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## ECOSYSTEM SERVICES PROVISION BY GULLY CONTROL. A REVIEW

A. ROMERO-DÍAZ<sup>1\*</sup>, E. DÍAZ-PEREIRA<sup>2</sup>, J. DE VENTE<sup>2</sup>

<sup>1</sup> Departamento de Geografía, Universidad de Murcia, Campus de La Merced, 30001 Murcia, Spain.

<sup>2</sup> Grupo de Conservación de Suelo y Agua, CEBAS, Consejo Superior de Investigaciones Científicas (CSIC), Campus de Espinardo, 30100 Murcia, Spain.

**ABSTRACT.** *Gully erosion causes severe damage to crops and infrastructures and affects the provision of ecosystem services worldwide. To assess the potential of gully control measures to protect ecosystem services and assess the conditions required for their large-scale implementation, this paper critically evaluates a range of gully control measures documented in the World Overview of Conservation Approaches and Technologies (WOCAT). Environmental and socio-economic impacts of technologies are assessed, as well as the implications for ecosystem services, costs and benefits of implementation, and stakeholder's perception. It is demonstrated how gully control measures provide notable on-site and off-site benefits for socio-economic, cultural, ecological, and production goals, and to protect crucial ecosystem services. Control measures particularly contribute to soil and water conservation and to regulating ecosystem services by controlling soil erosion, water cycling, and natural hazards. Most effective control measures consist of combined vegetative and structural measures and of catchment wide interventions. While implementation of gully control can initially be expensive, on the long term, the cost-benefit ratio is usually positive. Moreover, the results emphasize the importance of evaluating control measures considering monetary aspects and all ecosystem services they provide. Nevertheless, individual farmers can often not afford the implementation and maintenance costs due to barriers for implementation and therefore require sustained institutional support.*

**Servicios ecosistémicos proporcionados por el control de cárcavas. Una revisión**

**RESUMEN.** *La erosión de cárcavas causa graves daños a los cultivos e infraestructuras y afecta la prestación de servicios ecosistémicos en todo el mundo. Para evaluar el potencial que las medidas de control de cárcavas tienen en estos y evaluar las condiciones requeridas para su implementación a gran escala, en este trabajo se analizan críticamente una serie de medidas de control de cárcavas documentadas en World Overview of Conservation Approaches and Technologies, WOCAT. Se evalúan los impactos ambientales y socioeconómicos de las diferentes tecnologías, así como sus implicaciones en los servicios ecosistémicos, los costos y beneficios de implementación y la percepción de las partes interesadas. Se constata*

*cómo las medidas de control de cárcavas proporcionan notables beneficios “on site” y “off site” desde un punto de vista socioeconómico, cultural, ecológico y de producción, al tiempo que protegen servicios cruciales de los ecosistemas. Las medidas de control contribuyen particularmente a la conservación del suelo y el agua y a los servicios ecosistémicos de regulación a través del control de la erosión del suelo, el ciclo del agua y los riesgos naturales. Las medidas de control más eficaces consisten en la combinación de medidas vegetativas y estructurales y es importante la intervención en toda la cuenca hidrográfica. Si bien la implementación del control de cárcavas puede ser inicialmente costosa, a largo plazo, la relación costo-beneficio es generalmente positiva. Además, los resultados enfatizan la importancia de evaluar las medidas de control considerando tanto los aspectos económicos, como todos los servicios ecosistémicos que proporcionan. Sin embargo, a menudo los agricultores, de manera individual, no pueden sufragar los costos de implementación y mantenimiento, por lo que requieren un apoyo institucional sostenido.*

**Key words:** ecosystem services, gully control, soil and water conservation, sustainable land management, WOCAT.

**Palabras clave:** servicios ecosistémicos, control de cárcavas, conservación de suelos y agua, gestión sostenible de la tierra, WOCAT.

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\*Corresponding author: Asunción Romero-Díaz, Departamento de Geografía, Campus de La Merced, Universidad de Murcia, 30001 Murcia, Spain. E-mail address: arodi@um.es

## 1. Introduction

Gully erosion is one of the principal processes leading to land degradation in different environments (Nadal Romero and Regüés, 2010; Gallart *et al.*, 2013; Vanmaercke *et al.*, 2016) and at different spatial and temporal scales, causing considerable soil losses and exporting large amounts of sediment and important damage to infrastructure (Poesen *et al.*, 2003; Valentin *et al.*, 2005)

According to Ionita *et al.* (2015), gullies constitute one of the most important forms of water erosion and represent a significant environmental threat worldwide, affecting multiple functions of soil and land. Gully erosion is a significant driver of land degradation globally as is illustrated by the magnitude of soil erosion rates by gully erosion and the numerous countries that are severely affected (Pathak *et al.*, 2005; Brown, 1981; Castillo and Gómez, 2016).

A gully, as defined by the Soil Conservation Society of America (1982), is “a channel or miniature valley cut by concentrated runoff through which water commonly flows only during and immediately after heavy rains or during the melting of snow; it may be dendritic or branching or linear, rather long, narrow, and of uniform width”. Kirkby and Bracken (2009) stated that “a gully is normally defined as deep channel on a hillside, generally cut by running water, and often not containing a perennial flow”.

The distinction between rills and gully is usually done arbitrarily according to size. Another aspect to consider is the difference between ephemeral and permanent gullies. Ephemeral gullies (small in size) can be eliminated by tillage; by contrast, permanent gullies represent structures that cannot be eliminated by tillage (Gómez Gutiérrez *et al.*, 2001). A particular type of gully is associated with margins or crop terraces; known as bank gullies (Poesen and Hooke, 1997) that are usually formed in the topographic discontinuities caused by terraces.

Gully formation is linked to natural factors such as erodible soils, unstable slopes, or intense precipitation. Desmet *et al.* (1999) and Vandekerckhove *et al.* (2000) emphasized the importance that the slope and the contributing area have in the formation of gullies given their importance for the generation of runoff depth. Recently, demographic pressure and certain human activities - such as deforestation, inadequate land use, certain agricultural practices, or abandonment of agricultural land (Romero Díaz *et al.*, 2016) - have increased soil degradation and, in particular, the risk of erosion by gullies. Many studies suggested that under climate change scenarios, erosion rates, and in particular gully erosion, may increase (Nearing *et al.*, 2004; Zhang *et al.*, 2012), due to an increase in the frequency of extreme weather events (Sun *et al.*, 2007; Sillman *et al.*, 2013). Vanmaercke *et al.* (2016) also suggested that specifically gully erosion will become more intense and widespread worldwide in the following decades due to climate change.

Poesen *et al.* (2002) indicated that gully erosion contributes between 50% and 80% to total sediment yield on dryland agricultural land, even though the gullies occupy less than 5% of the watershed area. Gullies produce both on-site and off-site effects. Table 1 shows some of the main effects reported by different authors.

Table 1. Overview of “on site” and “off site” effects of gully erosion.

<b>“On Site” effects</b>	<b>Reference</b>
Notable losses of soil	Poesen <i>et al.</i> , 2002, 2006; Gómez <i>et al.</i> , 2003; Martínez Casasnovas <i>et al.</i> , 2003
Source of sediments	Poesen <i>et al.</i> , 1996, 2003; Martínez-Casasnovas <i>et al.</i> , 2003; Shellberg <i>et al.</i> , 2013; Martín-Moreno <i>et al.</i> , 2014.
Loss of agricultural land	Avni, 2005; Mansour Jahantigh and Pessarakli, 2011.
Decline in crop yields	Poesen <i>et al.</i> , 2003; Nyssen <i>et al.</i> , 2004; Den Biggelaar <i>et al.</i> , 2004; Bakker <i>et al.</i> , 2004, 2007; Ionita, 2011; Marzolff <i>et al.</i> , 2011; Ionita <i>et al.</i> , 2015; Ollobarren <i>et al.</i> , 2016; Li <i>et al.</i> , 2016.
Expansion of the drainage network and development of gullies	Nyssen <i>et al.</i> , 2004; Palacio Prieto and López Blanco, 1994; Vandekerckhove <i>et al.</i> , 2001; Ries and Marzolff, 2003
Rise in agricultural costs	Valentin <i>et al.</i> , 2005; Santos Telles <i>et al.</i> , 2011; Panagos <i>et al.</i> , 2018
<b>“Off site” effects</b>	<b>Reference</b>
Silting-up of reservoirs and loss of functionality	Poesen <i>et al.</i> , 2002; de Vente <i>et al.</i> , 2005; Haregeweyn <i>et al.</i> , 2003; Valentin <i>et al.</i> , 2005; Haregeweyn <i>et al.</i> , 2008
Increment in floods	Poesen and Hooke, 1997; Martineli Costa and Prado Bacellar, 2007; Obi Lawrence, 2017.
Contamination of soils and surface waters	Toy <i>et al.</i> , 2002; Gómez <i>et al.</i> , 2017; Issaka and Ashraf, 2017.

Source: Own elaboration

Due to the important on-site and off-site effects of erosion processes in gullies, their control is very necessary. Poesen (2018) states that actually there is a need for more research on innovative techniques and strategies to prevent soil erosion or reduce erosion rates in general. There are many different techniques, materials, and strategies, depending on the specific problems to be solved, the environmental characteristics, and the resources and labor available (Milton, 1971). For decades, structural measures, such as the construction of check dams (Heede and Mufich, 1974; Schouten and Rang, 1984) as well as vegetative measures, consisting of the establishment of different types of vegetation with the aim of stabilizing the soil or impeding gully development (Baade *et al.*, 1993) have been used for gully control. Structural-vegetative measures combine both types of measure (Okagbue and Uma, 1987; Sheng and Liao, 1997; Weinhold, 2007).

Gully erosion has received important attention within the scientific community over past decades (Poesen and Valentin, 2003; Nadal Romero *et al.*, 2010, 2013; Ionita *et al.*, 2015; Vanmaercke *et al.*, 2016; Zglobicki *et al.*, 2017; Poesen, 2018) but in spite of this, it only represents 10% of the research on soil erosion (Castillo and Gómez, 2016). This is a very small percentage considering that gullies are the most important form of soil degradation in agricultural areas (Castillo and Gómez, 2016). According to Liggitt and Fincham (1989), gully erosion is the neglected dimension in soil conservation research. Poesen *et al.* (2003) considered that most research on water erosion processes focused on sheet and rill erosion processes. Relatively few studies have focused on gully erosion and even scarcer are the studies on the control of gully erosion. Poesen (2011) mentioned many issues still to be resolved in the study of gullies, among which he cites the need to “determine effective measures for the prevention and control of gullies”, which is the central theme of our research. According to a review by Castillo and Gómez (2016), gully control was investigated in only 4.2% of the publications about gullies, despite it being a problem of fundamental interest.

A full understanding of the importance of gully control measures requires assessment of their contribution to ecosystem services. Ecosystem Services (ES) as “the benefits that we human beings get, directly or indirectly, from ecosystems” and can be classified in four groups: provisioning (i.e. wood, water), regulating (i.e. flood and pest control), cultural (i.e. spiritual, recreation), and supporting (i.e. nutrient cycling) services (MA 2005). The benefits can be tangible or intangible and are derived from nature for human benefit. These benefits can often be valued economically -in order to equate them with economic activities that involve changes in land use- and thus provide additional arguments for ecosystem conservation and management (Camacho Valdez and Ruiz Luna, 2012). An important application of the ES concept is that it allows the allocation of value to the provision of goods and services that would otherwise not be considered by political and economic decision-making bodies (Ferrer *et al.*, 2012) and facilitates its fair comparison with costs of prevention or restoration measures. ES can be considered either as benefits (Costanza, 2008) or broader as contributions to human well-being (Potschin and Haines-Young, 2011).

The general objective of our study was to evaluate the environmental and socio-economic (positive and negative) impacts and the ecosystem services provided by gully control measures worldwide based on review and assessment of gully control measures included in the WOCAT (World Overview of Conservation Approaches and Technologies) database and additional scientific literature, thereby specifically combining local and scientific knowledge. The evaluation includes aspects like: the cost-benefit ratio of the implementation of gully control measures, their effectivity in different contexts, and the opinions that farmers and experts have of the existing land degradation caused by gullies and the need to reverse it.

## **2. Methods**

The World Overview of Conservation Approaches and Technologies (WOCAT) is a global network that supports the processes of innovation and decision making in Sustainable Land Management (SLM). The overall objective of the network is to unite efforts in knowledge management and decision support, in order to scale up SLM among stakeholders, including national governmental and non-governmental institutions and international and regional (WOCAT, 2016). WOCAT provides universal knowledge of a wide range of experiments and techniques developed in the field, together with the advantages and disadvantages of their application, from which finally impacts on ecosystem services (ES) can be extracted. It also provides a standard method for documenting, assessing, comparing and analysing the application of technologies and approaches to the existing natural and human environment and is based on the knowledge and assessment of both land users and experts (Mekdaschi Studer and Liniger, 2007). The WOCAT database currently contains 600 technologies developed in 50 countries and is recommended as a reference for the documentation of SLM techniques by the United Nations Convention to Combat Desertification (UNCCD).

For the present study, all entries in the WOCAT database related to the control of gullies in all climates and continents were evaluated. The typologies of the different technologies, their environmental characteristics, the cost-benefit ratio of their implementation and maintenance, and the positive and negative impacts of the different technologies were analysed. Based on this assessment the benefits from gully control for ecosystem services been determined.

The classifications used for assessment of the advantages, disadvantages, impacts and categories (high, medium and low) are those that are listed in the World Overview of Conservation Approaches and Technologies Questionnaire on Sustainable Land Management (SLM) (WOCAT, 2016).

We analysed 26 technologies documented in detail in WOCAT, of which 58% correspond to Africa (Ethiopia, Morocco, South Africa, Senegal, and Tanzania); 31% to Asia (China, India, Nepal, and Tajikistan); and 11% to America (Bolivia and Nicaragua). The largest number of examples in the database originated from Ethiopia, which also reflects the numerous scientific studies related to the control of gullies (e.g. Nyssen

*et al.*, 2004; Moges and Holden, 2008; Yitbarek *et al.*, 2012; Haile and Fetene, 2012; Frankl *et al.*, 2013, 2014; Ehrensperger *et al.*, 2015; Addis *et al.*, 2015; Haregeweyn *et al.*, 2015). In addition to the analysis of the WOCAT database, which only includes measures applied in Africa, Asia and America, a review of studies involving analyses of the measures used for gully control in other countries appears further on in Table 4 and was used further in the discussion.

### 2.1. General and environmental characteristics of the technologies applied

From a climatic point of view, 21 of the gully control technologies documented in the WOCAT database originated from semiarid climates, three from subhumid climates, one from a semiarid-subhumid climate, and one from a humid climate (Table 2). Nineteen percent of the evaluated control measures were implemented in areas with precipitation below 500 mm; 42% between 500 and 750 mm, and 39% more than 750 mm. Of the territories involved, 60% lies at 500-2000 m altitude, with the most frequent slopes classified as moderate and steep (each representing 23%), followed by gentle and hilly slopes with 19% each. The forms of relief are diverse although hill slopes predominate representing 31% of the total. Plateau, mountain slopes, and footslopes represent 15% each (Table 2).

The area in which the technologies are applied is generally small, since they are specific actions on specific sites. In 61% of the cases the area involved was between 0.1 and 1 km<sup>2</sup>, in 19% between 1 and 10 km<sup>2</sup>, and in 12% between 10 and 100 km<sup>2</sup>. The type of degradation that gully control techniques aim to mitigate is exclusively due to water erosion. The causes of degradation indicated are usually a combination of natural and man-made causes. The main technical functions that is intended to be achieved are the control of the concentrated runoff (in 65% of the cases) or the combination of several functions –among which increased infiltration, storage of water, and sediment retention. The measures applied have been mainly structural (46%), vegetative (11.5%), and combinations of both (38.5%). Regarding the type of intervention, most have been measures for rehabilitation or combinations of rehabilitation, prevention, mitigation, and reduction of land degradation (Table 2). Where gully control measures are implemented, the soil use was mainly mixed land (46%) and cropland (31%). The applied technologies have an external origin in 61.5% of the cases, while 38.5% have their origin in local knowledge (Table 2). The soils where the evaluated control measures were implemented are generally characterized by an average depth between 20 and 80 cm (in 46% of cases); are of medium texture (58% of cases); with low fertility (54% of cases); and with a low percentage of organic matter in their upper layers (<1% in 65% of cases) (Table 2).

Table 2. Types of gully control technologies and environmental characteristics of the areas where they have been applied.

WOCAT Reference	SIM technology	Climate	Conservation measure	Type of intervention <sup>1</sup>	Type of land use	Origin <sup>1</sup>	Altitude m	Slope %	landform	Soil depth cm	Soil texture	Soil fertility <sup>4</sup>	Topsoil OM <sup>5</sup>
BOL004en	Gully control and catchment protection	Subh/Semi	Veg/Struc	Reh	Mixed land	EI	3000-4000	steep	hill slopes	50-80	loam	L/V/L	1-3%
BOL007es	Stabilization of slopes (biotraps)	Semiaрид	Veg/Struc	M/Red	Others	EI	-	steep	mountain slopes	50-80	loam	L	>3%
CHN047en	Check dam	Semiaрид	Struc	-	Mixed land	LK	-	hilly	mountain slopes	20-80	loam	L	1-3%
CHN052en	Check dam for land	Semiaрид	Struc	Pre	Cropland	EI	500-1000	gentle	valley floors	>120	loam	VL	<1%
ETH039en	Earth checks for gully reclamation	Subhumid	Veg/Struc	Pre/Mit/Reh	Cropland	EI	1500-2000	moderate	hill slopes	80-120	loam	M	1-3%
ETH050en	Gully rehabilitation	Subhumid	Struc	Mit/Reh	Mixed land	EI	1500-2000	hilly	mountain slopes	0-50	clay	L	<1%
ETH562en	Jatropha curcas Hedge	Semiaрид	Veg/Struc	Reh	Mixed land	LK	1500-2000	hilly	hill slopes	0-20	coarse	L	<1%
ETH604en	Stone wall check dam	Semiaрид	Struc	Reh	Mixed land	EI	1500-2000	hilly	hill slopes	0-20	coarse	L	<1%
ETH607en	Check dam ponds	Semiaрид	Struc	Mit/Red	Cropland	EI	1500-2000	gentle	plateau	>120	loam	L	<1%
IND018en	Sunken gully pits	Semiaрид	Struc	Pre/Mit/Reh	Mixed land	EI	500-1000	gentle	plateau	50-80	loam	L	1-3%
KEN024en	Gully rehabilitation	Semiaрид	Veg	-	Cropland	LK	-	moderate	plateau	20-50	coarse	L	<1%
KEN027en	Gully blocking by stone checks	Semiaрид	Struc	-	Cropland	LK	-	-	ridges	50-80	loam	M	1-3%
MOR015en	Gully control by plantation of Atriplex	Semiaрид	Veg	Reh	Grazing land	EI	100-500	rolling	hill slopes	20-50	loam	L	<1%
NEP014en	Gully plugging using check dams	Humid	Veg/Struc	Mit/Red	Mixed land	EI	500-1000	steep	footslopes	0-50	clay	VL	<1%
NEP051en	Controlled gullying	subhumid	Veg/Struc	M	-	LK	1000-1500	steep	footslopes	50-80	clay	H	<1%
NIC004en	Check dams from stem cutting	Semiaрид	Veg/Struc	Reh	Mixed land	EI	3000-4000	steep	mountain slopes	20-50	clay	L	<1%
RSA001en	Old Motor tire contours	Semiaрид	Struc	Pre	Mixed land	EI	1000-1500	gentle	footslopes	80-120	clay	L	<1%
RSA014en	Gravity type inverted tire structure	Semiaрид	Struc	Mit/Red	Grazing land	EI	1000-1500	gentle	valley floors	>120	loam	H	<1%
RSA031en	Gully control (gabions)	Semiaрид	Manag	Reh	Grazing land	EI	500-1000	moderate	plateau	20-80-120	sandy	M/L	1-3%
SEN011fr	Stone lines with hedges	Semiaрид	Struc/Veg	Reh	Mixed land	LK	<100	moderate	plateau	80-120	loam	H	>3%
SEN283fr	Gabions	Semiaрид	Struc	Reh	Mixed land	LK	<100	moderate	plateau	80-120	loam	H	1-3%
TAJ115en	Gully rehabilitation with native trees	Semiaрид	Veg	Pre/Reh	Others	LK	1000-1500	steep	hill slopes	0-20	coarse	M	<1%
TAJ349en	Gully rehabilitation	Semiaрид	Struc/Veg	Mit/Red	Cropland	EI	1000-1500	hilly	footslopes	20-50	loam	L	<1%
TAJ356en	Infilling of gullies with vegetative struc.	Semiaрид	Struc/Veg	Reh	Mixed land	EI	1000-1500	rolling	hill slopes	>120	loam	L	<1%
TAN010en	Gully healing using trash line	Semiaрид	Struc	Reh	Cropland	LK	100-500	moderate	plateau	20-50	coarse	L	<1%
TAN011en	Gully healing for growing bananas	Semiaрид	Struc	Reh/Pre	Cropland	LK	100-500	rolling	hill slopes	50-80	loam	M	<1%

Source: Own elaboration from WOCAT database

<sup>1</sup> Veg = Vegetative; Struc = Structural; Manag = Management

<sup>2</sup> Reh = Rehabilitation; Mit = Mitigation; Red = Reduction; Pre = Prevention

<sup>3</sup> EI = Externally Introduced; LK = Local Knowledge

<sup>4</sup> L = Low; M = Medium; H = High; VL = Very Low

<sup>5</sup> OM = Organic Matter

### 3. Results

Gully control measures documented in the WOCAT database are grouped in three classes: (i) structural, (ii) vegetative and (iii) structural/vegetative. In the next paragraphs, the impacts and effectiveness of the three different groups of control measures are analysed.

#### 3.1. Cost-benefit analysis and implementation and maintenance effects

An important factor constraining the implementation and maintenance of the different technologies is their cost, since in many cases farmers alone cannot afford them. Our evaluation of examples from the WOCAT database indicates that combined technologies of vegetative and structural types are usually cheaper in their establishment cost than the purely structural ones, especially the construction of stone walls that are usually the most expensive technologies. The cases with detailed costs information provided in WOCAT indicate that the establishment cost usually lies between \$100 and \$1000 per ha, only in 35% of the cases the cost is between \$1000 and \$10,000 per ha, although the exact costs of course strongly depend on the exact type of measure and their extent, or density, of implementation. Once the technology is in place, the annual maintenance cost is not very high: in 50% of cases, it is less than \$100 per ha, and for the other 50% between \$100 and \$1000 per ha.

Of special interest is the cost-benefit ratio of each of the implemented measures. During establishment, 30.7% of the documented technologies reported a negative cost-benefit ratio on the short-term, while in 19.2% of cases it was neutral, and in 50% there was a positive ratio (Fig. 1). However, on the long-term, the cost-benefit ratio of establishment was considered positive in 46.2% of cases and very positive for 53.8% of cases. With respect to short-term maintenance, in 65.4% of cases it is positive and in the long-term the percentage rises to 92% of all cases (Fig. 1). The most optimal cost-benefit ratios were reported for combined vegetative-structural techniques.

#### 3.2. Impacts of the gully control technologies

Different technologies, once applied, can have positive or negative impacts. The impacts to be considered are: i) socio-economic and productive; ii) socio-cultural; iii) ecological; and iv) off-site impacts. WOCAT differentiates between high medium and low impacts. Impacts are considered high (H) when they are above 50%, medium (M) between 20 and 50%, and low (L) if a measure results in a change between 5 and 20% in a variable.

- i) *Socio-economic and production impacts.* In most cases, gully control provides very positive benefits, with a very high impact on farm income, crop yield, quantitative fodder production, and wood production. With a moderate impact, and in a smaller number of cases, positive impacts are reported for the reduced risk of production failure, forage quality, diversification of income sources, the simplification of farming operations, and the availability/quality of irrigation water. Finally, with a low impact and in a very small number of cases, we can include the reduction of agricultural expenses (inputs), job creation and farm employment, and improvement of water quality and availability (Fig. 2).



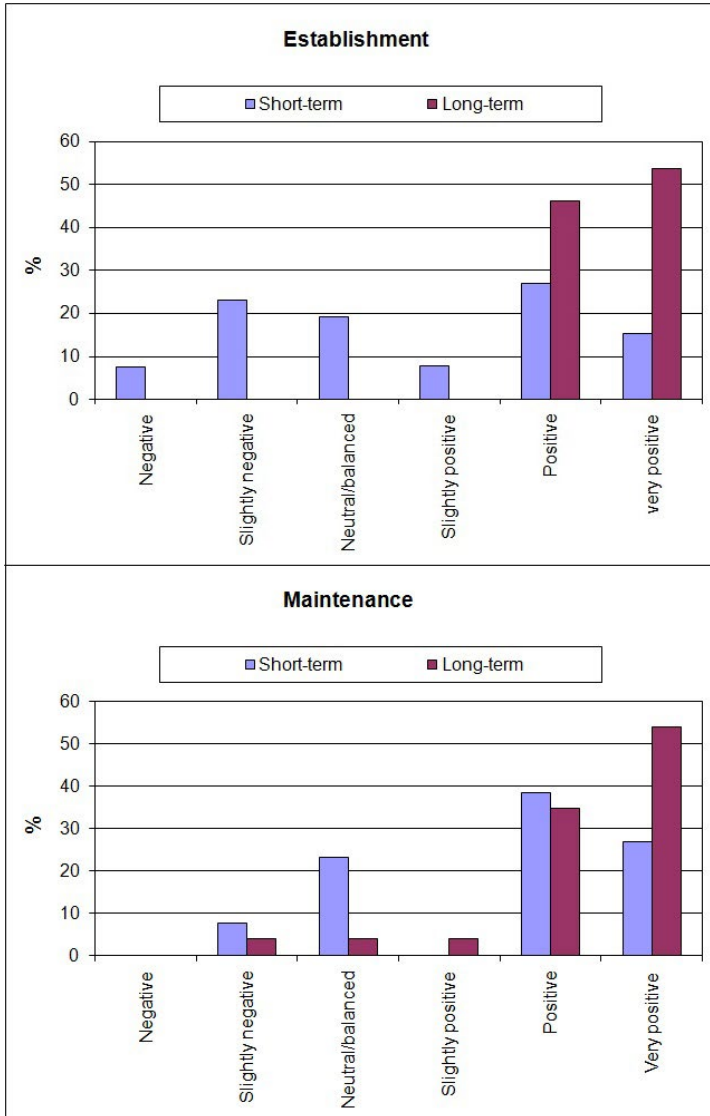


Figure 1. Cost-benefit ratios for the establishment and maintenance of gully control measures.

Some of the technologies discussed also have some disadvantages. The most negative effects are the increase in labour restrictions associated with eight of the technologies and the decrease in the productive area for five of them. Other aspects cited as disadvantages are the hampering of agricultural operations (3 cases), increased economic inequality and expenditure on agricultural inputs (2 cases), blockage of the movement of herds/flocks, the establishment work required, or the increased risk of harvest loss (1 case) (Fig. 2).

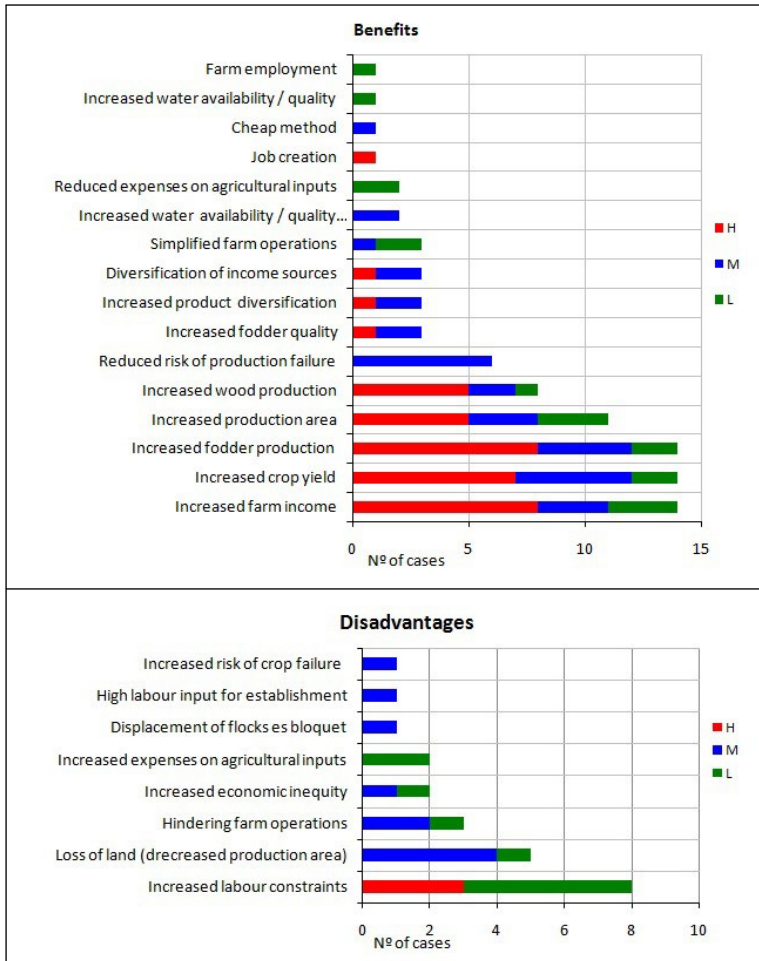


Figure 2. Productive and socio-economic benefits and disadvantages.

ii) *Socio-cultural impacts.* From the socio-cultural point of view and with a high-medium positive impact, for the majority of the analysed cases, the greater knowledge and awareness of the importance of soil conservation and erosion and the strengthening of community institutions stand out. In a smaller number of cases, and with a high impact, is the increase in food security, while the strengthening of national institutions and the improvement of disadvantaged socio-economic groups has a moderate impact. At the same time, in other cases, cultural opportunities, conflict mitigation, health, and recreational opportunities are enhanced (Fig. 3). The socio-cultural disadvantages are scarce: in just one case, a reduction of grazing land, the need for specialized labour, or a lack of benefit for the farmers were mentioned. In three cases, with a low average impact, increased socio-cultural conflicts were mentioned (Fig. 3).

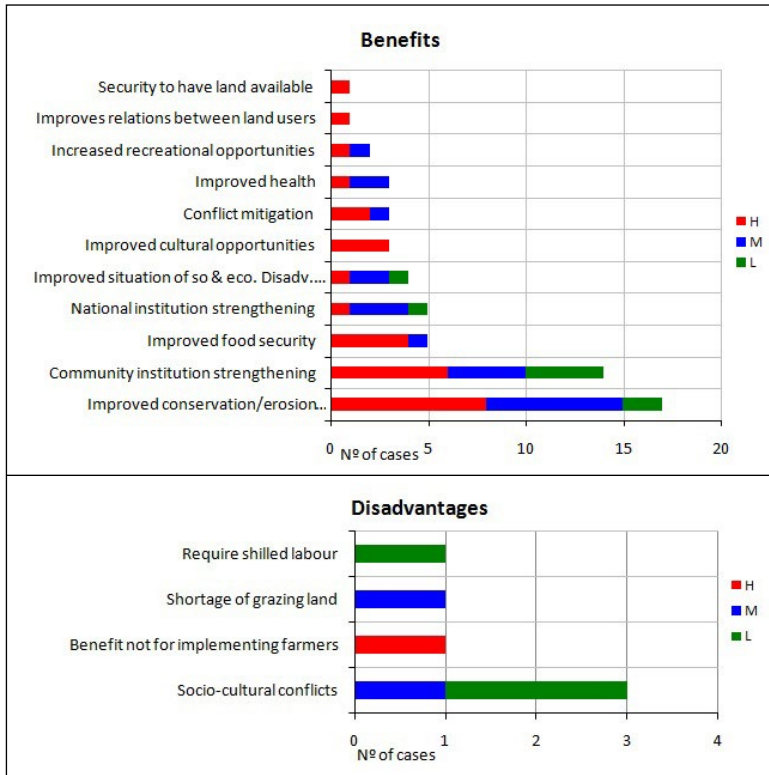


Figure 3. Socio-cultural benefits and disadvantages.

iii) *Environmental impacts.* The environmental benefits of gully control technologies are most prominent. In order of importance the following impacts are highlighted: reduction of soil loss, increase in soil moisture and coverage, reduction of runoff, biodiversity protection, reduction of adverse events, recharge of aquifers (especially with the construction of check dams), increased biomass, improvement in excess drainage water, or improvement in water harvesting and collection. With a lower impact, and in fewer cases, are the benefits of increases in soil fertility, nutrient cycle recharge, carbon sequestration, plant diversity, quantity and quality of water, or soil organic matter. Finally, in a smaller number of cases, are the positive impacts of increased numbers of beneficial species, reductions of evaporation, soil compaction and sealing, and wind speed, and increased animal diversity (Fig. 4).

The ecological disadvantages are very scarce. Two cases mentioned an increase in niches for pests (high impact) and in flooding (moderate impact). One case reported an increased competition among species (moderate impact) and (with low impact) competition for water, sunlight, and nutrients (Fig. 4).

iv) *Off-site impacts.* In the majority of cases, and with high impact, the reduction of floods and sedimentation downstream are important off-site impacts of gully control. Damage is also reduced in neighbouring fields and in infrastructure, both public and private. Likewise, the buffering capacity is improved, the contamination of rivers and groundwater is reduced and, in some cases, the flow of runoff in the dry season increases together with the availability of water (Fig. 5). Only two disadvantages are mentioned (Fig. 5): the reduction in sediment production (in 4 cases) and the reduction of river flow (in 2 cases).

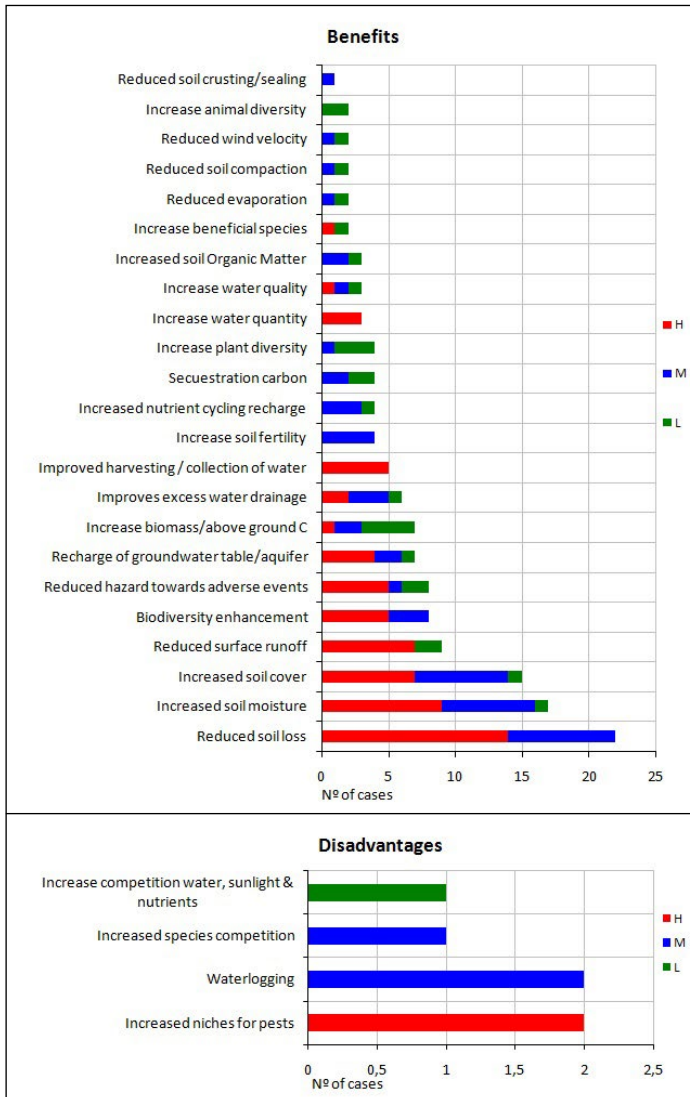


Figure 4. Environmental benefits and disadvantages.

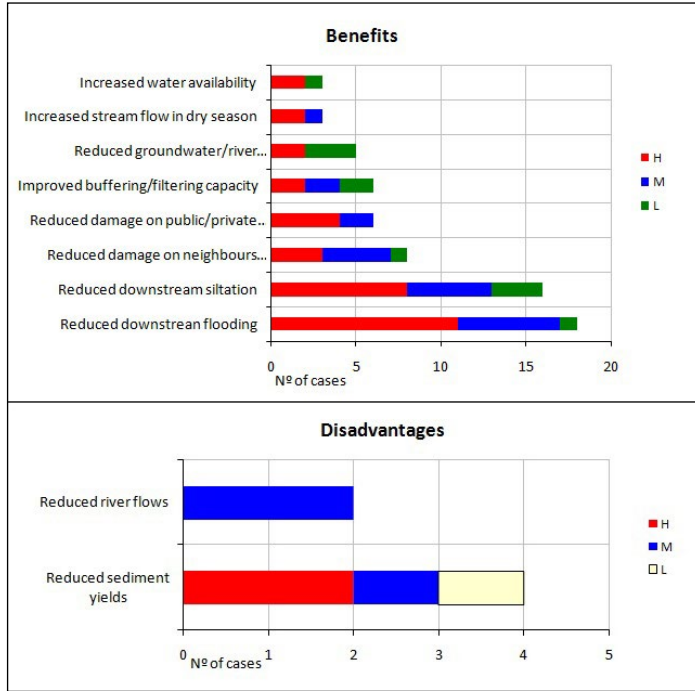


Figure 5. Off-site benefits and disadvantages.

### 3.3. Ecosystem services related to gully control

To assess the ecosystem services (ES) supported by the different gully control measures, we have considered the impacts shown in Figures 6 to 9 in relation to the four main groups of ES (provisioning, regulating, supporting and cultural) and building on the framework for the provision of ES from soil resources as presented by Dominati *et al.* (2010).

- i) *Provisioning services.* Generally, in this category of ES are included production of food, fiber, fuel, and water. Gully erosion affects production in several ways, directly through the loss of land for production and indirectly through damage to crops and vegetation by sedimentation and floods downstream. Gully control measures protect both the availability of land for production and prevent damage to production areas. In order of importance, the impacts of gully control are most significant in relation to: (i) food supply, due to increased crop yield and reduced production failure; (ii) increased forage production; (iii) the provision of clean water - reduced pollution of rivers and groundwater, enhanced filtering, improved water quality; (iv) the provision of land by increasing the area of production; (v) increased timber yields; and (vi) the provision of more water through water harvesting and retention (Fig. 6).

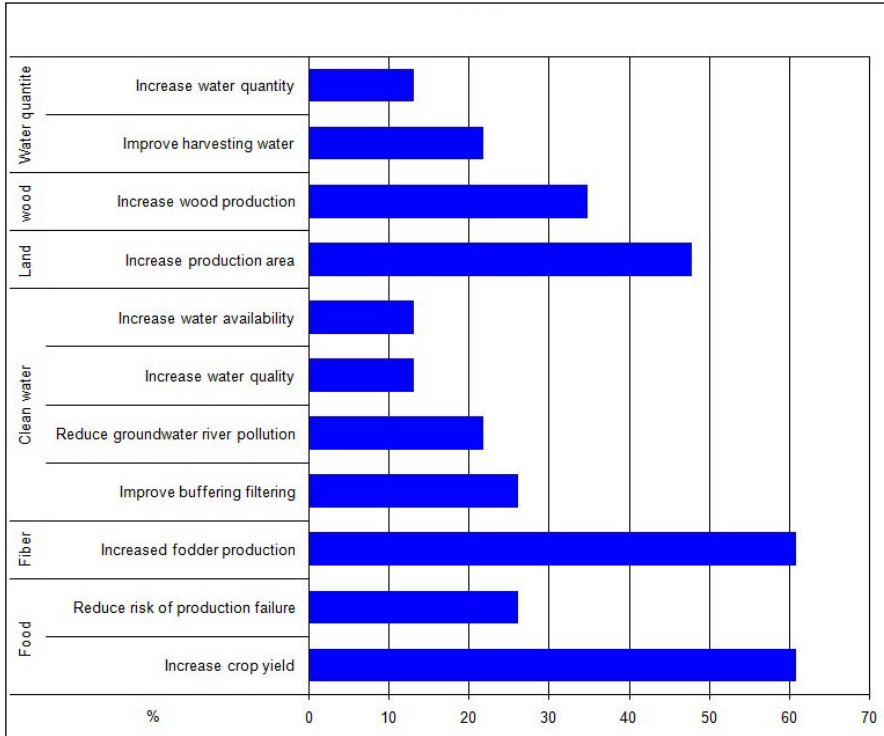


Figure 6. Provisioning ecosystem services.

ii) *Regulating ecosystem services.* Regulating ecosystem services represent amongst the most important aspects of gully control. The application of some of gully control techniques can improve the regulation of climate, natural hazards, water and nutrient cycling, soil erosion, biodiversity, and health. Climate regulation can arise through increases and maintenance of organic carbon in the vegetation cover and in soil organic matter. Natural hazards (Fig. 7) constitute one of the main regulatory systems, through the reduction of floods, sedimentation, damage to neighbouring fields, risks of adverse events, and damage to infrastructure. Water regulation is achieved by increasing soil moisture, recharging of the water table, improving excess water drainage, reducing evaporation losses, or increasing the availability of water for irrigation. Regulation, or prevention, of soil erosion is the most important ES provided by gully control. In almost all cases analysed (96%), a reduction of soil erosion is mentioned. The reduction of runoff and, to a lesser extent, the reduction of wind speed and of the compaction and sealing of soils are also highlighted, evidently influencing runoff and erosion. The regulation of biodiversity has minor effects, resulting in some cases from the increase in the diversity of plants, animals, and beneficial species used for gully control. The improvement of health is cited in only three cases.

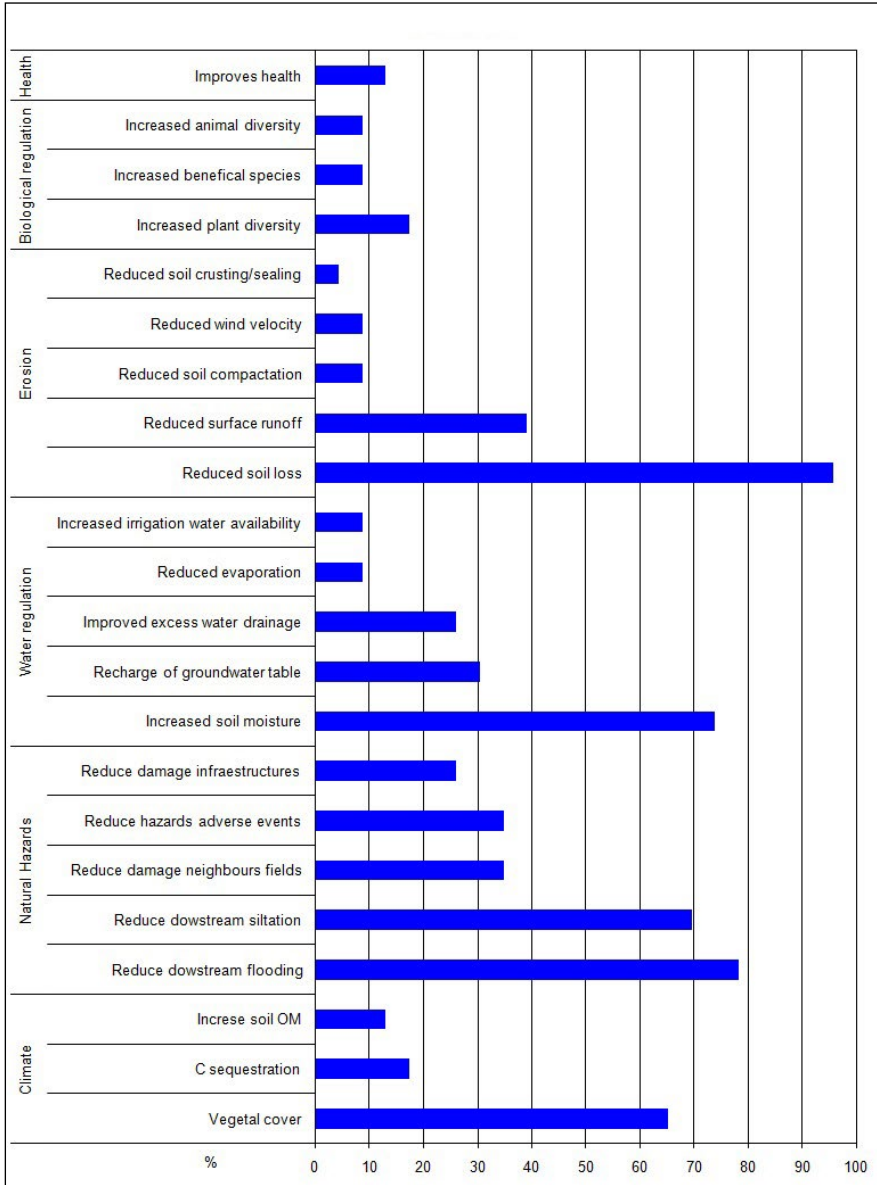


Figure 7. Regulating ecosystem services.

iii) *Supporting ecosystem services.* Although supporting ES are not principally affected by gully control in most cases, some of the benefits include: (i) protection of genetic pools due to improved biodiversity; (ii) enhanced nutrient cycling by recharging the nutrient cycle; (iii) soil formation through increased vegetation cover and enhanced soil quality facilitating soil biodiversity and processes of soil formation (Fig. 8).

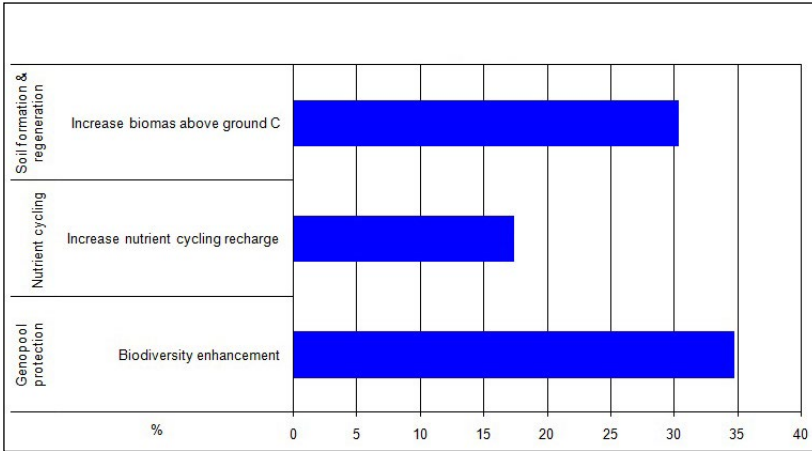


Figure 8. Supporting Ecosystem Services affected by gully control measures.

iv) *Cultural ecosystem services.* Cultural ES include the potential for recreation, education and the strengthening of institutions. It is worth noting that implementing gully control measures contribute to a greater knowledge of soil erosion and conservation processes and their impacts (74% of the cases) and the strengthening of community institutions to prevent land degradation in general (61% of cases) (Fig. 9).

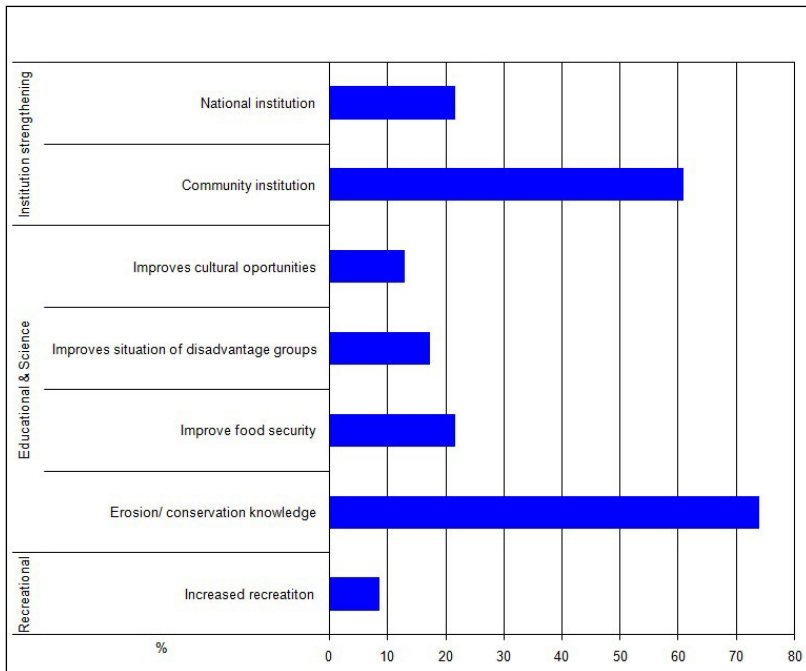


Figure 9. Cultural ecosystem services.



### 3.4. Expert and land owners opinions on the need for gully control

WOCAT documents farmer and expert opinions regarding the main land degradation problems in each area that make it necessary to implement gully control measures. Table 3 summarizes these views and although experts and farmers show, in general, a consensus in the identification of the problems, some differences are evident. Experts often point to the causes of erosion, while farmers focus more on the problems that this erosion poses to them, such as the loss of agricultural land or the inability to produce food. In many cases, linked effects are mentioned; for example, as a result of overgrazing or cultivation in unsuitable areas, erosion processes can occur, leading to a loss of cultivated land and poor crop yields, food insecurity, or destruction of roads. One of the main drivers of land degradation and gully formation, indicated by both experts and farmers, is overgrazing.

Table 3. Main drivers and impacts of land degradation by gullies documented in WOCAT.

Country	Cases	Expert opinion	Farmer's opinion
Bolivia	2	Overgrazing, agriculture on steep slopes, erosion, floods	No opinion
China	2	Serious gully erosion	Loss of agricultural land
Ethiopia	5	Overgrazing, monocultures, soil erosion, low fertility, cultivation in zones prone to erosion	Land erosion and degradation, scarce vegetation cover, demographic pressure, overgrazing, loss of productivity
India	1	Gully development	Sedimentation of harvest and unproductive land
Kenya	2	Erosion, overgrazing, loss of fertility	Lack of tools and credit, poor communication
Morocco	1	Hydraulic erosion, abandonment of land, desertification	Yield decline, lack of water
Nepal	2	Small areas of land, low fertility, intense precipitation	Overgrazing
Nicaragua	1	Soil degradation, gullies in cultivated land, lack of knowledge and resources	No opinion
South Africa	3	Overgrazing, poor planning of land use, population density	Overgrazing, drought, shortage of land, insecurity
Senegal	2	Unusable land due to gully erosion	Erosion, loss of fertility, destruction of means of communication
Tajikistan	3	Soils very prone to erosion, intense precipitation, overgrazing	Water shortage, unproductive soils, serious erosion, lack of infrastructure to stop erosion
Tanzania	2	Formation and expansion of gullies	Formation and expansion of gullies

Source: Own elaboration from the WOCAT database

## 4. Discussion

### 4.1. Cost-benefit analysis of gully control

Generally, gully erosion is more difficult and costly to control than sheet or rill erosion (Lal, 1992), so the control of gullies is expensive and the farmer, in most cases, lacks the resources necessary for the rehabilitation of these areas (Bravo-Espinosa *et al.*, 2010). Farmers often prioritize their immediate need to produce food and income and do not invest in the restoration of gullies, especially in the case of subsistence farming or under conditions with insecure land tenure (Moges and Holden, 2008). This means that preventive or control measures for gullies should yield short-term benefits in terms of increased yields, availability of more land for cultivation, and reliable crop yields through better use of soil and water (Pathak *et al.*, 2005). According to Desta and Adugna (2012), the cost-benefit ratio of gully control should be carefully evaluated. Techniques that exercise maximum control with the least possible cost should be prioritised (Heede, 1982). Costly measures of gully control and/or restoration have sometimes been unsuccessful (Heede, 1982; Lal, 1992). On the other hand, other studies (e.g. Mora Jordano *et al.*, 2013) have demonstrated that some control measures can be implemented with little technological knowledge or skills and at costs affordable to many owners and with reasonable benefits.

When evaluating the real costs and benefits of the various means of rehabilitation of gullies, it is necessary to contemplate the different ES that the control contributes. Zhou *et al.* (2009) stressed that in a cost-benefit evaluation of soil conservation practices it is necessary to consider the economic value of the soil that is lost and the damage generated by off-site erosion to reflect the true value of long-term conservation practices. In Ethiopia, Yitbarek *et al.* (2012) evaluated the on-site cost of erosion in gullies in addition to the cost-benefit ratio of rehabilitation, considering the loss of yield as well as the cost of the fertilizers needed to replace the eroded soil nutrients. Kennedy *et al.* (2001), in a study in Austria, commented that although soil conservation measures can be costly, the environmental damage, aesthetic impact, and the cost of restoring roads due to impacts by erosion can be much higher. Therefore, the cost-benefit evaluation shows how investments in the rehabilitation of gullies may be an economically viable in some cases. Ohde (2011) considered that agricultural lands provide society with an abundance of services. While agro-ecosystems are currently managed primarily for the production of food, fibre and fuel, they can also provide many other ES benefits, such as carbon sequestration, improved water quality, erosion and flood control, and habitats for flora and fauna (Boody *et al.*, 2005; MA, 2005). Hence, is necessary to prevent erosion or to rehabilitate already eroded areas, especially those that have highest erosion rates and contribute most to off-site damages by sedimentation and floods. The use of an ES approach to gully control, where the multiple impacts and costs of degradation are considered, may allow a more appropriate assessment of the actual cost-benefit ratio for the farmer and for society as a whole (Hein, 2007).

Although the need to control gullies is beyond doubt since the cost-benefit ratio is often positive on the long term and gully control supports crucial ES, farmers often

face multiple barriers for implementation of prevention or restoration measures. Most important barriers include limited access to capital, scarce direct benefits, land tenure insecurity, limited technical support, and poor community participation (Haregeweyn *et al.*, 2015; Sanz *et al.*, 2017). Hansen and Law (2008) mentioned the need to share the costs between farmers and the administrative bodies that facilitate the various treatments. Cotler *et al.* (2011) argued that in Mexico the institutional participation in soil rehabilitation issues is weak and discontinuous, and in fact has accentuated soil degradation. Therefore, they stressed the need to increase and strengthen participatory development strategies to ensure that conservation and, in general, the sustainable use of soils occupies an important place in the economic and political national agendas. Schmiedel *et al.* (2016), in a study of the ecological and financial impacts of soil erosion and its control in South Africa, demonstrated how the costs of restoration measures, although involving low-cost material and local labour, require financial support from the public sector through an accessible and sufficient payment for protected ES. This is justified by the fact that the implementation of these techniques by the owners benefits society as a whole, for example by reducing the risks of flooding. Stakeholders should therefore continue to invest in, and be incentivised and supported to apply appropriate gully rehabilitation, and prevention management techniques, to ensure the benefits and the use of surrounding farmland.

Our evaluation shows that the cost-benefit ratio of all three groups of technologies (i.e. vegetative, structural, vegetative/structural) is positive to very positive in both their establishment and maintenance phase, and in the short- and long-term. This confirms the results presented by Giger *et al.* (2015) who specifically assessed the economic benefits and costs of SLM technologies (including gully control) based also on analysis of the WOCAT database. Overall, both land users and experts perceive that most SLM practices for gully control described in the WOCAT database have benefits that justify the required investments. Nevertheless, to make such investments, the land users require stable economic conditions and secure tenure rights, since the adoption of these technologies is usually a gradual process that lasts for many years.

#### 4.2. Analysis of different gully control measures

In the cases analysed, most of the control measures are structural or structural/vegetative, or, to a lesser extent, purely vegetative (Table 4). Structural measures have a primary preventive function, while the main function of vegetative and structural/vegetative measures is rehabilitation.

A broad range of gully control techniques are described in detail in several manuals (e.g. FAO, 2000; Pathak *et al.*, 2005; Sagarpa, 2009; Gómez Gutiérrez *et al.*, 2011; Cisneros *et al.*, 2012; Desta and Adugna, 2012).

Table 4. Literature review of studies involving analysis of the measures used for gully control.

Reference	Structural	Vegetative	Structural/ vegetative	Country
Addis <i>et al.</i> , 2015			X	Ethiopia
Belmonte Serrato and Romero Díaz, 2009	X			Spain
Blanco-Canqui <i>et al.</i> , 2016		X		USA
Bravo Espinosa <i>et al.</i> , 2010		X		Mexico
Burkard and Kostaschuk, 1997	X			USA
Burylo <i>et al.</i> , 2012		X		France
Castillo <i>et al.</i> , 2007	X			Spain
Castillo <i>et al.</i> , 2014	X			Spain
Cisneros <i>et al.</i> , 2012		X		Argentina
Daniels and Giliam, 1996		X		USA
De Baets <i>et al.</i> , 2007		X		Spain
De Baets <i>et al.</i> , 2009		X		Spain
Ehrensperger <i>et al.</i> , 2015		X		Ethiopia
Ene and Okogbue, 2015	X			Nigeria
Erktan <i>et al.</i> , 2013		X		France
Frankl <i>et al.</i> , 2014	X			Ethiopia
Gómez Gutiérrez <i>et al.</i> , 2011	X			Spain
Kennedy <i>et al.</i> , 2001	X			Australia
Leguédois <i>et al.</i> , 2008		X		Australia
Mekonnen <i>et al.</i> , 2015			X	Various
Meyer <i>et al.</i> , 1995		X		¿?
Mongil <i>et al.</i> , 2015		X		Spain
Mora Jordano <i>et al.</i> , 2013			X	Spain
Morris and Jonson, 1943	X			USA
Nyssen <i>et al.</i> , 2004	X			Ethiopia
Ohde, 2011		X		USA
Okagbue and Uma, 1987			X	Nigeria
Poesen, 2011			X	Various
Polyakov <i>et al.</i> , 2014	X			USA
Romero Diaz <i>et al.</i> , 2007	X			Spain
Schmiedel <i>et al.</i> , 2016		X		South Africa
Sheng and Liao, 1997			X	China
Weinhold, 2007			X	USA
Pathak <i>et al.</i> , 2005	X			India
Yuan <i>et al.</i> , 2009		X		Various

Source: Own elaboration

#### 4.2.1. Structural measures

Structural gully control measures usually consist of the placement of loose stones, stone walls and barriers, gabions, check-dams, sandbags, or old tires. However, dikes are often the most commonly used measures. They are generally constructed transversally to the gullies in order to control the flow of runoff, decrease the longitudinal gradient, retain the eroded sediments upstream, conserve soil, and improve soil characteristics (Romero Díaz *et al.*, 2007). There are examples of successful restoration projects in gullies using check dams (Heede, 1977; Burkard and Kostaschuk, 1997; Weinhold, 2007; Polyakov *et al.*, 2014). However, several authors have shown how check-dams may favour incision and erosion downstream or lateral of the dam (e.g. García Ruíz and Puigdefábregas, 1985; Martínez Castroviejo *et al.*, 1990; Romero Díaz *et al.*, 2007; Boix-Fayos *et al.*, 2007; Belmonte Serrato and Romero Díaz, 2009). Other studies mention that in areas with favourable climatic conditions for vegetative techniques (reforestation), check dams are usually relatively expensive and, although they are effective in sediment retention, they have a short life expectancy due to their rapid siltation (Quiñonero *et al.*, 2016). In other cases, structures may collapse due to faults in their construction (Nyssen *et al.*, 2004) or due to piping processes (Sherard *et al.*, 1972). In areas prone to piping processes, experiments with subsurface geo-membrane placement have been performed (Frankl *et al.*, 2014). Yet, application of geoen지니어ing structures for gully control does not always give good results as was illustrated by Godwin Ezekwesili and Celestine Obialo (2015) who reported that many structures were destroyed and new ravines appeared near existing ones in a study in Nigeria. This corroborates the opinion of Gómez Gutiérrez *et al.* (2011) who mention that an isolated retention dam alone is not a gully control measure if it is fed by other upstream waters against which measures have not been taken.

Desta and Adugna (2012) stressed the importance of good maintenance of the gully control structures. Structures built in gullies for stabilization should be checked for damage, especially during rainy seasons and after heavy storms. Damaged dams must be repaired immediately to avoid the eventual risk of collapse with possible domino effects on check dams downstream.

#### 4.2.2. Vegetative measures

The vegetative measures consist mainly of the planting of grasses, shrubs, and trees in the bottom of the gully, in the headwaters, or in the margins. The principal effects of these vegetative measures are interception of rain (Belmonte Serrato and Romero Díaz, 2013), increased infiltration of water into the soil, increased soil roughness, reduction of runoff and of erosion by concentrated flows (Styczzen and Morgan, 1995), filtering of nutrients, sediment retention (Daniels and Gilliam, 1996; Rey, 2003; Blanco-Canqui *et al.*, 2006), and if sufficiently dense vegetation cover is used a significant the reduction of hydrological connectivity (Ohde, 2011).

It is evident that vegetation plays an important regulatory role in the control of erosion (De Groot *et al.*, 2002) and is a factor of great influence on the erosion rates on slopes prone to instability (Thornes, 1990; Morgan, 1995), and has been used for decades in ecological restoration of degraded lands (Coutancier, 2004; Stokes *et al.*, 2010). Several

studies recommend the establishment of biophysical control barriers in gullies and slopes (Pathak *et al.*, 2005; De Baets *et al.*, 2006), because they promote sedimentation and the growth of native vegetation, which creates new hydraulic conditions that modify the transport capacity in the channel, as long as it is accompanied by diversion and control of the overland flow upstream.

The effects of vegetation are manifold (Cisneros *et al.*, 2012). The establishment of vegetation exerts a stabilizing influence on soil materials through the action of both the living and dead fractions, in both the surface and soil layers. Thus, in the stabilization of gullies, the architectural properties of the root systems are very important (De Baets *et al.*, 2007; Burylo *et al.*, 2012). Some species may be more efficient in soil stabilization than others, and may have a stronger impact on erosive dynamics and ecosystem stability (De Baets *et al.*, 2009; Stokes *et al.*, 2009). De Baets *et al.* (2009) demonstrated how the grasses *Stipa tenacissima* and *Lygeum spartum*, and the shrub *Salsola genistoides* would be very suitable plant species to control erosion in gullies. In degraded areas, several authors have emphasized the need to identify the best species that contribute to the provision of ecosystem services (Díaz, 2006; Luck *et al.*, 2009). Ehrensperger *et al.* (2015) analyzed the effectiveness of *Jatropha* barriers to rehabilitate canyons in northern Ethiopia, demonstrating that the introduction of this species is a cheap, effective technology regarding soil and water conservation in the rehabilitation of gullies, providing food, animal feed, fuel, and fiber, and having an additional function as a windbreak, which helps to reduce the loss of water by evaporation in semiarid areas. Dabny *et al.* (1996) and Ritchie *et al.* (1997) showed that vetiver (*Vetiveria zizanioides*) and miscanthus (*Miscanthus sinensis*) planted close to the areas of flow concentration were effective, causing the deposition of eroded sediments and preventing the incision of the gullies. Leguédois *et al.* (2008) studied the efficacy of sediment traps through the use of buffer strips, concluding that - even for intense rainfall events - tree belts are very efficient. Knight *et al.* (2010) verified the capacity of the remaining riparian forests, with and without a grass filter, to diminish the concentrated surface runoff and thus the initiation of gullies. Meyer *et al.* (1995) analysed the effectiveness of narrow hedges of tall and rigid species to trap sediments, showing that they have great potential to retard runoff and reduce sediment losses. Richet *et al.* (2016) noted the role of vegetative barriers comprised by dense shrub hedges in reducing runoff and erosion, and indicated how the effectiveness of this measure is greater in traps that are placed immediately downstream of the erosion sources.

Bravo Espinosa *et al.* (2007) suggested a scheme to stabilize slopes and reduce erosion in gullies in a micro-catchment in Mexico. This scheme included planting plant species that showed good development in the slopes and gully bottoms, but the authors mentioned that for these measures to be effective grazing must be eliminated. Mongil *et al.* (2015) evaluated a 50-year-old forest and gully restoration in Spain using Pine trees. The current state of this restoration demonstrates the rehabilitation of the ecosystem and the important reduction of the problems of concentrated erosion. Other studies have focused on introducing plant barriers consisting of various species (Erktan *et al.*, 2013), and concluded that morphological diversity does not increase sediment retention in marl

gullies, while grass barriers with native species retain the sediment better and are the best strategy to initiate the ecological restoration of gullies.

Yuan *et al.* (2009) conducted a review of the effectiveness of vegetation traps for sediment retention in agricultural areas, and concluded that retention efficiency does not vary according to vegetation type. Rather, it declines as the size of the sediments decreases - suggesting that the retention efficiency depends on the soil type from which the sediment is derived and the rainfall energy, as the primary source of aggregate dispersion. Desta and Adugna (2012) mentioned that the recovery of vegetation will be slow on poor soils and therefore hampering gully control or restoration.

#### *4.2.3. Combined structural and vegetative measures*

The techniques that combine structural and vegetative measures undoubtedly have the highest efficiency (Nyssen *et al.*, 2009; Zhang *et al.*, 2010), although they are not always the most used. In the WOCAT database, they have been applied in 10 cases, corresponding to 38.5% of our sample.

In various experiments, the combination of vegetative and structural measures has shown positive results. In southern China, Sheng and Liao (1997) successfully implemented control measures combining check dam construction and reforestation. In Germany, Fiener and Auerswald (2006) combined soil conservation measures with structural measures and reduced sediment by 87%; the effectiveness increased to 93% when vegetative measures were integrated. In Ikali Creek (Colorado, USA), Weinhold (2007) evaluated a restoration project carried out 40 years earlier using a combination of structural and vegetative measures, and reported excellent results. Its success is explained by the large-scale basin wide implementation of measures and involving management of vegetation and grazing, perfection of hydraulic designs, the use of textiles to install vegetation in the bottoms of the channels, and the fertilization of the vegetation. Forty years after their construction, the structures had not failed, the ephemeral course had become perennial, and the erosion had been controlled. In Córdoba (Spain), Mora Jordano *et al.* (2013), in an experiment on the control of gullies through the use of forest vegetation and gabion check dams on farms, achieved control of the erosion in the gully head area and on its slopes. They reported specifically the important role of root development of the vegetation. At the same time, the revegetation had enhanced the biodiversity and substantially improved the landscape. In Ethiopia, Addis *et al.* (2015) found that structural erosion control measures along with biological measures resulted in a reduction of soil loss and the stabilization of gully expansion providing an important benefit to maintain crop productivity. In the North Cape province of South Africa, Schmiedel *et al.* (2016) reported that, two years after the application of the combined restoration measures, soil depth and vegetation cover had increased. Mekonnen *et al.* (2015) reviewed the effectiveness of different sediment trapping measures (both structural and vegetative) for sediment retention and concluded that in most cases their efficiency is very high, with average values between 70% and 100% of trapped sediment.

### 4.3. Ecosystem services derived from gully control

Our analysis illustrates that gully control measures especially benefit regulating ES (Fig. 10). However, the application of these technologies also improves our knowledge of soil erosion and conservation, helps strengthening institutions, (i.e. cultural ES) and, in some cases, enhance the supply of food, water, fiber, land, and wood products (i.e. provisioning ES). Gully control seems to be least relevant for supporting ES, although protection of genetic pools, soil formation and regeneration are worth mentioning.

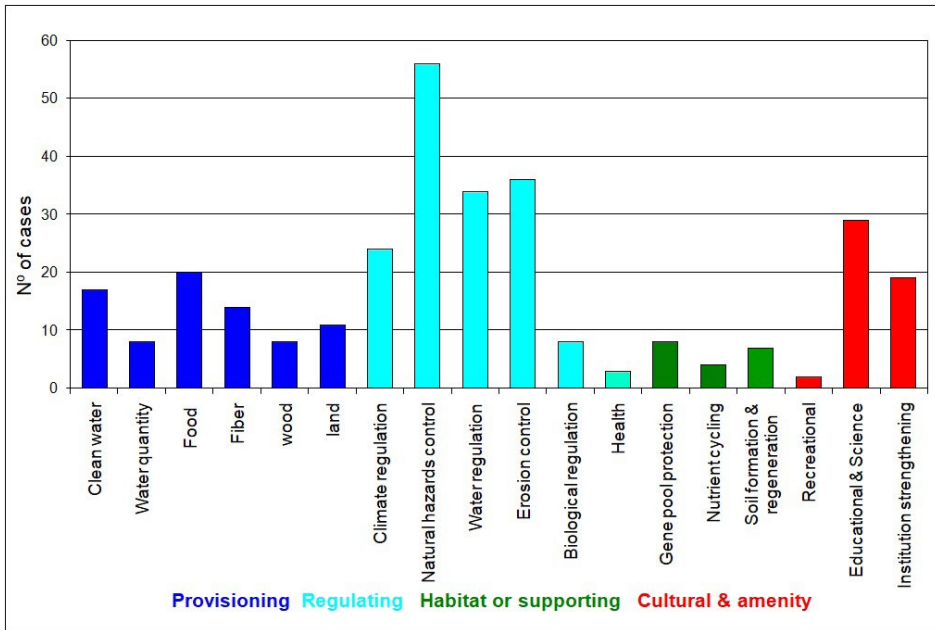


Figure 10. Main ecosystem services provided by gully control quantity.

The main objective of gully control is to stabilize them and prevent their further development by controlling the concentrated erosion processes by water. This study has verified that most of the techniques used to control such erosion have been quite effective, judging by the results documented in WOCAT and many other scientific studies. Erosion control exerts a series of chain effects mainly related to water regulation (surface runoff and underground flows), climate regulation (carbon sequestration due to improved soils and vegetation cover), and regulation of biological diversity (increased plant and animal diversity). All this contributes to regulating or minimizing the natural risks related to floods, sedimentation, damage in neighbouring fields, adverse events, and damage to infrastructure.

With regard to natural hazards, it is difficult to fully assess or account for all the costs to society, including costs by sedimentation in farmland, maintaining drains or



drainage channels clean, damage to different infrastructures, the loss of capacity and functionality of reservoirs, or other damage caused by floods. Nevertheless, it is evident that implementation of gully control measures is certainly worth the effort if they can minimize the natural hazards including local and regional impacts.

## **5. Conclusions**

Soil erosion and their on-site and off-site impacts is one of the major problems facing sustainable agriculture around the world today. Gully erosion is the most important water erosion process often contributing to major soil losses and sedimentation downstream. The “on site” effects mainly affect crop productivity and yields, and “off site” effects refer to increased flooding, reservoir siltation, damage to crops and infrastructure, and non-point source contamination.

In spite of the great number of existing studies on erosion processes in gullies, those related to their control are in the minority and there is still a need to investigate effective techniques to control, prevent or restore this type of erosion. The WOCAT database has shown to be a very important source of worldwide information, enabling global reviews and knowledge exchange regarding SLM practices and their effectiveness. We provided an evaluation of gully control technologies applied at a global level based on a representative sample of documented technologies in the WOCAT database and additional critical review of broader scientific literature. Our review based on expert assessments from WOCAT and additional review of scientific literature illustrates the effectiveness of a great variety of techniques – from structural, to vegetative, and combinations between vegetative and structural. Results indicate that application of combined vegetative/structural measures and catchment wide integrated implementation plans are most effective and contribute notably to soil and water conservation.

It is important to highlight the opinions of both experts and farmers regarding the different technologies and the problems of land use that have led to different actions of gully control. Experts often point out the causes of erosion, while farmers focus more on how erosion affects them, such as the decline in usable land or crop yield. Experts and farmers agree on highlighting overgrazing as one of the fundamental causes of land degradation and gully formation in almost all countries.

Our evaluation emphasises that the implementation of gully control measures yields socio-economic production benefits, as well as socio-cultural, local ecological, and off-site benefits. Some, especially socio-economic, disadvantages of gully control measures are outweighed by the many advantages - particularly the increases in farmers’ income, crop yields, or wood and forage production. The most compelling argument for farmers to adopt a measure and invest in soil and water conservation is to increase land productivity and provide economic benefits. From a socio-cultural point of view, farmers’ knowledge of soil erosion and conservation is improved and community institutions are strengthened. The ecological and off-site benefits are the most important, particularly the reduction of soil loss, the increase in soil moisture and vegetation cover, and the reduction of floods and the societal risks derived from them.

In general, the cost-benefit ratio of the different technologies is positive or very positive, especially in the long-term. However, despite their important benefits, it is not always possible to implement gully control measures because farmers or land users encounter multiple technological, economic, institutional and cultural barriers for implementation. Often farmers cannot assume the costs of implementation and maintenance, lack sufficient knowledge, or are in a situation with insecure land tenure. For this reason, institutional assistance is necessary to ensure that the most effective locally adapted measures can be implemented. To support and stimulate wide scale adoption of effective measures it is crucial to have detailed and reliable information on the costs and benefits at local and regional levels.

Therefore, the cost-benefit assessment should be made considering not only the monetary aspects of implementation and maintenance, but also the ES that the different gully control measures contribute locally and regionally to society as a whole. If these ES were evaluated and quantified in detail, the cost-benefit ratio would undoubtedly be even more positive.

The implementation of the different gully control measures strengthens important Ecosystem Services (ES) in all categories, but especially regulating ES stand out (e.g. erosion, water cycling, natural hazards, floods).

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