in general now? (1-Increasing, 2-Same, 3-Decreasing)	-0.047	(0.129)
Where are gullies most frequently observed?		
Farmland (1- Yes, 0 – No)	0.246	(0.087)*
Grazing land (1- Yes, 0 – No)	-0.087	(0.093)
Communal land (1- Yes, 0 – No)	-0.159	(0.180)
Do you think the watershed activities used help control gully formation? (1-Yes, 0-No)	0.049	(0.101)
What measures are you aware of that are taken to control further gully formation?		
Tree planting (1- Yes, 0 – No)	-0.101	(0.055)
Watershed activities (1- Yes, 0 – No)	-0.131	(0.027)**
Terracing (1- Yes, 0 – No)	0.117	(0.068)

Note: The treated-non-treated estimates represent the estimated coefficient on the variable for the kebele from a simple fixed effects difference in difference estimation using the matched 2021 and 2023 sample. The Standard errors allow for clustering at the kebele level. * and ** indicate differences which are statistically significant different at 10% and 5% respectively. There were 522 respondents in 2021 and 500 respondents in 2023.

Table 6 reports the estimates using questions specifically asked in the 2023 survey and represent the difference between the mean in the treated and non-treated areas. The questions asked drew on the marketing literature to consider recall and recognition of different interventions (Boshoff and Gerber 2008; Macdonald and Sharp 2000; Hoyer and Brown 1990). This approach has been also used to explore how knowledge and understanding may relate to attitudes about nature conservation

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(Pearson et al. 2022; Veríssimo et al. 2017; Schlegel and Rupf 2010). Here the recall questions consider whether respondents were aware and able to recollect different land degradation measures from a general cue. The respondents were asked to name three interventions or activities that they thought were important in reducing land degradation in an open-ended question format. The answers were then grouped and weighted to provide an awareness score ranging from 0 for completely unaware to 3 for very aware (Boshoff and Gerber 2008). The results of the differences in these scores between the treated and non-treated areas are reported in the first panel of Table 6. Some differences in the levels of recognition were apparent, e.g. there was higher significant recognition of mountain measures such as terracing, high recognition but weak evidence (p-value 0.12) of gully measures, lower recognition of grassland management measures.

The second set of questions explored the extent to which the respondents have knowledge of specific interventions. Here the respondents were shown pictures of different interventions, where the first two (gully head treatment and reshaping gully banks etc) linked directly to treatments one and two implemented in the on-farm field experiments, while the third and fourth interventions shown could be more loosely related to treatment 3. First, to explore respondents' recognition and understanding, they were asked their view of the effectiveness of the measures. Second, to explore their perception of their capacity to implement the measures, they were asked whether they could undertake these measures on their own, or if they needed the help of neighbours or full community mobilization.[2]

The results of the recognition questions were consistent with the hypothesis that the intervention in the treatment kebele (the on-farm experiments, plus field demonstration) influenced knowledge and understanding of similar gully treatments among respondents in the treated areas. The average measures of effectiveness were all higher for those in the treated group, with the greatest differences for the gully shaping and check dams. Testing the set of questions using Cronbach's alpha confirms that these can be interpreted as measuring a single underlying characteristic (alpha 0.74). Testing the averaging aggregate score also suggests that there was a statistically significant difference between the knowledge and understanding of these measures in the area where the on-field experiments took place.

The answers to the second set of questions on the respondent’s capacity to implement the measures were analysed by estimating a simple multinomial logit to model the probability that a respondent felt interventions could be implemented on their own, needed neighbours, or needed community mobilization. The estimates reported represent the marginal effects of those in the treated area on the probability of selecting a particular option. For the gully head treatment, for example, respondents in the treatment group selecting “could do this alone” had a 0.085 lower response than for those respondents in the areas where no experiments took place. Overall, there was evidence that the respondents in the treated area have a different view of the resources required to undertake the measures, being generally more pessimistic of their ability to undertake this alone or with neighbours.

[2] The original 5-point answers were aggregated into the three categories reported on (on own, with neighbours, community)

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The final set of questions assessed possible differences in behaviours related to gullies between the sample in the areas with and without the on-farm experiments, and between treated and non-treated areas. Here there was clear evidence of greater effort to undertake work to reduce gullies in the treated area, with significantly higher averages for all questions, especially for those involving individual work and work with neighbours and friends. This is consistent with the hypothesis that the on-farm experiments and field day demonstration have empowered farmers to act (despite their greater pessimism about their capacity to do so).

The gully erosion interventions deployed in this study are low-cost and practical for application in any region. By combining understanding on impacts to people with environmental benefits, best practices that are most likely to be deployed and maintained were identified. Further research in other regions will disentangle the global significance, but we found good agreement between the effectiveness of interventions in Halaba district, to what has been observed in studies exploring similar interventions in other regions. Communities have a strong desire to act to improve their farming livelihood, with an appreciation of environmental benefits too. Effective policy development therefore should focus on small-scale, cost-effective interventions, over engineered systems like gabion baskets that are beyond local resources.

Table 6. Impact of on-farm field experiment. Differences in Recall, Recognition and Capacity to deal with Gullys across Treated and Non-treated areas (2023 Survey).

	Treated-Non-treated[1]	**St. Error**
Recall Awareness Scores		
Hillside SWC- terraces etc	0.023	(0.008)*
Farmland SWC - bunds etc	0.000	(0.017)
Gully Rehab. measures	0.024	(0.011)
Afforestation/reforestation	-0.041	(0.021)
Biological measure grass planting	-0.027	(0.039)*
Water harvesting structures	0.020	(0.008)**
Grazing land management	0.042	(0.009)
Recognition Effectiveness of Different Treatments (Likert Scale 1-5)[2]		
Gully head treatment –using stone rip rap/rubble at gully head	0.121	(0.072)
Reshaping the gully banks at 45° and planting forage grasses	0.206	(0.038)**
Making check dams made of relatively small rocks	0.118	(0.042)*
Making check dams constructed using vegetation or logs	0.202	(0.044)**
Making small barriers constructed of a series gabion baskets	0.067	(0.053)
Aggregate – Gully head + Reshaping Gully Banks	0.164	(0.055)*
Aggregate - overall	0.134	(0.032)**
Capacity to deal with different Treatments[3]		
Gully head treatment –using stone rip rap/rubble at gully head		
Could do it on own	-0.085	(0.019)**
Need neighbours	0.034	(0.033)
Need community mobilization	0.050	(0.035)
Reshaping the gully banks at 45° and planting forage grasses		

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Could do it on own	0.030	(0.047)
Need neighbours	-0.079	(0.001)**
Need community mobilization	0.049	(0.046)
Making check dams made of relatively small rocks		
Could do it on own	-0.045	(0.023)**
Need neighbours	-0.113	(0.039)**
Need community mobilization	0.158	(0.053)**
Making check dams constructed using vegetation or logs		
Could do it on own	-0.044	(0.030)
Need neighbours	-0.151	(0.012)**
Need community mobilization	0.195	(0.042)**
Making small barriers constructed of a series gabion baskets		
Could do it on own	-0.021	(0.011)*
Need neighbours	-0.116	(0.015)**
Need community mobilization	0.137	(0.011)**
Behaviour (5-point Likert scale) [4]		
In the last 6 months, I have undertaken work on my own or with neighbours and friends to help restore and prevent gullies on the land which I use	0.397	(0.024)**
In my farming, I actively try to decrease gully formation	0.248	(0.024)**
In the last 6 months, I have undertaken work as part of the community to help restore and prevent gullies	0.282	(0.013)**

[1] For each variable the reported coefficients represent the average difference in responses between the treated and non-treated. [2] Scale 1-Not at all effective, 2-Not really effective, 3-Somewhat Effective, 4-Effective,5-Very Effective. [3] These estimates represent the marginal effect of being in the treated area on the probability of selecting the option - *Could do it on own, Need neighbours, Need community mobilization.* The underlying coefficients for this calculation are estimated using a simple multinomial logit with treatment as the only covariate. [4] Scale 1-No, not at all, 2-Yes, once or twice, 3-Yes, occasionally (more than twice), 4- Yes, regularly (at least once a month). 5-Yes, very often (at least once a week). The Standard errors allow for clustering at the kebele level. * and ** indicate differences which are statistically significant different at 10% and 5% respectively. Data based on 500 responses. SWC – soil water conservation.

4 Conclusions

Effective gully expansion mitigation was achieved by community mobilization. All gullies treated with low-cost gully rehabilitation measures displayed zero upward expansion irrespective of the types of gully treatment. This suggests that gully erosion can be halted within the capacity of farmers, provided that context specific measures are available, the right time to act on gully rehabilitation is known and technical support is provided. Ongoing rehabilitation activities and on-farm field trails in the studied watershed influenced knowledge and understanding of similar gully treatments among respondents in the treated areas. The results indicated that the respondents in the treated area have a different view of the resources required to undertake the measures, being generally more pessimistic of their ability to undertake this alone or with neighbours. There was clear evidence of greater effort to undertake work to reduce gullies in areas where mitigation measures had been implemented, suggesting that the on-farm experiments and field day demonstration had empowered farmers to act despite their greater pessimism about their capacity to do so.

Authors contribution. WM: writing – original draft, data collection, analysis, investigation, visualization, methodology. EP: writing – original draft, data analysis, conceptualization, supervision, validation. GY: data collection, review and editing. DT: data collection, analysis, review. AM: data collection, analysis, review. YT: data collection, analysis, writing – original draft. DM: data collection, analysis, review. CG: data analysis, conceptualization. PDH: writing – review and editing, conceptualization, validation. JS: writing – review and editing, conceptualization, validation.

Competing interest. At least one of the (co-) authors is a member of the editorial board of SOIL.

Acknowledgements. This work was supported by the Economic and Social Research Council Grant ES/T003073/1.

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Preprint. Discussion started: 24 April 2024

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