Towards climate-smart sustainable management of agricultural soils

SCALE

Managing Sediment Connectivity in Agricultural Landscapes for reducing water Erosion impacts

Deliverable WP5-D4

Guidelines for implementation of the mitigation measures with end-users adapted to local conditions

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Abstract

This report presents a structured framework designed to assist practitioners and decision-makers in identifying, selecting, and implementing erosion control measures (ECMs) tailored to local conditions for reducing both on-site and off-site erosion impacts and sediment transport at agricultural catchment scale.

The proposed framework leverages insights from previous SCALE tasks, guiding land managers and decision-makers to: (i) detect the most prevalent erosion processes and asses associated risk; (ii) evaluate various erosion control options, emphasizing those supported by the CAP's National Strategy Plans; (iii) provide criteria and tools for assessing and selecting ECMs, and (iv) develop erosion control management scenarios to be used in public participatory decision processes.

By integrating technical, economic, and social evaluations and emphasizing participatory methods, the framework aims to support the development and implementation of effective erosion control plans that are context-specific and widely accepted by stakeholders.

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1 Introduction

This report presents a structured framework that guides practitioners and decision makers in identifying selecting and implementing erosion control measures tailored to local conditions for reducing on-site and off-site erosion impact and sediment transport at agricultural landscape scale.

The selection of appropriate erosion control measures (ECMs) is a crucial yet difficult task. The available erosion control measures need to be assessed considering the technical and economic, and financial, aspects as well as social acceptance. The use of participatory evaluation methods has come to be a widely accepted tool to foster discussions, negotiations and agreements among the different stakeholders as to reconcile the various views and interest in land use.

However, participation of different stakeholders in identifying and selecting ECMs does not necessarily result in selection of better solutions. There is lack of guidance for decision-makers and stakeholders to select the most efficient options to be implemented by erosion control management plans (Schwilch et al., 2012). Yet few practical tools for facilitating the process in which land managers and decision makers share select and decide on most suitable ECMs.

The proposed framework is built upon on results and benefits from the knowledge gained in previous SCALE tasks as reflected in subsequent reports. Specifically, the framework guides land managers and decision makers to: (i) detect the most prevalent erosion processes and evaluate associated risk and impacts; (ii) screen the different options for erosion control with special emphasis in those measures supported by the CAP´s National Strategy Plans; (iii) provide criteria and tools for assessing and selecting erosion control measures, and (iv) elaborate erosion control management scenarios as basis for discussion and negotiations between the stakeholder involved in the formulation, development and implementation of soil erosion control plans at local and regional level.

In the first part of this report, we present the elements and structure of the integrated framework. The proposed framework is then applied to pilot catchments as exemplar case studies in the second part. The report finalizes with a comprehensive summary, highlighting the most remarkable conclusions.

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2 The integrated decision framework: Elements and structure

The integrated decision framework (IDF) is composed of four pillars that are applicable across a wide range of scale, although preferably at catchment or landscape level. Figure 1 shows how to translate the core pillars into operational steps and tasks.

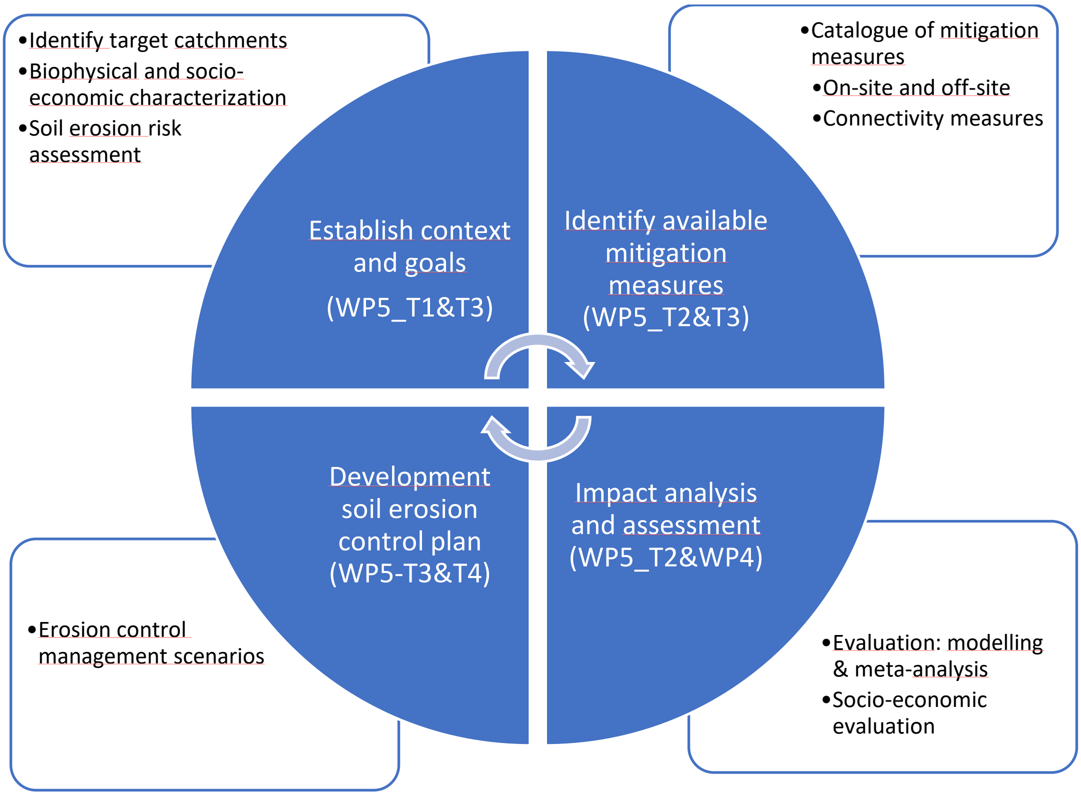

Figure 1. Integrated decision framework.

2.1 Establishing context and goal

To effectively develop and implement an erosion control plan, it is essential to establish the biophysical, socio-economic, and political/institutional contexts. This involves the identification and characterization of the target catchments to define and delineate the spatial context and systems boundaries for erosion control plans and programmes.

The target agricultural catchments for applying an erosion control plan are those experiencing unsustainable soil erosion rates (Panagos et al., 2015), with both on-site and off-site impacts threatening soil health and water quality. For each selected catchment a detailed description of physiographic features, soil properties and land use characteristics should be provided. Additionally, a preliminary enumeration of the most prevalent erosion processes and sediments transports impacts is included.

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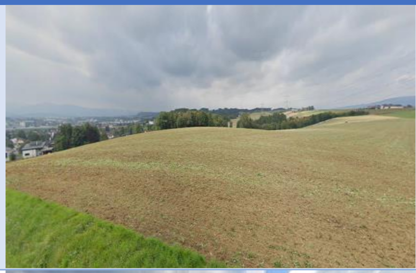
Given that the perception of erosion problems and the identification of possible measures to cope with them are highly context-dependent, it is advisable to conduct this analysis through a public, participatory approach incorporating various stakeholder's perspectives and interest.

The SCALE project used two primary criteria for selecting target catchments: the extent and intensity of soil erosion processes, and land use distribution. Thus, the selected catchments showcase a representative sample of European agricultural landscapes. For each of these catchments a summary of the physiographic features, soil properties and land use characteristics as well as the description of erosion and sediment impact observed is provided (Table 1).

Table 1. Characterization of target catchments.

Catchment	Topography	Soil/Geology	Land Uses	Erosion and sediment impacts	
HOAL-Austria	Rolling hills	Cambisols over fluvial and loess deposits	Conventionally farmed croplands with typical crop rotations for pig farms	On-site erosion problems on unfavourable locations and high connectivity between fields	
Maarkebeek-Belgium	Hilly landscape	Sandy loam to loamy soils	Arable lands (76%) occupied by pasture (29%), corn (13%) and potatoes (9%)	Evidence de soil loss by surface erosion and gullies. Muddy flows and sediment transport through connectivity elements	
Molenbeek-Belgium	Hilly landscape	Loamy soil	Arable land (77%) occupied by pasture (8%), corn (14%), potatoes (9%) and fruits (10%)	On site soil losses and gullies. Muddy flows impacting infrastructure	
Hesselbaek-Denmark	Gently rolling	Luvisols, Cambisols and Podzols, fine-sandy loam sands over late glacial marine deposits and glacial tills	Mixed arable lands	High erosion rates on steepest topography and high connectivity to first order streams	
Varbro-Denmark	Gently rolling	Podzols and Alisols fine-sandy loamy sands over late glacial marine deposits and glacial tills	Mixed arable lands	High erosion rates on steepest topography and high connectivity to first order streams	

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Aurajoki-Finland	Flat landscape with steep river banks	Clay soils	Arable land (33%) predominantly occupied by spring cereals and perennial grass	High erosion rates near rivers and river banks and well connected through subsurface drainage and ditches to rivers networks	
Barriga-Spain	Rolling hills	Clastic rocks with calcarenites and siliceous sandstones and white marls	Woody permanent crops (olives and vineyards)	High erosion rates and gullies formation. High connectivity between parcels	

The description of the targeted catchments is supplemented with a soil erosion risk assessment to determine the current status of soil erosion in the catchments: the main active erosion processes, their intensity, and locations. Although field-based methods exist, risk analysis is predominately carried on by soil erosion models tailored to the specific types of soil degradation processes, the available data, and team expertise. The results of the soil erosion risk analysis will later aid in identifying, selecting and prioritizing the most appropriate soil conservation measures for the catchment through a participatory evaluation process, as well as optimize the spatial location pattern. It also serves to set up the baseline scenario against which compare other erosion control and evaluate the benefits resulting of the implementation of mitigation measures (see section 2.4 on scenarios).

Three of the most commonly applied soil erosion models—RUSLE, RUSLE together with a connectivity index (IC) and sediment delivery ratio (SDR), and WaTEM/SEDEM—were used in the SCALE project to show the inherent soil erosion risk of each agricultural landscape. The results of the soil erosion risk assessment were utilized as communication tools, in the form of erosion risk maps, to facilitate discussions with stakeholders during the participatory process (Table 2).

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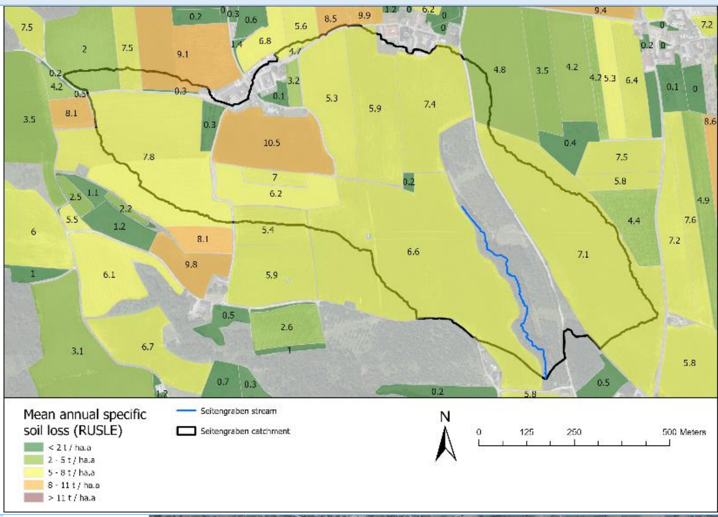
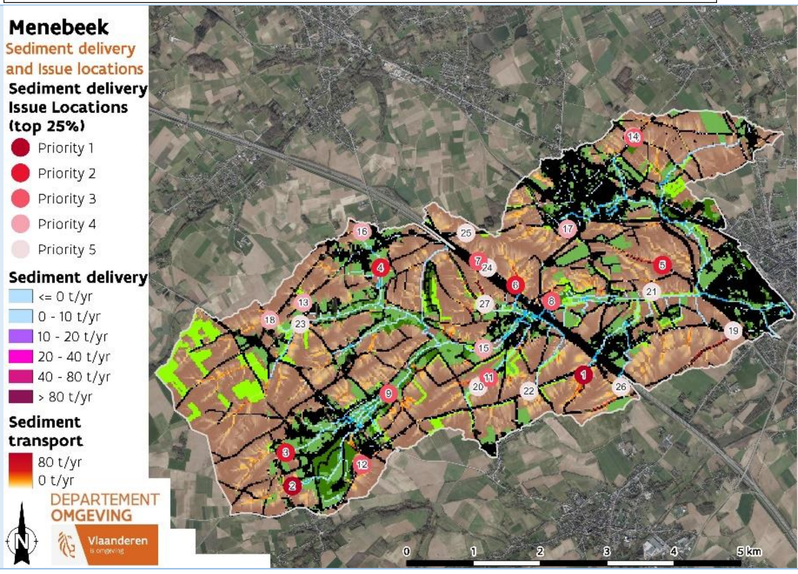
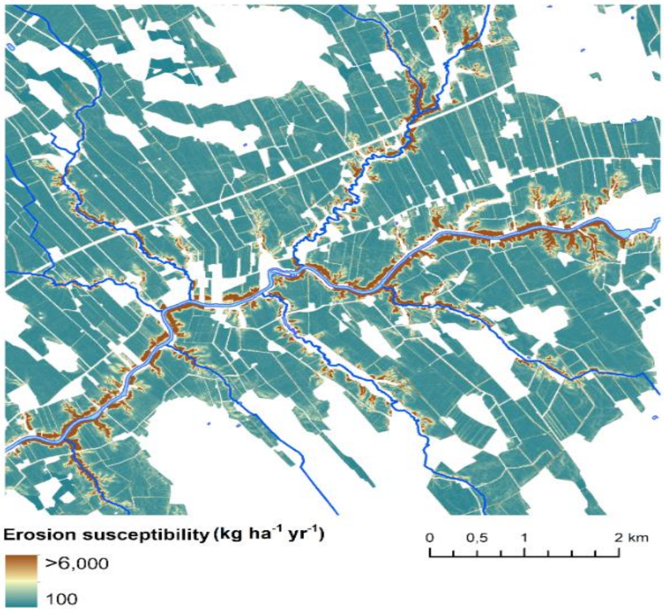
Table 2. Erosion risk assessment in three selected catchments of SCALE project.

Catchment	Erosion Risk Assessment		
	Erosion processes	**Assessment erosion model(s)**	**Risk erosion map**
HOAL	Interrill Rill Gullying	RUSLE	
Molenbeek	Interrill Rill Gullying	WaTEM/ SEDEM	

Aurajoki	Interrill Rill	RUSLE, Connectivity Index Sediment Delivery Ratio	

2.2 Identify available mitigation measures

Once the intervention context has been established, the next step is to identify available mitigation measures. Various databases and catalogues of sustainable soil management and best practices for soil and water conservation can be screened to compile a list of potential available mitigation measures (Gomez Calero et al., 2021). The objective is to identify a list of possible erosion control measures tailored to the erosion problems and impacts identified in the previous step. These practices will be assessed through a participatory evaluation process considering their technical, economic and social feasibility. The SCALE project focused on practices aimed at reducing soil erosion losses and sediments delivery by reducing hydrological and sediment connectivity at the landscape scale (Table 3). A more detailed description of these practices is given at SCALE (2023a).

Table 3. Erosion control measures considered in SCALE.

Measures	**Short description**		
		On-site/ Off-site measure	Disconnection measures (Y/N)
Land use			
Afforestation	Conversion of agricultural land to forest	On	Yes
Permanent grassland	Maintenance of a permanent grassland cover	On	Yes
Perennial crops	Cultivation of crops all around the year than implies longer growth season, denser vegetal cover and stronger root systems than annual crops	On	Yes
Crop rotations, crop diversification	Alternate crops less prone to erosion with main crop. Diversify the patchwork of land uses at landscape level	On	Yes
Set aside	Taking out part of the arable land temporarily	On	No
Intercropping	Simultaneous cultivation of two or more crops in the same plot	On	No
Agroforestry	Housing woody plants and crops (or livestock) in the same parcel	On	No
Parcel size	Reducing parcel lengths to reduce accumulation and erosive power of runoff	On	Yes

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Terracing	Alter landscape topography alternating flat and steep segments to store and reduce runoff volume	On	Yes
Agronomic			
Cover crops	Establish crops to provide soil cover and avoid bare soils during winter and fallow period	On	No
Mulching, crop residues management	Apply natural or artificial layer of plant residues or other material (inert) to soil cover	On	No
Tillage practices	Reduce or avoid (non-till) tillage operations	On	No
Contour farming	Perform tillage, planting and other farming operation along contour of the field slope	On	Yes
Sowing practices	Modifying (doubling or wide -spreading) sowing operations to reduce soil erosion	On	No
Micro-dams between ridges	Building small earth dams transverse to furrow lines	On	Yes
Soil surface roughness	Increase surface depression and barriers to trap water flows and sediments	On	No
Reduction of soil compaction	Avoid increasing bulk density caused by heavy machinery	On	No
Increase of soil organic matter	Implement measures that avoid and reduce soil carbon losses and incorporate carbon from plant residues or exogenous sources	On	No
Buffering			
Grass buffer strips	Buffer strips made by grass and implemented within filed, at field margin or adjacent to watercourses	Off	Yes
Hedges and hedge rows	Linear plantation of grasses or shrubs	Off	Yes
Grassed waterways	Grassed areas set in thalwegs and flow lines to reduce flow velocity and energy	Off	Yes
Fascines	Vegetative barriers across the flow made of bunches of stems	Off	Yes
Dams in organic material	Vegetative barriers made of vegetal residues	Off	Yes
Silt fences	Fence of geotextile material sustained by wooded post set across the slope	Off	Yes
Earthen dams and retention ponds	Structures to store and delay runoff and increase sediment settling duration	Off	Yes
Buffering ditches	Mand -made channels to collect surface and subsurface runoff. They often follows the limits of agricultural parcels	Off	Yes
Walls	Structures made of stone to retain soil and water upslope	Off	Yes

2.3 Impact analysis and assessment

The selection and prioritization of erosion control measures for implementation in the target catchments are based on a suitability analysis considering both technical and economic criteria as well as social criteria. The technical assessment helps land managers decide which mitigation measures are most appropriate, considering the type and intensity of identified degradation processes and their on-site and off-site impacts. This assessment evaluates the effects and efficiency of available erosion control measures (ECMs) in reducing soil losses and diminishes water and sediments flows through dis-connectivity.

Erosion control measures impact water flow by enhancing soil infiltration capacity through increased soil organic matter content and enhanced aggregate stability, thereby reducing the volume of surface runoff. Other measures increase soil surface roughness, which enhances depressional water storage of runoff. Additionally, soil conservation measures reduce the energy of runoff by decreasing its velocity, increasing surface roughness, and shortening or altering flow paths by interrupting or redirecting them.

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Regarding sediment flow, erosion control measures reduce the detachment of the soil matrix into erodible particles by covering and protecting the soil from raindrop impact and lowering the shear stress of runoff capacity transport.

A third group of effects are those concerning hydrological and sediment connectivity across catchments. While some practices and connectivity elements (parcel size and borders, roads, ditches, tillage directions) favour water and sediment flows and amplify the structural and functional connectivity of the landscape, other measures impede or retard the evacuation of water and sediment, sometimes by disrupting or changing the direction of the flow paths, thereby reducing the off-site effects.

Table 4 summarizes the effects of soil erosion and connectivity of the ECMs considered in the SCALE project. A detailed description of the effects of the erosion control measures and connectivity elements are given in SCALE (2023b).

Table 4. Impact of mitigation measures on soil erosion and connectivity.

Measures	Effects on water				Effects on sediments		Effects on connectivity		
	Infiltration	Surface storage	Flow velocity	Flow direction	Detachment	Transport capacity	Connecting	Disconnecting	Altering flow direction
Land use									
Afforestation	✓	✓	✓		✓	✓		✓	
Permanent grassland	✓		✓		✓	✓		✓	
Perennial crops	✓		✓		✓	✓		✓	
Crop rotations, crop diversification	✓	✓	✓		✓	✓		✓	
Set aside	✓	✓	✓		✓	✓		✓	
Intercropping	✓		✓		✓	✓		✓	
Agroforestry	✓		✓		✓	✓		✓	
Parcel size			✓			✓	✓	✓	
Terracing	✓	✓	✓	✓	✓	✓		✓	
Agronomic									
Cover crops	✓		✓		✓	✓		✓	
Mulching, crop residues management	✓		✓		✓	✓		✓	
Tillage practices	✓		✓		✓	✓		✓	
Contour farming and sowing practices	✓	✓	✓	✓	✓			✓	✓
Micro-dams between ridges	✓	✓	✓			✓		✓	
Soil surface roughness	✓	✓	✓		✓			✓	
Reduction of soil compaction	✓							✓	
Increase of soil organic matter	✓				✓			✓	
Buffering									
Grass buffer strips			✓			✓		✓	
Hedges and hedge rows			✓			✓		✓	

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Grassed waterways	✓		✓		✓	✓		✓	
Fascines			✓			✓		✓	
Dams in organic material			✓			✓		✓	
Silt fences			✓			✓		✓	
Earthen dams and retention ponds		✓	✓					✓	
Buffering ditches			✓	✓			✓		✓
Walls			✓	✓	✓	✓		✓	

Technical evaluation of the erosion control measures is supported by the use of soil erosion models. The depth and extent of this evaluation depend on the model´s capacity to incorporate the effects of ECMs in their parameterization and structure. SCALE (2023b) provided a thorough description on the capabilities and potential of the common erosion models used across Europe to support the evaluation of the impact of mitigation measures on soil erosion and connectivity that are summarized in Table 5.

Table 5. Capability of two erosion models to simulate impacts of ECMs.

Measure	**RUSLE**		**WaTEM/SEDEM**
	Field slope/Plot scale	Spatially distributed	
Land use			
Afforestation	R	R	R
Permanent grassland	R	R	R
Perennial crops	R	R	I
Crop rotations, crop diversification	R	R	I
Set aside	R	R	I
Intercropping	R		I
Agroforestry			I
Parcel size	R	R	R
Terracing	R		
Agronomic			
Cover crops	R	R	I
Mulching, crop residues management	R	R	I
Tillage practices	R	R	I
Contour farming and sowing practices	R		R
Micro-dams between ridges	I		I
Soil surface roughness	R	R	I
Reduction of soil compaction			I
Increase of soil organic matter	R	R	I
Buffering			
Grass buffer strips	R		I
Hedges and hedge rows	I		I
Grassed waterways			I
Fascines	I		I
Dams in organic material	I		I
Silt fences	I		I
Earthen dams and retention ponds			R
Buffering ditches		I	I
Walls	R		

(R, ready, green cell: the model at its current formulation can incorporate the effect of the measures, I improvement orange cell: an improved version of the model and the parameterization procedure could account for the effect of the measure; Red empty cell: the model cannot simulate the effects of the mitigation measure).

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The technical evaluation should be accompanied by an assessment of socio-economic issues that influence the adoption and implementation of ECMs by farmers and other stakeholders. The adoption of erosion control measures heavily depends on their economic aspects and how they affect the perception of the farmers about the profitability the farming system. Two elements were considered in the SCALE project to account the economic dimension for assessing the ECMS: whether or not the measure is subsidized by the CAP Strategic Plans and the local costs estimated from CAP subsidies. Social acceptance in terms of farmers preference and capability was assessed through focus groups meetings held in each catchment. Table 6 shows the economic and social assessment in HOAL catchment in Austria as an example.

Table 6. Economic and social evaluation of mitigation measures at HOAL catchment (Austria).

Measure	Economic Assessment		Social acceptance	
	Subsidized by the CAP? (Y/N)	Local costs (€/ha)	Farmers´ Preference[1]	Capability[2]
Land use				
Crop rotations: grass rotation	No	114[3]	4	3
Agronomic				
Cover crops	Yes	Arable lands: 75-90 Vineyards: 180-880 Fruits: 180-385 Hops: 180-220	2	5
Mulching, crop residues management,	Yes	50	1	5
Tillage practices: no till or strip till	Yes	80	4	2
Micro-dams between ridges	Yes	150	Not relevant	1
Buffering				
Grass buffer strips	No	633[3]	4	3
Grassed waterways	Yes	550	3	2

[1] Farmer´s preferences is ranked from 1 most to 4 less preferable option. Not relevant indicates practices that were not considered by participants in the focus group meeting but are subsidized by CAP Strategy Plan.

[2] Capability is ranked from 1: incapable to 5: fully capable.

[3] For those practices not subsidized by the CAP, the estimation of local cost is based on SCALE (2024 b).

2.4 Building erosion control management scenarios

The final phase involves developing erosion control and sediment connectivity management scenarios across various scales, from farms to catchments. This process integrates selected erosion control measures into soil erosion model simulations, as detailed in SCALE (2023c). These models serve as valuable tools for stakeholder discussions and decision-making by comparing the baseline, also referred as the "As-is" scenario, with different options created by implementing mitigation measures in various spatial arrangements.

Deploying erosion control management scenarios is a step-wise process (SCALE, 2023c) that builds on the outcomes of previous phases (Figure 2).

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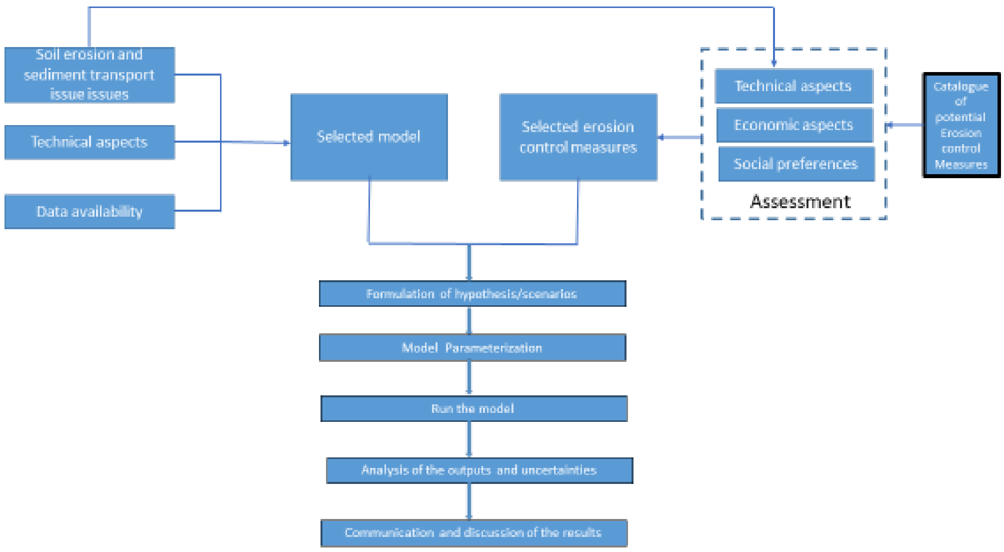

Figure 2. Flow-chart for building erosion control management scenarios.

The initial step is identifying critical soil erosion issues and the most suitable measures to address them. This step benefits from the characterization of the target catchments in Phase 1 of the IDF and the assessment of potential mitigation measures in Phase 3. An example of the outputs of this step in selected catchment within the SCALE project is shown in Table 7.

Table 7. Identification of critical erosion issues and potential solutions.

Study areas	Objective	Erosion control measures and connectivity in the simulations
Slovenia: Drnica (29 km^2) catchment in Istria and Grosupeljščica catchment (36 km^2) in Dolenjska region.	To assess the effects of mitigation measures, including terracing, in two areas with contrasting soil erodibility	Terraces, reduced tillage practices; crop residues; cover crops in inter-row spaces of vineyards and olive crops.
Finland: Aura (147 km^2) and Mustio (116 km^2) in southern Finland	To evaluate the impacts of erosion and connectivity measures on soil erosion and sediment transport Benefits of considering connectivity in allocating erosion control measures at catchment scale	No-till (winter-time stubble) and riparian buffer strips (30 m wide) in spring cereals crops
Belgium/Flanders: Maarkebeek (50 km^2) and Menebeek catchments (30 km^2), in southern part of Flanders	To incorporate future landscape management plans and to evaluate impact of management scenarios Combine different scenarios as guidelines to erosion control management planning	Reduced tillage; riparian buffer strips; extra buffer strip scenario; conversion and conservation of grasslands in terrains above a specific slope

Next, a suitable erosion simulation model should be selected based on the physical and geometric representation of the agricultural landscape. This includes a conceptual model that represents the geometric configuration and the main landscape elements: sediment sources areas affecting by on-site erosion issues, connection elements, flow routing and transport paths, deposition areas, and connected water bodies receiving off-site impacts. The landscape configuration affects structural and functional connectivity, helps identify sensitive locations for action, and determines the spatial context and scale of the plan.

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Considerations for model selection include data availability for model inputs and validation, and the model's capacity to simulate main erosion processes, represent landscape connectivity, and incorporate mitigation measures by modifying structure or parameter values. Once selected models need to be set up for running simulation scenarios, involving parameterization, validation of simulated outputs, and conducting sensitivity analyses to provide information about result uncertainty.

Creating simulation scenarios involves formulating specific hypotheses and questions, often using "what if?" scenarios, to resolve problems through a participatory approach (Table 8). Scenario formulation should consider the uncertainty in model outputs.

Table 8. Definition of soil control scenarios and parameterization of simulations erosion models in piloting catchments of the SCALE project.

Study area	Models	Scenarios	Parameterization
Slovenia	RUSLE	Arable lands with or without mitigation measures: reduced tillage, crops residues management and cover crops. Vineyards with inter-rows covered by cultivated fallow or by other winter soil covers Intensive orchards and olive crops with inter-rows covered by cultivated fallow	C factor adjusted o based on Panagos et al. 2015 Terracing effects accounted by modifying LS factor
Finland	RUSLE/ IC_SDR	Erosion rates and sediment delivery under mitigation measures: no-till, buffer strips at field scale. Allocation of mitigation measures at catchment scale with or without considering connectivity	C factor adjusted to erosion control measures through an optimization process against erosion rates measured at experimental sites. IC/SDR parameterization based on literature
Belgium/ Flanders	WaTEM/ SEDEM	As-is scenarios or baseline considering the current land use and all known and in-use erosion control measures. Standard mitigation scenarios to evaluate the effects of common mitigation measures Specific scenarios including mitigation measures identified from local stakeholders	Parameters values based on guidelines (Van Oost et al., 2000, Van Rompaey et al., 2001, Verstraeten et al., 2002) Transport capacity parameter estimated through calibration with long-term transport and loads in water courses and ponds

The final step is communicating the results, including potential ranges or differences between alternatives, to farmers, land managers, extensionists, technicians in public and private administrations and institutions, and decision and policy-makers. Effective communication builds trust and ownership among stakeholders with differing interests, helping to reach a common agreement on action plans. It also facilitates the adoption of planned measures at the ground level. Decisions on how to communicate results include determining which model outputs to share, the format of the presentation (tables, graphs, maps), and how to incorporate the uncertainty of the results (Table 9).

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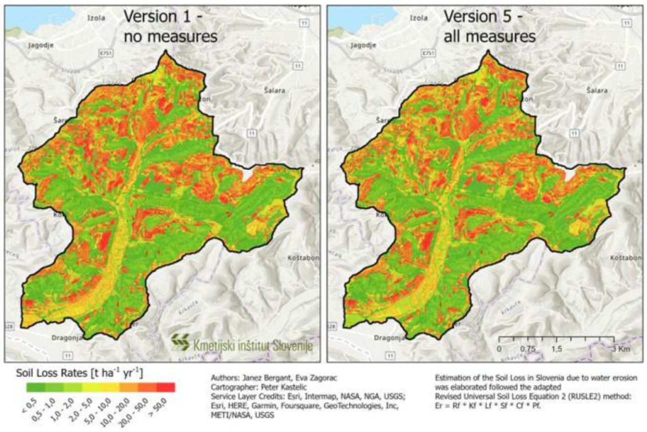
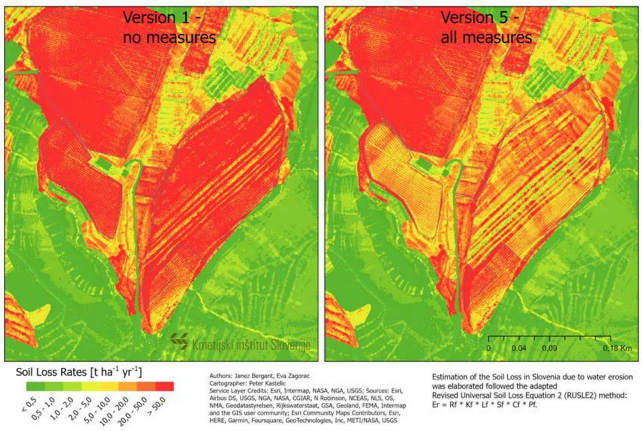
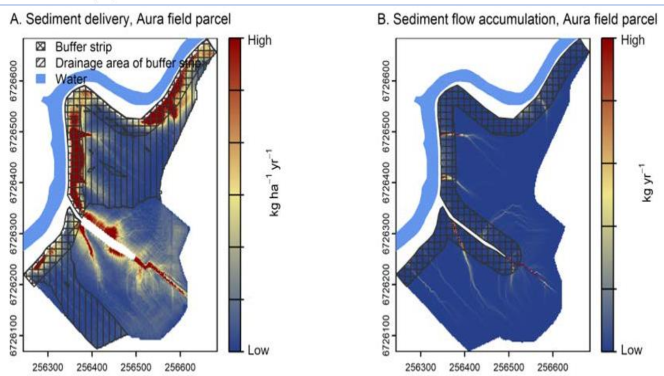
Table 9. Comparison of the impact of different erosion control scenarios in selected SCALE catchments.

Study areas	Scenarios	Description	
Drnica catchment, Slovenia	No-erosion control measures versus current implemented measures at catchment level. Erosion measures were implemented only under vineyards, intensive orchards and olive crops but not in all arable lands	9 % of reduction of soil erosion losses (from 17,6 to 16,1 t/ha/year)	
	Comparison of soil erosion losses between baseline (no measures) and erosion control in vineyard plots	Adoption of cover crops in vineyards reduce soil losses by 63% (from 48.9 to 8.1 t/ha/y)	
Aura river Finland	Implementation of no-tillage practices, buffer strips and an extended buffer strip in a 13 ha filed parcel with a current erosion rate of 3 t ha^{-1} year^{-1}	No-till reduce sediment delivery by 71-82% and buffer strips by36-52%. An extended buffer strip around the gully reduce an extra 13-17%	

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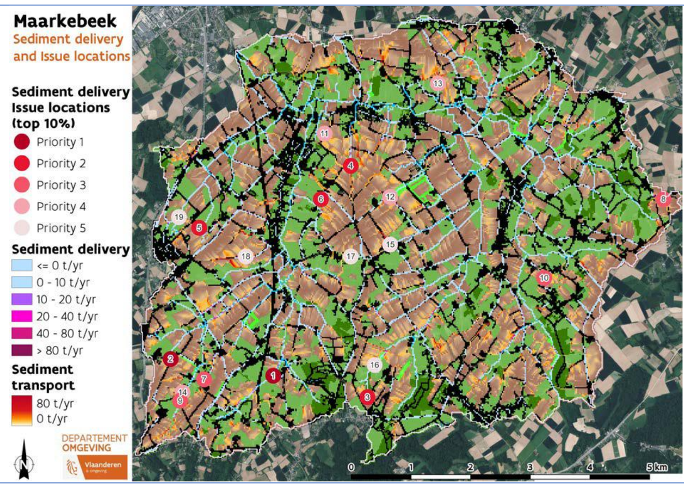
Maarkebeek catchment. Belgium/ Flanders	An as-is scenario representing the current land uses and implemented mitigation measures; null-scenarios where all the implemented measures are removed. A municipal plan scenario where all desired measures are implemented as planned.	The remotion of the current erosion control measures (null scenarios) mean an increase by 1% of erosion rate and 6% of the sediment yield delivered to watercourses as compared with As-is scenario. The implementation of Municipal Plan would entail a reduction of 26% and 51% of erosion rate and sediment delivery.	

3 Case study: The Barriga watershed

3.1 Introduction and biophysical context

Barriga watershed is an agricultural catchment with a high need for mitigation measures to address on-site problems (such as soil loss), and off-site damages (such as sediment delivery to waterways or infrastructure damage).

It is located between 37.48 and 37.51° N, 4.63 and 4.69° W, in the western valley of the Guadalquivir basin in southwestern Spain, and comprises an area of 17.1 km^2. The watershed’s relief ranges from 230 m at the outlet and 485 m at its Eastern limit. Gentle hills prevail in the study area, with altitudes ranging from 340 to 390 m high and a mean slope of 10 %. The soils in the area are dominated by Regosols and Fluvisols, formed mainly in marls, and calcareous sandstones deposited during the Miopliocene. Mean annual precipitation varies between 500 and 600 mm. The distribution of the precipitation shows a marked dry season between June and September, while the main wet period occurs from October to May. In the mid-20th century, land use consisted mainly of herbaceous crops and, to a lesser extent, olive groves, with some vineyards. This watershed falls under the Montilla-Moriles D.O., where the small agricultural area dedicated to vineyards has gained national acclaim. In recent decades, herbaceous crops have been replaced by olive groves progressively, occupying most of the study area (Table 10). Land use and soil management changes in olive groves, where ground cover is often removed, have exacerbated soil erosion processes. It is common to observe the formation of rills after rainfall, and the size and density of gullies in the area have increased in the last decades. In some vineyards, terraces were established to reduce the slope of the land. Today, this translates to areas with steep slopes that can become ecological focus areas (e.g., agroforestry, grass strips, hedgerows). Except for these exceptional cases, there are few physical boundaries, likely due to the current parcels being formed by the segregation of larger plots, resulting in high connectivity between plots.

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Table 10. Frequency of land uses within the Barriga watershed according to CORINE Land Cover 2018 and PAC 2023 (code adapted to CORINE land uses).

Barriga Watershed	**Non-irrigated arable land**	**Mixed forest**	**Vineyards**	**Olive groves**	**Complex cultivation patterns**	**Water bodies**	**Fruit trees and berry plantations**	**Urban use and infrastructures**
(CORINE Land Cover 2018)	0.0	0.0	5.1	76.8	5.1	0.0	0.0	13.0
(PAC 2023)	4.3	0.6	2.8	68.7	0.2	0.6	1.2	21.6

3.2 Socio-economic context: stakeholders and drivers

Most farmers face significant challenges related to erosion on their agricultural land. The main erosion problems in this watershed are associated with olive groves. The main issues for farmers are the sediment transport and the soil losses in their plots. Most of them are resistant to changing their agricultural management to mitigate erosion, and few of them have real interest in changes due to long-term problems. It would mean a major effort and small farmers do not obtain enough economic resources to board efficiently these issues. Typically, farm sizes are small, which affects profitability, especially when combined with the low market value of their products. Additionally, not all farmers are exclusively dedicated to agriculture; for some, it is a supplementary source of income. This can make it difficult for them to invest in necessary erosion control measures. The level of education and training in specific agricultural practices also varies. Some farmers have formal training, while others rely on knowledge passed down through tradition and custom. This disparity in expertise can impact their ability to effectively manage and mitigate erosion on their farms.

3.3 Erosion risk assessment

Barriga watershed shows visible signs of erosion in its olive crops, characterized by deep gullies and numerous rills. Monitoring some gullies has been conducted both in the field and with GIS. This process involves comparing flow accumulation maps with orthophotos showing the gullies (Figure 3).

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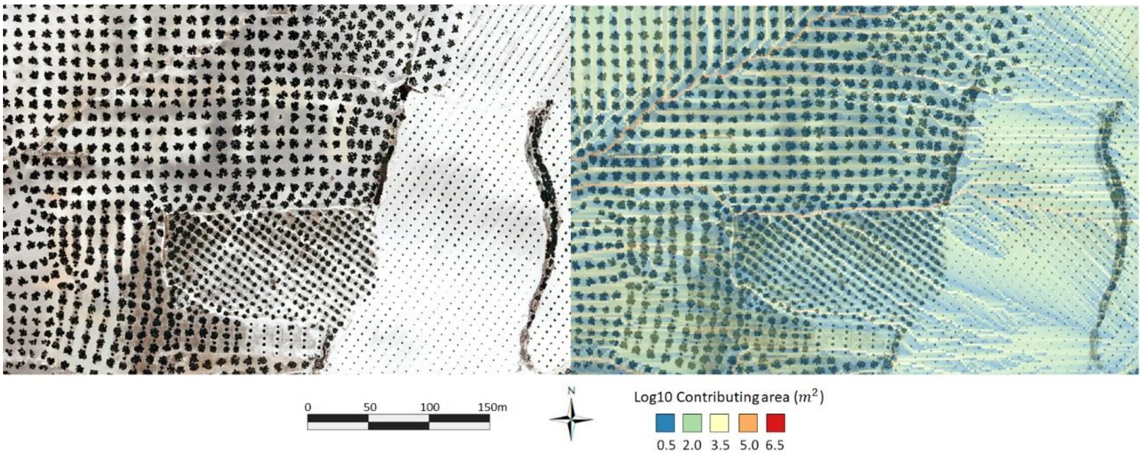

Figure 3. Comparison between orthophotos showing the presence of gullies (left), and contributing area maps [$\log_{10}(m^2)$] overlaid on the corresponding orthophoto (right). The legend is displayed with linearly interpolated colours.

Despite finding visible signs of soil erosion through field visits and orthophoto visualization (Figure 3), our empirical evaluation of soil loss (RUSLE) in the agricultural plots revealed fewer alarming perspectives. Applying RUSLE to the 2022-2023 management data, we found that 0.4, 3.3, and 83% of the agricultural parcels had soil loss of less than 0.12, 1, and 12 t ha^{-1} $year^{-1}$ respectively (Figure 4).

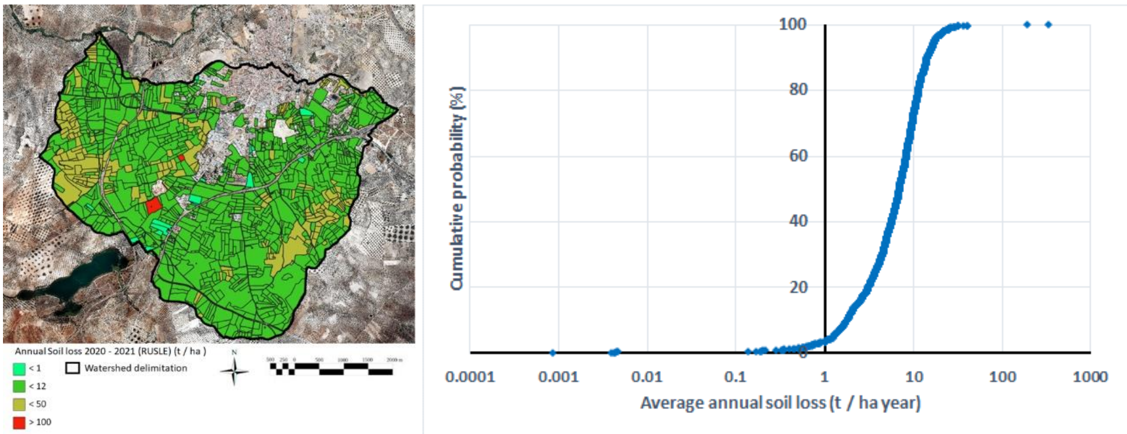

Figure 4 Left: Calculated soil erosion using RUSLE in Barriga Watershed (No urban land). Right: Cumulative probability distribution function of average annual soil loss in the croplands of Barriga Watershed.

3.4 Catalogue of mitigation measures

There exists a high number of erosion mitigation measures that are potentially applicable to address the soil erosion issues identified at Barriga watershed some of them have been already implemented in similar agricultural landscape in southern Spain. They are grouped in:

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i. Measures to be applied on sediment source areas (on-site impacts)

1. **Terraces** in crops are earthen embankments established across the dominant slope portioning the field in uniform and parallel segments. These terraces reduce soil erosion, manage water runoff, and improve the arability of hilly regions. Terraces are one of the most effective techniques to enhance soil and water conservation, particularly on steep slopes. However, their high construction and maintenance cost is one of the major obstacles to their implementation.
2. **Cover crops** under tree crops offer numerous benefits for sustainable agriculture and soil management. they are used for nutrient management, erosion control, weed and pest control, and improving soil properties and biodiversity. Today, cover crops are primarily viewed as an effective technique for controlling water erosion on hillslopes.
3. **Mulching** between tree crops implies using inert material to cover the lanes to protect the soil against erosion, improve soil quality, and control weed growth. It involves applying a layer of organic or inorganic material on the soil surface around trees. For cost and environmental reasons, mulching is carried out using pruning residues from the trees, although in some situations pruning residues or straw are brought from other farms. Mulching is also used as a substitute for, or complement to, cover crops, especially in arid and semiarid areas.
4. **Contour farming**: Tilling following the contour can be implemented depending on the slope, regularity of terrain, and layout of the plantation. On steep slopes contour cultivation is less effective for reducing soil erosion. Contour farming is most effective on moderate slopes on uniform terrain.
5. **Conservation agriculture** implies minimizing soil disturbance during agricultural management, known as conservation tillage. Conservation tillage is part of practically all national agro-environmental schemes worldwide, as in the regulations of the CAP in the EU. This is mainly due to their potential effectiveness in reducing soil erosion and (partially also runoff) for arable land.
6. **Agroforestry** is a land management system that integrates trees and/or shrubs with crops and livestock production on the same piece of land. The main goal of agroforestry is to develop more resilient and sustainable agricultural systems diversifying the uses and products produced in the same land.

ii. Measures oriented to control and detention of water and sediment flows

1. **Contour planting** of trees and vines consists of planting perennial vegetation on the contour to ensure that all the operations are made in the direction perpendicular to the maximum slope. Its purpose is to reduce runoff and water erosion. The contour planting practice implemented without terracing is not as effective as terracing because of the difficulty of keeping the tree lines perpendicular to the maximum slope, and the easiness of runoff to breach the tree lines. For this reason, it is usually implemented when the terrain has been terraced.
2. **Vegetative barriers** are permanent strips of dense vegetation located across concentrated flow areas whose main purpose is to trap sediment and agrochemicals transported by runoff, reducing sediment and agrochemical connectivity from upslope areas to the fluvial system.

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3. **Gully erosion control techniques**: Gullies are incised areas where concentrated runoff flow has eroded the terrain creating an ephemeral stream. In addition to becoming a major source of sediment, gullies divide fields increasing costs of farm operations and creating risks for staff that have to cross them or work nearby. Gullies can be of many different sizes, but they are usually classified as ephemeral or permanent gullies. Permanent gullies need more sophisticated techniques for their control. Check dam establishment with a good structural design, complemented with revegetation (shrubs and herbaceous plants in the gully boundaries), ensures gully restoration over time.

iii. Riparian zone management

1. **Landscape elements**: In those riparian zones belonging to farmers, landscape elements could be employed. They can provide numerous benefits in ecosystem services unrelated to yield. The major landscape element in riparian zones is the buffer strips (hedges or vegetative barriers located in the margins of the watercourses). In the current orientation of the CAP, these landscape elements typically fall under the category of "Ecological Focus Area (EFA)" and have been recognized for their significant role in enhancing biodiversity.

3.5 Impact assessment and selection of mitigation measures

The results of the public participatory assessment process, conducted through a focus group meeting (Figure 5), revealed that the most preferred practices for farmers to implement were the simplest and those already included in the CAP as part of the eco-schemes: cover crops, vegetal residue management, and no-tillage. The use of vegetated barriers (hedgerows), although not commonly implemented, could be an option if economic incentives and technical assistance are provided. More detailed information on the results of the focus group meetings can be found in SCALE (2024).

Figure 5. Focus group meeting with farmers of Barriga watershed.

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The impact of selected agronomic practices, such as cover crops and no-tillage, was assessed through changes in soil cover and management practices (C) for RUSLE by calculating differences in the Enhanced Vegetation Index (EVI) using SENTINEL images (Figure 6). On the other hand, the effectiveness of vegetative barriers, such as the proposed hedgerows, can be assessed by modeling the area connected or disconnected with and without the establishment of the barriers (Figure 7).

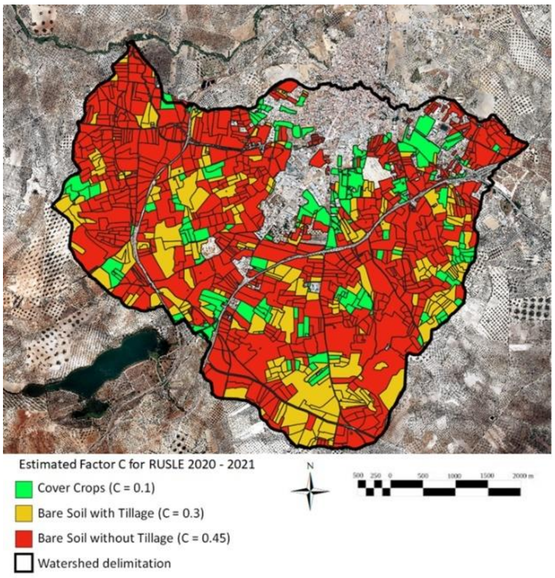

Figure 6. Estimated Factor C, obtained with the Enhanced Vegetation Index (EVI) difference between 17th March 2022 and 16th August 2023, in Barriga Watershed (No urban use).

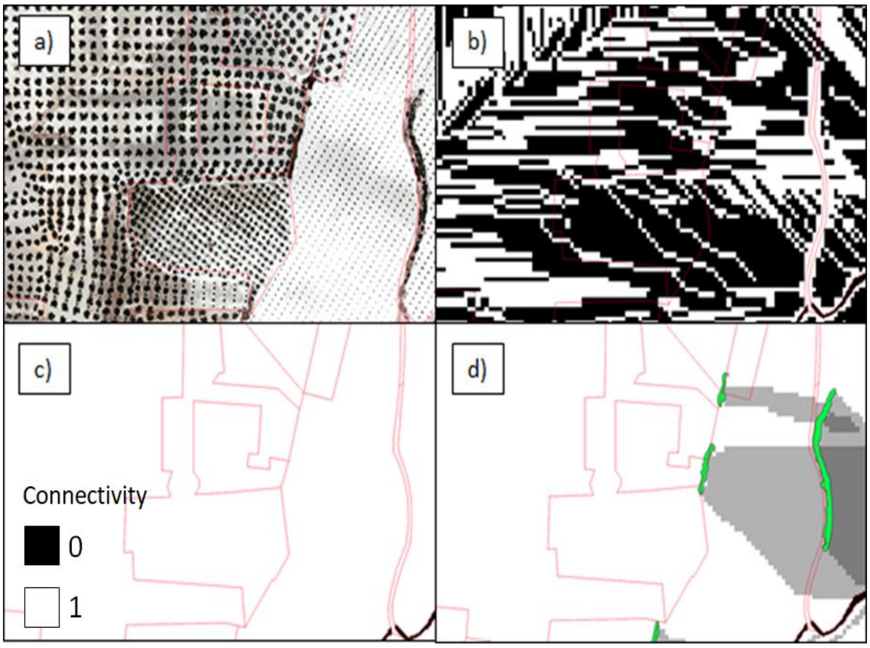

Figure 7. a) Orthophoto of an agricultural area within the Barriga watershed; b) Sediment connectivity with a rainfall event of 5.5 mm and an antecedent moisture condition II. The black area represents the disconnected area (value 0), the white area is the connected one (value 1);

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c) Sediment connectivity with a rainfall event of 45 mm and an antecedent moisture condition I and; d) the same case as c) but with vegetative barrier establishment in one of the parcels. the grey area is the partially disconnected area due to the effect of vegetative barriers.

To supplement the technical and social evaluations, the local costs of the most commonly applied mitigation measures and one specific measure addressing connectivity were calculated (Tables 11 and 12).

Table 11. The average cost of most common operations in cover crops management in woody crops.

VARIABLE	Cost (€/ha)
Brush-clearing	53.28
Harrowing (harrow cropper, subsoiler, etc.)	20.37
Pruning + rowing	182.42
Rowing + chipping	83.33
Chipping	28.35
Fertilisation	91.88
Sowing	84.91

Table 12. Cost of operations for implementation and maintenance for an experimental hedgerow per unit of area (m^2) unit of length (m) and per plant unit. The costs are based on the real costs of a previous project (Project) and the catalog prices of a Spanish public company (TRAGSA, catalog).

Costs	**Operations**	**Project cost (€ m^{-2})**	**Catalog cost (€ m^{-2})**	**Project cost (€ m^{-1})**	**Catalog cost (€ m^{-1})**	**Project cost (€/plant)**	**Catalog cost (€/plant)**
Implementation costs	Plantation	1.7	2.1	6.9	8.3	2.7	3.2
	Tillage	0.1	0.0	0.5	0.2	0.2	0.1
	No tillage	0.1	0.1	0.3	0.6	0.1	0.2
	Mulching	2.5	1.4	10.0	5.5	3.9	2.1
	Hose irrigation	0.7	1.3	2.7	5.4	1.0	2.1
	Drip irrigation	1.6	2.6	6.6	10.5	2.5	4.0
	Cylindrical growth tubes with tree stake	0.6	1.2	1.2	2.5	2.0	4.2
	Square growth tubes with a tree stake	1.5	2.7	3.0	5.4	1.5	2.7
	Tree stake	0.3	1.2	1.2	4.8	0.5	1.9
Maintenance costs (first year)	Maintenance without mulching	2.2	1.5	8.9	5.8	3.4	2.2
	Maintenance with mulching	0.4	0.5	1.4	2.0	0.5	0.8

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3.6 Definition of a control gullying development plan

Gully erosion is one of the most prominent features of soil degradation in the Barriga watershed as identified and observed by field and GIS-based inventories (Figure 3) as well as by farmers (SCALE 2024). Farmers also emphasized gullying as one of the major impacts of soil erosion on their farms, since it compromises mechanical operations such as tillage and mobility through field parcels. Besides, gully development increases the hydrological and sediment connectivity of the catchment resulting in significant off-site impacts such as reducing capacity of water reservoirs due to sediment siltation, degrading terrestrial and aquatic habitats linked to the drainage network and deteriorating water quality of water courses and bodies within the catchment.

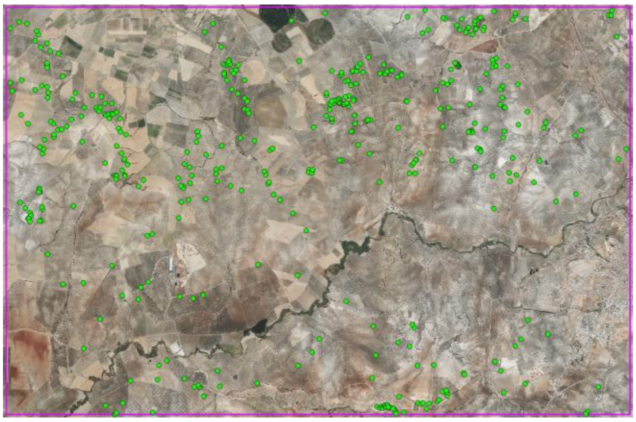

Figure 8. Gully heads identified in the northwest of Aguilar de la Frontera from the 2022 PNOA orthophoto. Gully density: 4.37 gullies/km².

To address this issue, an erosion control plan is proposed aimed at controlling gully development, preventing their expansion and reducing sediment transport and off-site impacts. The identification of gullies (Figure 8) and the boundaries of farmers' parcels is a decisive step in developing intervention proposals for gully restoration. Additionally, by including sediment connectivity models in our analysis, we can detect areas with higher connectivity and implement conservation measures to assess their effectiveness in significantly reducing sediment connectivity, such as vegetative barriers (Figure 9).

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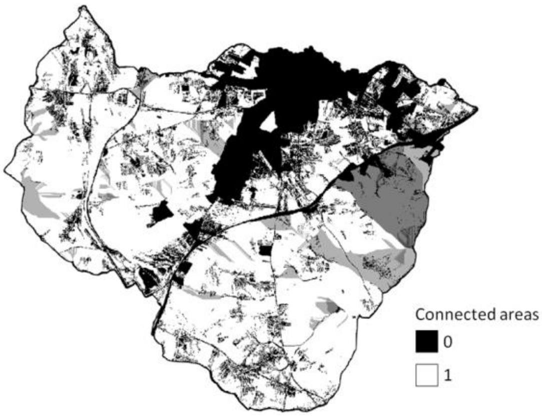

Figure 9. Sediment erosion processes exemplified within the probability of connectivity results in the Barriga watershed. The black area represents the disconnected area (value 0), the white area is the connected one (value 1), and the grey area is the partially disconnected area due to the effect of vegetative barriers. This example was conducted for a 45mm rainfall, with an antecedent moisture condition I and a sediment trapping probability of the vegetative barrier of 30%.

Although farmers are aware of the magnitude and impact of gully erosion, the implementation of vegetative barriers is not widely practiced in the watershed. According to the outcomes of the focus group meeting, farmers are reluctant to implement measures like hedgerows or buffer strips, which they perceive as competitors with main cropland. The two main reasons for this lack of interest are the costs incurred by the loss of cultivated areas and the decline in yield. Farmers perceive these practices as diminishing farm profitability, and if they experience a poor harvest due to these measures, it is challenging for them to trust similar strategies in the future.

Moreover, the complexity and lack of flexibility of regulations and administrative procedures likely contribute to farmers' discomfort with these measures. In Spain, the management of controlled cutting in forest areas or non-productive lands requires significant time to resolve administrative requirements.

To overcome these concerns and promote the adoption of vegetative barriers and other disconnecting measures, farmers need new funding sources, particularly during the initial years of implementation. The only way to voluntarily adopt these measures is if the area to be adapted is less problematic for management or near the farmhouse. Simplifying administrative regulations regarding the management of woody vegetation will also encourage farmers to adopt these types of measures. Enhancing agricultural extension services would help overcome traditional barriers and promote the adoption of new mitigation measures.

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4 Conclusions

This report presents a guideline for practitioners and decision-makers to identify, select, and propose locally fitted erosion control measures to tackle erosion and associated transport at agricultural catchment scales. The goal is improving the management of sediment connectivity in agricultural landscapes through the development of catchment´s control erosion plans.

The guideline benefits from the outputs and results achieved within the SCALE project. It is based on an analysis of major soil erosion and sediment transport issues affecting European agricultural landscapes. A representative sample of pilot catchments across Europe was used to identify catchments needing mitigation measures against on-site and off-site impacts of water erosion, including soil loss, sedimentation, nutrient and organic carbon losses, impaired water quality, and flood risk due to high sediment load.

A catalogue of available mitigation measures was developed, addressing hydrological connectivity specifically. The catalogue is based on the thorough knowledge and extensive experience in protecting soils against water erosion and reducing sediment transport and delivery. The efficiency of potential measures was evaluated by incorporating them into erosion simulation models after assessing the capability and performance of these models in simulating the mitigation effects.

Selection of most applicable measures was made through public participatory approaches. The adoption of erosion control measures by farmers depends on their performance, economic aspects, and perceived benefits. Economic evaluation relied on analysis of potential mitigation measures included in the National Strategic Plan under the Common Agricultural Policy and subsidies provided as proxies for implementation costs. Social preferences were assessed based on farmers' perceptions of erosion problems, available practices, and their capability to implement these practices.

A participatory approach combining scientific, technical, and local knowledge helps overcome existing barriers at ground level, upscale best management practices, and use simulation models as tools for exploring the effects of erosion control measures and communicating options. Simulated results integrating different aspects and representing desired states under each scenario can greatly favour discussion and negotiation processes.

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