Towards climate-smart sustainable management of agricultural soils

SCALE

Managing Sediment Connectivity in Agricultural Landscapes for reducing water Erosion impacts

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1 Introduction

Soil erosion by water negatively impacts soil quality, potentially causes ecological and economic damage to the environment, farm systems and infrastructure, as it causes loss of water storage capacity, organic carbon and essential nutrients and the transport of sediment into aquatic environments and urban areas (Pimentel et al., 1995, Pimentel, 2006, Quinton et al., 2010, Borrelli et al., 2017). However, there is a considerable disparity in soil erosion rates and sediment transport through the landscape between different European regions (Verheijen et al., 2009, Cerdan et al., 2010, Panagos et al., 2015), leading to incongruent perceptions of the impact of soil erosion (Prager and Posthumus, 2010) and heterogenous mitigation strategies in the EU (cf. Borrelli and Panagos, 2020, Panagos et al., 2020). On-site mitigation measures to prevent or reduce the initiation of soil erosion in the first place are of course a priority. Still, they have to be combined with measures that reduce the off-site effects by effectively inhibiting runoff and sediment transport across the landscape (Ledermann et al., 2010). Sediment connectivity describes how soil eroded by water can move through the landscape via linkages between landscape elements. Consequently, it is imperative that any proposed mitigation strategies address sediment connectivity between land and surface waters (Poeppl et al, 2017, Keesstra et al., 2018). The successful prediction of runoff pathways and associated sediment transport (e.g. by soil erosion modelling; cf. Bosco et al., 2015, Baartman et al., 2020) is of considerable importance for tailored mitigation. Improving the knowledge of sediment connectivity and how to model it at different scales and locations across Europe would enhance our understanding of erosion, sediment transport and delivery, as well as advance the efficient implementation of mitigation measures within and between field parcels. The SCALE project addresses these issues and hypotheses that a better understanding of sediment connectivity in agricultural landscapes will improve the effectiveness of on-site and off-site mitigation strategies. Four questions build the scientific background:

i. How can agricultural management practices be optimised on local soil erosion hot spots (i.e. agricultural fields) and reduced drawbacks, on soil organic carbon (SOC) stocks, soil biodiversity and water resources, so that sediment connectivity and thus off-site impacts can be reduced at catchment scale?
ii. Which are the most suitable approaches for the upscaling of local and long-term soil erosion monitoring observations to draw conclusions about the connectivity within agricultural catchments and to individuate the areas where breakdown, detachment, transport and deposition occur inside the catchments?
iii. How can existing and well-established modelling techniques be improved to predict and quantify water erosion effects on cultivated soil functions within agricultural landscapes?
iv. How can evaluation procedures (e.g. soil erosion modelling and monitoring techniques) be harmonised considering individual environmental peculiarities that account for the diverse agricultural landscapes in the European Union?

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The SCALE project is part of the EJP SOIL research programme, which works towards climate-smart sustainable management of agricultural soils. SCALE consists of 13 project partners from 9 EU-countries, who aim to improve soil erosion mitigation strategies by the introduction of sediment connectivity as a key consideration in mitigation strategies, which account for regional differences in erosion damages supported by erosion modelling at different scales.

The project aims to provide a strategy and methodology for practitioners and decision makers to improve the coordination of mitigation strategies across multiple fields within connected agricultural systems, thereby enhancing the effectiveness of on-site erosion measures. Additionally, approaches are highlighted to harmonise erosion mapping and indicators for soil loss, and sediment transport towards waterways and provide guidelines to farmers, consultants, and regulatory bodies to improve their understanding of erosion risk and impact and to showcase targeted, cost-effective mitigation strategies tailored to specific agricultural landscapes.

The project is divided into six work packages (WP), which focus on the current state-of-the-art of connectivity principles in modelling and legal standards (WP1), data sharing and dataset harmonisation (WP2), harmonisation of up- and downscaling methods (WP3), evaluation of on- and off-site measures and connectivity elements in common modelling approaches (WP4), development of frameworks with mitigation measures and best management practices for stakeholders (WP5) and the communication of the project's output (WP6).

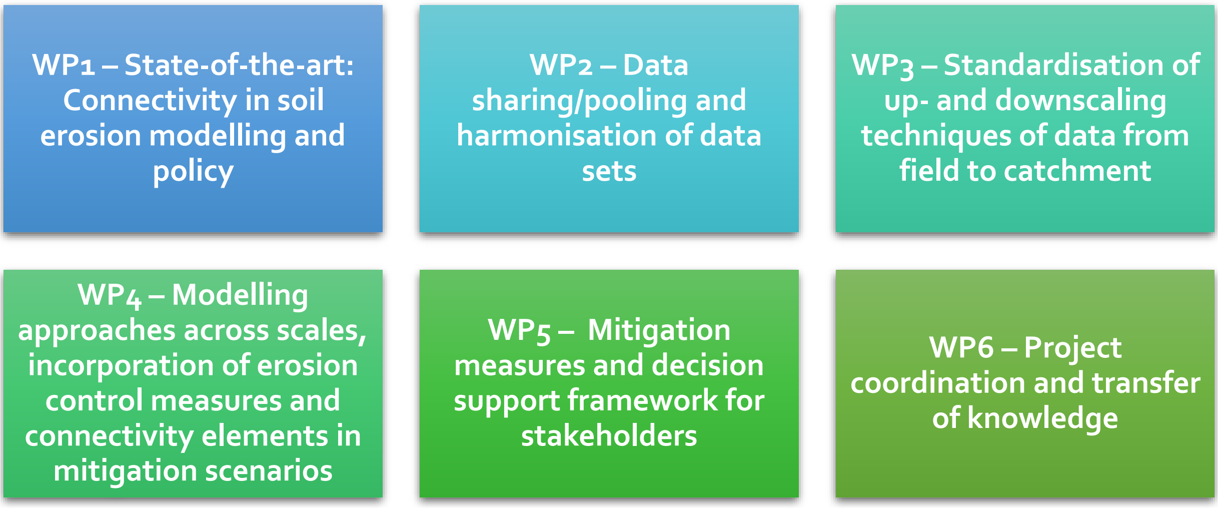

Figure 1. The six work packages within the SCALE project.

This final project report summarises the outcomes of the work performed in the project within each work package and intends to give recommendations and point to further research needs.

For more detailed information on the results, access to all deliverables and presently published scientific articles please visit the SCALE project website https://scale-ejpsoil.eu/.

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2 Outcomes of the project

2.1 State-of-the-art: Connectivity in soil erosion modelling and policy (WP1)

The first tasks of the project intended to gather information on the state-of-the-art and current inclusion of connectivity in soil erosion modelling and policy. To gain insight into the soil erosion modelling applications in use in Europe and how soil erosion mitigation measures are implemented in national legislation, we conducted two surveys aimed at soil erosion modellers and relevant national or regional authorities, respectively.

2.1.1 Report on parameterisation of connectivity and mitigation strategies in the frequently-used soil erosion models (WP1-D1)

The results of this deliverable were also published in a scientific article by Schmaltz et al. (2024) and the outputs of both the deliverable and the article will be summarised in the following.

Soil erosion is considered one of the key soil threats in the European Union (EU Commission, 2023) and member states have to comply with regulations that aim to reduce the negative effects of such environmental threats. The EU's Common Agricultural Policy (CAP) and the Water Framework Directive (WFD) as well as other EU and national legislations require the implementation of mitigation measures which target and minimise the effect of soil erosion. In this connection, soil erosion risk assessments produced by soil erosion models may function as important tools to support decision-makers by identifying erosion-prone areas and ensuring targeted implementation of mitigation measures for maximum efficacy. However, information on how soil erosion model applications are being used to support environmental planning and decision-making in Europe is limited. Furthermore, the diversity of input data and parameterisation of model applications, and especially how certain landscape elements and soil erosion mitigation measures are implemented within these models to account for connectivity, is not well described.

Thus, our research aimed to address the above knowledge gaps by asking the following questions:

- Which soil erosion models are used in Europe to assess the risk of soil erosion and the effect of mitigation measures?
- Which environmental parameters are included in the models and which data sets are being used to estimate these parameters?
- How are connectivity elements and mitigation measures considered or parameterised in the models used?

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A European-wide, exploratory survey on the current use of policy-relevant soil erosion and sediment transport model applications in Europe at various spatiotemporal scales resulted in 46 model applications from model users in 18 European countries.

About two-thirds of the described model applications were used for by an authority for soil erosion risk assessment or implementation of mitigation measures at a range of spatial scales (national, regional, catchment, field). We found that the majority of model applications used the Universal Soil Loss Equation (USLE) or versions thereof and appears to be an important tool for decision-support and not only for research purposes (Borrelli et al., 2021). The analysis revealed an apparent prevalence towards the use of national or regional datasets and a high variation in parameterisation and use of different methods even when using the same model. This provides inconsistent soil erosion assessments, hinders comparison of model predictions across Europe and may lead to inefficient management requirements. In certain cases, where comparability of model outcomes is needed, such as large-scale model applications for use in European policy programs (e.g. CAP), harmonisation of datasets and parameterisation may be beneficial for conducting more consistent erosion assessments.
Landscape elements and mitigation measures with connectivity characteristics were applied in most model applications, but they were rarely included with focus on modelling connectivity in the landscape. Thus, there is still a need for increased focus on sediment connectivity modelling in agricultural landscapes to improve erosion assessment and mitigation measure implementation at multiple scales.

2.1.2 Report on implementation of soil erosion and mitigation strategies in national legal standards (WP1-D2)

As stated above, the EU's CAP and other (national) legislation require implementation of mitigation measures which target and prevent or minimise the adverse effects of soil erosion. EU Member States (MS) are required to develop a national CAP Strategic Plan, outlining the allocation of EU funding for the agricultural sector. With the new CAP for 2023-2027, allowed for a greater freedom of allocating the funding. To understand how national policies in each MS target the risk of soil erosion on agricultural land and associated off-site effects driven by connectivity in the landscape, we designed a survey to explore the content of national and regional erosion mitigation measures implemented as part of the CAP Strategic Plan 2023-2027, the Statutory Management Requirements (SMR) and other national legislation.

The survey was directed at relevant authorities (agencies, ministries) in all EU MS that regulate the implementation of soil erosion mitigation measures. The survey had two main parts: 1) Provisions implemented for selected standards for Good Agricultural and Environmental Conditions (GAEC); 2) Other mandatory and voluntary measures under EU or national regulation. We chose to focus on the national implementation of the GAEC standards that are most relevant to consider with respect to soil erosion mitigation – GAEC 4 (buffer strips), GAEC 5 (management of tillage, reduction of the risk of degradation and soil erosion), GAEC 6 (minimum soil cover) and GAEC 8 (non-productive areas).

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The survey mainly reached the countries involved in the SCALE project, but we also had responses from other EU MS. Altogether we received survey responses from Austria, Belgium (Flanders and Wallonia), Czechia, Denmark, Estonia, Finland, France, Italy, Latvia, Luxembourg and Spain.

Throughout the surveyed countries some variation in the implementation of the GAECs exist. For buffer strips the required width ranges from 1-30 m depending on the type of river system, and management options vary from no allowed activities to only exemption from tillage or fertilizer use. For GAEC 5, which can be considered the main erosion mitigation standard, the assessment method for designating risk areas and the permitted activities in these areas differ between countries. Some MS use regionalised erosion risk assessments based on model applications (mainly RUSLE-based), while others only use simple terrain models (e.g. over a slope of 10 % measures must be adhered to) or expert knowledge. Regarding minimum soil cover, provisions are in place across all surveyed countries, although exact timings of soil cover requirement varies, which may be given by the climatic variation in the countries. Different landscape features are allowed as non-productive areas across the MS. Some may have a greater potential effect on mitigating soil erosion and connectivity such as terraces in Italy and Spain, although their effect depends greatly on the placement in the landscape.

Additional measures beyond the CAP and GAECs are implemented (mostly on a voluntary basis) in the surveyed countries. Although, few measures are targeted specifically towards erosion mitigation in identified erosion-prone areas and the effects of off-site erosion damages are mostly not explicitly considered. This may imply that farmers can place the measures as they see most convenient for their farm management, but not where they would have the greatest mitigating effect.

The results of our survey may act as Europe-wide inventory of measures for mitigating water erosion and facilitate exchange of experiences among policymakers on erosion control. Further, our analysis indicates that the current CAP policy does not promote targeted mitigation measures implementation. It is thus uncertain whether the required measures have a substantial effect on mitigating soil erosion and further evaluation of this is needed.

Key messages of WP1

The results of WP1 were also summarised in an EJP SOIL policy brief entitled *"From Risk to Resilience: Policy challenges for Soil Erosion Control"* (Schmaltz & Johannsen, 2024) and key messages to stakeholders based on these outcomes were reported. The three key messages are:

Harmonisation and standardisation

Harmonisation of datasets and parameterisation across erosion models to facilitate consistent soil erosion assessments and improve the efficiency of management requirements.

Targeted erosion mitigation measures

Erosion mitigation measures ought to be applied specifically in areas exhibiting a heightened risk of erosion. It is important to enhance effectiveness by more firmly promoting voluntary measures in these risk areas, and, where needed, instituting mandatory measures in a more focused manner.

Enhanced sediment connectivity modelling

Sediment connectivity ought to be a principal consideration when modelling erosion risks, particularly when utilising erosion risk maps for policy or planning purposes. It is typically recommended that validation of these maps is undertaken through the use of empirical data and threshold values from these maps should be tailored to meet regional conditions. This approach enhances the reliability and comparability of policy-relevant soil erosion risk maps.

Overall, soil erosion models should be selected based on their ability to reflect erosion risk at different spatial scales. Thus, for models used to produce policy-relevant erosion assessments, regional adaptation may be needed at smaller scales, while comparability, and hence dataset harmonisation and standardisation of parameterisation, is essential at certain (larger) scales. We believe an improved system understanding of the erosion and sediment transport process through incorporation of connectivity aspects in modelling and policy design will ensure better decision-support for the implementation of targeted mitigation measures.

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2.2 Data sharing/pooling and harmonisation of datasets (WP2)

Work package 2 dealt with data collection, sharing and dataset harmonisation within the project and as such the outputs were more of relevance for the internal project management. Commonly, the collection, sharing and management of datasets is highly relevant and thus the experiences from this project may be generally applicable.

2.2.1 Description of common database including functionality and management (WP2-D1)

As we demonstrated in WP1, a variation in soil erosion models and parameterisation exists. Each of these models have their own input data demands, requires different datasets for calibration and validation and produces various output data. All these datasets may be of different technical and semantic background and as such lack interoperability. Thus, this task aimed at harmonising dataset description and collection to allow for sharing of measurement and model data among project partners to enhance research into sediment connectivity and targeted soil erosion assessment for policy support across Europe.

Datasets for soil erosion and sediment transport modelling were collected from six project partners. The datasets provided were for selected catchments or regions or national scale data in Austria, Belgium-Flanders, Denmark, Finland, Poland and Spain. First, a metadata scheme, based on the INSPIRE principles, was prepared for collection of metadata to give an overview of the datasets from each partner. The datasets were relevant to soil erosion modelling approaches performed by the partners during the project. As such the metadata and common database allowed for greater insight into the datasets which was worked on within the project and also for sharing of data for specific modelling exercises.

The common database was created on the project's web cloud, which was managed by the coordinating partner. Only project partners had password-protected access rights. Open access to data was promoted on voluntary basis. A fair exchange of datasets and data access was assured by addressing intellectual property rights, licensing and sharing of the collected datasets within the harmonised database. Some relevant datasets had sharing restrictions due to data rights. This data was just described in the metadata scheme but not uploaded to the database. Often links to external websites, where the datasets were already available for direct download was provided instead of uploading the whole dataset to the project database.

The harmonised metadata scheme and shared database allowed for analysis of data and observation techniques between catchments/regions. This aided in understanding the need for dataset harmonisation and fostered the project goals towards assessing tools, methods and practices to be used in policy support targeted to soil erosion problems across Europe.

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2.2.2 Guidelines for best-practice of selecting model-relevant parameters (WP2-D2)

Task 2 under WP2 was dedicated to developing guidelines for selecting model-relevant parameters. Soil erosion significantly impacts ecosystem services, causing both on-site effects like loss of organic matter and off-site effects such as environmental damage from sediment export. Effective sediment management on a catchment scale is essential, but it requires understanding the complex and dynamic sediment connectivity processes. Accurate selection of parameters in water soil erosion modelling is crucial for understanding soil erosion, transport, sedimentation, and their relationship with landscape features.

Topography, derived from Digital Elevation Models (DEMs), is crucial in hydrological modelling for water management and flood protection. DEMs, digital representations of Earth's topographic surface, are invaluable in geomorphic studies and soil erosion assessments. DEM accuracy and resolution are vital for reliable soil erosion modelling. Optimal DEM resolution depends on the study area's size, research goals, and available geospatial technologies. DEMs are categorized into low, medium, and high resolution, each suitable for different scales and applications in soil erosion studies.

Landscape connectivity, a key characteristic influencing soil erosion, can be modelled using connectivity indices and spatially distributed soil erosion models. Structural connectivity is based on topographic data, while functional connectivity involves dynamic processes. Accurate representation of landscape features in high-resolution DEMs is essential for modelling sediment transport and connectivity. High-resolution DEMs are necessary for detailed terrain analysis and accurate soil erosion predictions.

The precision and accuracy of DEMs are critical for evaluating erosion risk. Higher resolution DEMs capture geomorphological changes more precisely, resulting in accurate erosion factor estimations. DEM quality can be assessed through control points, 3D views, and flow tracing. Vertical precision is essential, with centimetre precision preferred over meter precision. Hydrological correction of DEMs is recommended to address errors and ensure accurate water flow simulations.

Besides DEMs, other parameters such as land cover-land use maps, soil maps, climatic data, and anthropogenic landscape features are important for accurate erosion modelling. Input data must be checked for spatial and temporal accuracy, datum and projection, and semantic accuracy to ensure overall model accuracy.

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Key messages of WP2

The key messages of WP2 from the project are centred around the harmonisation of datasets, metadata creation and the enhancement of research and policy support, particularly for WPs 4 and 5. These efforts aim to improve data interoperability, facilitate data sharing and ensure accurate and reliable soil erosion modelling in the different other WPs. The following points highlight the core achievements and guidelines established by WP2:

Harmonisation of datasets and metadata creation

The project focused on standardising and harmonising soil erosion and sediment transport datasets across various European regions to improve data interoperability and facilitate sharing among partners. A metadata scheme based on INSPIRE principles was developed, and a common, password-protected database was established on the project's web cloud, ensuring consideration of intellectual property rights and data licensing.

Guidelines for data use

The harmonised datasets and shared database enabled more effective analysis and comparison of soil erosion data, aiding the development of tools and methods for targeted soil erosion assessment and policy support across Europe. The guidelines provided accurate and reliable soil erosion modelling by standardising the selection of model-relevant parameters, such as DEM resolution and accuracy, and input data consistency.

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2.3 Standardisation of up- and downscaling techniques of data from field to catchment (WP3)

Measurements of soil erosion at different scales are needed to calibrate/validate the estimates of soil erosion models and it is thus vital that the measurement accuracy is high. This work package intended to stocktake available soil erosion observation techniques at the project partner institutions and compare their accuracy and estimated cost. Further, an analysis of up- and downscaling of datasets and resampling methods was performed to demonstrate the potential effect of model outcomes on the zoning of non-tolerable soil erosion, when used as a basis for delineating areas to implement regulatory measures. Finally, we compiled a catalogue of necessary input data for different spatial and temporal scales and different modelling designs as an overview for model users.

2.3.1 Final report on the comparative analysis of accuracy and costs of the different soil erosion measurement and observation techniques, based on partner experience (WP3-D1)

Soil erosion models need to be calibrated and validated based on actual erosion measurements to ensure reliable results, especially when the model estimates are used to set threshold erosion values or for implementation of soil erosion control measures. The accuracy of measurement methods is thus vital for consistent soil erosion estimates. A variety of techniques exist to measure soil erosion at both the field and catchment scales. Measurements can be event-based, which are often used for monitoring activities and require significant investment of time and work, or they can be on a wider temporal scale, requiring less time and work, but providing averaged results.

Three project partners shared their experience with the accuracy and costs of different soil erosion measurement and observation techniques. The measurement methods were categorised according to applicability for calibration or validation at sub-field, field and catchment scale.

At sub-field scale rainfall simulation measurements were described as a technique to investigate the impact of rainfall kinetic energy on the soil surface condition, which is relevant for the understanding of the initial soil erosion process. At field scale, observation techniques such as tipping buckets, disdrometer rainfall measurement, measured visual inspection, qualitative observations in the field and Unmanned Aerial Vehicle (UAV) image analysis had been used by the project partners. At catchment scale, observation records of sedimentation and erosion, sediment monitoring in watercourses, retention ponds and reservoirs and the use of flumes for flow and sediment concentration measurements were employed.

Some conclusions derived from this collection of soil erosion observation techniques were that, qualitative observation was used by partners at both field and catchment scale to qualitatively

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validate modelled erosion and sedimentation processes, but this method should be improved by standardising observation procedures. Waterflow and sediment concentration monitoring in watercourses, retention ponds and reservoirs provides crucial data to calibrate and validate erosion models at catchment scale, and have also been used for this purpose in national scale models. Photogrammetry (e.g. via UAV) seemed to be a promising technique, which was applied by all partners. However, regulations on the use of UAVs in restricted airspaces, due to privacy and safety regulations in densely populated areas, as well as bad weather conditions may hamper the data collection. The cost of equipment in general is independent of the observation scale. The temporal and spatial resolution of high-quality data collection is decisive for the actual cost. The cost of personnel to maintain equipment and analyse data is usually much higher than the purchasing costs. Overall, only rough estimates of accuracy and costs could be given from personal experience of the project partners.

2.3.2 Final report on the comparative evaluation of up- and downscaling methods (WP3-D2)

This deliverable was submitted as a scientific article entitled “*Beyond pixels: trade-offs in RUSLE-based soil erosion risk mapping and their implications for the implementation of regulatory measures by farms*” (Schmaltz et al., in prep.).

Soil erosion maps help identify risk areas and guide agricultural policy and farmer implementation of erosion mitigation measures. These maps are crucial for delineating action areas under certain regulations. Accurate methodologies reduce mapping errors and enhance practical implementation.

Numerous soil erosion risk maps exist across Europe, including national maps for Austria, Belgium, Finland, Germany, Poland, Romania, Switzerland, Hungary, and broader scales for Europe and globally. A common method for identifying erosion risk zones is the Revised Universal Soil Loss Equation (RUSLE) and its successors, which, despite limitations, consider environmental factors like rainfall erosivity, soil erodibility, slope characteristics, and agricultural practices. RUSLE's empirical nature makes it suitable for identifying risk areas, but it often overestimates actual soil erosion. Results depend on equation parameters and data quality, which vary significantly by region, affecting the reliability and comparability of maps.

Despite uncertainties in empirical models, soil erosion risk maps are used in policy-making in parts of Europe, including standards for Good Agricultural and Environmental Conditions (GAEC) in Belgium and Germany. While farmers are key to implementing erosion control, there is no analysis of the impact of these maps on farm practices. The lack of consensus on map production and data handling within the EU means the impact varies based on the modelling methods used. In this deliverable, an analysis of up- and downscaling of datasets and resampling methods was performed to demonstrate the potential effect of model outcomes on the zoning of non-tolerable soil erosion, when used as a basis for delineating areas to implement regulatory measures.

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A series of modelling scenarios were tested to determine the influence of raster resolution on soil erosion risk maps using the Revised Universal Soil Loss Equation (RUSLE) in the regions of Flanders (Belgium) and Lower Austria (Austria). To assess the impact of varying data resolution on the accuracy of erosion maps, three different resampling techniques were analysed. These techniques included i) resampling input data, ii) resampling RUSLE factors and iii) resampling the output erosion risk map.

The results showed significant discrepancies in model outcomes due to aggregation methods, neighbourhood effects, and scenario-specific resampling techniques. These discrepancies highlight the need for careful consideration of modelling procedures to ensure the precision and reliability of erosion risk maps. Based on the study's findings, modellers should adopt a pragmatic approach when aggregating raster data to fields (i.e., polygons). Individual RUSLE factors should be calculated using the most accurate and detailed data sets, and resampling of factor maps should be done cautiously, as resampling inputs (e.g., DEM) and outputs (i.e., erosion risk map) can lead to volatile results or significant underestimation of actual soil erosion.

While it is positive that soil erosion rates are aligned with soil formation rates for sustainable, comprehensive, and region-specific soil protection, it is recommended to avoid using an arbitrary threshold value for action area decisions if validation data is insufficient or soil formation is not quantified. To ensure farmers' acceptance of erosion risk maps, particularly those with policy relevance, it is crucial that the methods used do not favour or disadvantage specific farm sizes from the outset.

2.3.3 Catalogue on data sets to be used on different scales and models (WP3-D3)

When setting up a specific modelling scenario, it is important to identify the modelling aim and define the scope and processes within the scenario, as the modelling scale and scenario purpose may require different datasets. Model selection can also be influenced by the available data and the simulated scenario. Depending on the scale of development soil erosion models differ in their parameterisation. The simulation often assumes a simplified description of complex erosion and sediment transport processes to reduce computation effort, time and needed input as well as calibration/validation data. Therefore, it is vital to select the appropriate model for the needed modelling scale and provide it with the right input data for the intended modelling scenario.

The aim of this deliverable was to compile a catalogue to assist model users in selecting appropriate datasets for their modelling approach and intended spatio-temporal scale. We provided an overview of criteria to consider and examples of possible datasets for field, catchment and regional/national scale. We limited the presented information to the specific soil erosion models described in WP4-D2 and their model parameters. These models included RUSLE, WaTEM/SEDEM, CASE, EROSION-3D, IBER, MHYDAS, OpenLISEM, SHETRAN and WEPP. Three tables of possible datasets were compiled. The first table presented basic data which most models need such as rainfall, soil, topography, land cover and management and conservation practices (RUSLE factors stated as basis for these parameters). The second table contained more model-specific parameters and input data, which was also more directed towards process-based models. The third and last table gave an overview of more advanced or experimental parameters e.g. those that model users have to parameterise themselves and require calibration and validation.

The selected soil erosion models share many common traits in their parameterisation. Especially the well-known RUSLE factors are engrained in the structure of most models. The common use of these parameters should also mean suitable datasets at different spatial scales are comparatively easy to find for these parameters. Process-based models tend to require parameters for which data is more difficult to obtain (especially at larger scale) and where calibration is needed. Often simpler models can be used without the need for calibration data, while more advanced model applications need both measured data and specialist knowledge. The use of literature values or pedotransfer functions may be necessary for some parameters. With recent advances in digital soil mapping, the use of remote sensing data and machine learning models, availability of high-resolution data at a range of scales may be improved.

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Key messages of WP3

WP3 explores the importance of measurement accuracy, resolution, and resampling techniques in soil erosion modelling, and the selection of appropriate datasets to enhance erosion risk assessments and mitigation planning.

Accuracy and costs of soil erosion measurement methods

It is essential that soil erosion measurement methods used for calibration or validation of erosion models are highly accurate to ensure the most reliable results. Further, the cost of measurement will influence the availability of data at high spatial or temporal resolution. This is especially relevant in case of long-term monitoring campaigns. The quality of the dataset and its inherent uncertainties should be considered throughout the modelling and reporting of results.

Considering the effect of soil erosion modelling resolution and resampling techniques

Soil erosion risk maps are essential for identifying vulnerable areas and guiding agricultural policy, but accurate methodologies and careful resampling techniques are crucial to avoid mapping errors and ensure reliable, practical implementation. While soil erosion maps are valuable for policy-making and regulation, their impact on farm practices varies due to differences in modelling methods and data quality, underscoring the need for pragmatic, detailed approaches to data aggregation and validation.

Selection of appropriate datasets for the right spatio-temporal scale

Selecting suitable dataset sources and data quality for the intended spatio-temporal scale of s specific modelling scenario is imperative to successful soil erosion mitigation planning. Improving existing datasets or creating new accurate datasets for specific parameters that are shared between several models would be beneficial to the wider erosion modelling community.

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2.4 Modelling approaches across scales, and incorporation of erosion control measures and connectivity elements in mitigation scenarios (WP4)

Modelling of soil erosion and sediment transport across scales, while evaluating the model uncertainty and its ability to incorporate erosion control measures and connectivity elements in the modelling approaches, was investigated in work package 4. Further, various scenarios to investigate the applicability of a connectivity approach and an updated representation of erosion mitigation measures were explored.

2.4.1 Guidelines on uncertainty and optimized parametrization strategies depending on scale and modelling approach (WP4-D1)

As soil erosion models are used to estimate areas of high erosion risk and potentially for policy relevant implementation of mitigation measures, it is important that the model estimates are as reliable as possible or that the uncertainties are assessed and communicated to the stakeholders. However, models are inherently uncertain and the many decisions and assumptions made during the modelling process all contribute to the uncertainty of the final model outcome. Uncertainty of modelling results arise from several sources such as lack of knowledge of described processes (epistemological uncertainty), from in data and parameters (technical uncertainty) and arising from the used approach and its assumptions (methodological uncertainty). By evaluating frequently used soil erosion models in terms of uncertainty and incorporation of sediment connectivity elements, this deliverable aimed to provide guidelines on uncertainty and optimised parameterisation strategies depending on scale and modelling approach.

Case studies from Finland (RUSLE), Flanders (WaTEM/SEDEM) and Italy (RUSLE+USPED and WEPP) modelled at both plot/field and catchment scales were analysed to enhance the understanding of how to improve the incorporation of sediment connectivity in specific soil erosion models.

The results of the analyses showed that, it is of particular importance to consider aleatoric uncertainty, which refers to the errors that arise from different and sometimes unknown sources linked to the measurements used to calibrate and validate model predictions. In general, a lack of data to calibrate and validate models with is also a source of uncertainty in the estimation. A lack of experimental field research also means that some sediment transport processes are not fully understood. Several statistical methods for uncertainty assessment exist, but they are not always readily comparable.

Nonetheless, uncertainty assessments are highly important to understand how useful and applicable model predictions are. Further studies can advance the knowledge on sediment connectivity modelling, but also on how to minimise uncertainty by improved model parameterisation. In addition, it is also crucial to communicate the uncertainty of model predictions to stakeholders to heighten the understanding of the issue and improve the acceptance of the use of model estimations.

2.4.2 Guideline on the current implementation of erosion measures and other connectivity elements depending on scale and modelling approach (WP4-D2)

The presence of connectivity elements exerts a significant influence on the processes of soil erosion and sediment transport across the landscape. These elements influence the extent to which the transport of water and sediment occurs between landscape features during hydrological events. Erosion control measures (ECMs), such as conservation tillage, grass buffer strips or retention ponds, are explicitly implemented with the intention of preventing soil loss and reducing the connectivity of the landscape. However, other connectivity elements, such as roads, ditches, and parcel borders, can influence the connectivity of a landscape. Thus, the incorporation of ECMs and other connectivity elements in modelling approaches is essential for calculating runoff and sediment transport through a landscape and simulating the impact of current land use and future mitigation scenarios for reducing on-site and off-site consequences of soil erosion.

In this deliverable, a literature review was performed to describe the effectiveness of selected erosion control measures and connectivity elements. These were grouped into land use changes, agronomic measures, buffering measures and other connectivity elements. The current implementation of ECMs and connectivity elements in the models RUSLE and WaTEM/SEDEM, as well as seven process-based models (CASE, EROSION-3D, IBER, MHYDAS, OpenLISEM, SHETRAN, WEPP) were summarised.

The literature review showed that the effectiveness of ECMs and other connectivity measures in mitigating soil erosion and sediment transport vary depending on how they are spatially situated in the landscape and on the spatio-temporal conditions of the study site. Some connectivity elements may even work as both disconnective or connective depending on the site-specific situation. Therefore, detailed modelling approaches may benefit from field observations and monitoring to get the most accurate assessment of erosion risk and possible placement of control measures.

The ability of soil erosion models to incorporate ECMs and connectivity elements depends on how well they can describe the often complex physical mechanisms in their model structure. For RUSLE an overview of the existing possibilities to consider selected ECMs and connectivity elements at field/plot scale and spatially distributed scale were given. The spatially distributed RUSLE is constrained in its ability to consider structural sediment connectivity due to a lack of description of the sediment transport. Consequently, the impact of an erosion control measures on sediment retention cannot be evaluated; however, the effect on erosion reduction can be estimated.

For WaTEM/SEDEM tables indicating the whether a certain type of ECM or connectivity element could be modelled and by which parameter were presented. This model is capable of calculating the impact of ECMs and can incorporate connectivity elements into its modelling procedure. This is primarily due to the integration of the RUSLE model with a sediment transport model, which employs a spatially distributed sediment transport capacity for the calculation.

For each of the seven process-based models an overview of the model and their capabilities was given, together with a concluding summary on the representation of connectivity elements in process-based models. The process-based models were generally capable of modelling connectivity, but most models do not have these features build-in. This means the model users need strong expertise in the effect of connectivity elements and which parameters to alter. As this is also time-consuming, this may be a limiting factor in developing successful soil erosion management scenarios.

2.4.3 Guideline on how to improve the representation of erosion control measures and other connectivity elements in models (WP4-D3)

Based on the assessment of the existing implementation of ECMs and connectivity elements in models in WP4-D2, we suggested improvements for better modelling simulations of ECMs and connectivity elements in deliverable WP4-D3. It presents an overview of how to implement these elements in soil erosion models, which may not already have them in-built.

First an overview of the same ECMs and connectivity elements researched in WP4-D2 is presented. Then the typical geometry (line or surface) of these measures and elements at small catchment scale is stated. The specific effect of an ECM or connectivity element can vary depending on the site-specific context and its implementation in the landscape. Therefore, we classified them according to the four considerations below:

• Does the ECM or connectivity element affect both water and sediment transfers, or mostly sediment transfer?

• Main effects of the ECM or connectivity element on water (infiltration, surface storage, flow velocity, flow direction).

• Main effects of the ECM or connectivity element on sediments (detachment, transport).

• Main effects of the connectivity element or erosion measure on connectivity of both water and sediments (connecting, disconnecting, altering connectivity direction).

This classification system could assist model users in anticipating the potential effects that the ECM or connectivity element may have on their study area. Such classifications could be employed when constructing management scenarios. In all cases, it is advisable to consider the type and location of an ECM or connectivity element before running a soil erosion model, regardless of the chosen approach.

Further, an account of how the models RUSLE, WaTEM/SEDEM and the seven process-based models could improve their inclusion of ECMs and connectivity elements in the modelling approaches. For example, for a spatially distributed RUSLE model, the implementation of

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sediment delivery ratio (SDR), transport capacity or a combination of index of connectivity and SDR were presented as methods to address the limitations of this particular model.

At the end of the report, a section on how to account for organic carbon transfer in soil erosion modelling, by proposing a coupled modelling of soil erosion and organic carbon fate, is included. Looking at the efforts on soil health monitoring and climate change impacts this is an important aspect to include in soil erosion modelling. However, the topic of how erosion exactly affects organic carbon transfer is still debated within the scientific community and needs further research.

2.4.4 Guideline on the practical use of the connectivity approach in modelling using mitigation scenarios (WP4-D4)

As it was found that sediment connectivity is not well integrated in landscape scale soil erosion management modelling, this deliverable intended to explore how to practically implement the connectivity approach in the modelling of mitigation scenarios. Through a synthesis of the explored and exemplified modelled mitigation scenarios with a connectivity approach we presented a guideline for model users on its practical implementation.

The guideline encompasses eight categories as according to the general modelling process: problem identification, conceptual mapping of modelled processes, data availability, model selection, model setup, parameterisation and evaluation, simulation scenarios, uncertainty management, and communication of simulation results.

Four different modelling approaches were described: RUSLE, RUSLE combined with the Index of Connectivity (IC) and Sediment Delivery Ratio (SDR) methods, WaTEM/SEDEM and a General Additive Model (GAM) with topographical indices.

The RUSLE approach showed how implementation of erosion control measures which may have an impact on the connectivity through the landscape reduced overall soil erosion of the two investigated catchments in Slovenia. The RUSLE/IC/SDR approach was used to simulate no-till and grass buffer strips at field scale in two Finnish catchments. It was found to be a feasible approach, although further research is needed as the parameterisation of IC/SDR affected the modelled absolute sediment delivery rates considerably. Nevertheless, this approach expanded the RUSLE model framework by allowing for consideration of sediment connectivity at field scale, which enables the designated planning of erosion management according to local connectivity characteristics. The WaTEM/SEDEM model was used for several ECM scenarios in two catchments in Flanders, Belgium. The model outcomes were used to estimate the efficiency of a specific ECM scenario as compared to other scenarios. The SDR can be used as an indicator for sediment connectivity in the landscape, and it was explained how the relation between mean erosion rates and SDR can be used to classify scenarios into on-site or off-site erosion mitigation scenarios. The GAM approach was used to predict the location of linear erosion features with a set of topographical indices as predictors. These linear erosion

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features can be important connectivity elements in the landscape as they act as preferential flow paths or create ephemeral gullies. Although this model approach does not calculate the magnitude of eroded or transported sediment, it is useful to indicate areas in need of mitigation such as implementation of grassed waterways.

Overall, these modelling approaches and different scenarios demonstrated that incorporating ECMs and sediment connectivity elements into models improves our understanding of erosion, sediment transport and possible management decisions. Nevertheless, it also highlights the need for further advancements to enhance the integration of sediment connectivity in modelling.

2.4.5 Stepwise tutorial for USLE approach with different dataset qualities and scales (WP4-D5)

The use of erosion risk assessment models is a crucial technique in the planning of soil erosion mitigation strategies. These models can be applied at both local and larger scales, facilitating the mapping of erosion hotspots and the placement of specific erosion control measures. Depending on the modelled scale, the available datasets, and the quality and accuracy of these, may vary. The aim of this study was to further the knowledge about up- and down-scaling effects on soil erosion models by analysing datasets of varying scales and input data accuracy.

To demonstrate the effect of different datasets and parameter calculation methods, we analysed two specific modelling parameters in the Universal Soil Loss Equation (USLE) and its derivatives, namely the rainfall erosivity factor (R-factor) and the soil erodibility factor (K-factor). The Hydrological Open Air Laboratory (HOAL) Petzenkirchen catchment in Austria was used as the study site. Both the R-factor and the K-factor were modelled using a large-scale dataset and a local catchment dataset and by applying different parameter calculation equations.

For the R-factor a national dataset of rain gauge stations and a local dataset of three rain gauges installed in the HOAL catchment were analysed for the same time period. Further, the effect of using four different kinetic energy-intensity (KE-I) equations was analysed, and direct rainfall measurements from a disdrometer in the catchment were used for validation purposes. The results indicate that R-factor estimates based on national and local datasets were largely comparable, with differences arising due to computation and spatial interpolation methods. As expected, the use of different KE-I equations on the local dataset led to some variation in R-factor estimation.

For the K-factor, the LUCAS dataset was employed for large-scale analysis, whereas a comprehensive soil sample network within the HOAL catchment provided the local dataset. The effect of seven different K-factor equations was analysed. A notable degree of variability was observed in the K-factor estimation across the various methods and scales employed. The study highlights the significance of accurate in-situ soil data and the limitations of interpolation methods, emphasising the importance of exact soil texture information for reliable K-factor estimation.

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The utilisation of large-scale datasets is beneficial for the identification of general erosion risk hotspots. Nevertheless, for effective planning of erosion mitigation strategies and the design of detailed measures, validation with local data of high accuracy is critical. It is recommendable to implement a standardised approach to up- and down-scaling in soil erosion modelling, with the objective of ensuring consistency and comparability of model outcomes. The application of advanced interpolation techniques and integration of multiple data sources, such as remote sensing and radar data, can improve the precision of soil erosion risk assessments, thereby supporting more effective soil conservation strategies.

2.4.6 Optimising the locations of grassed areas for erosion control in agricultural lands of Finland (WP4-M5), summary written by Mika Tähtikarhu (LUKE)

While spatial distribution of grass areas clearly impacts soil erosion, their optimal locations in field- and landscape-scale have been rarely studied. This study aimed to assess how and how much grass areas should be spatially allocated in Finnish landscapes to control erosion efficiently. We compared current policy-based targeting (buffer strips along main streams) with RUSLE-based optimal targeting of grassed areas (2×2 m^2 resolution) in two topographically contrasting sub-catchment. We also demonstrated how different amounts of grassed areas can affect erosion in landscape scale and how the RUSLE-based grassed areas can be computationally merged to continuous areas with reasonable shape in terms of trafficability. The erosion reductions were estimated based on recent national-scale RUSLE-estimate (Räsänen et al. 2023).

Our results show how the policy-based allocation of grass areas may not optimally reduce erosion in the studied areas. Up to 24 percentage point reduction in erosion could be achieved with RUSLE-based targeting of the grass areas, compared to the buffer strips. Overall erosion reductions up to 46% could be achieved with the targeted grass areas. The results show how the majority of erosion reductions could be achieved in disproportionally small land areas (~20% of the area), often not located adjacent to the streams, and the distance of the erosion hotspots from the steams varied between the sub-catchments and fields. This points out the importance of hotspot areas and the potential of models in considering spatial variations in grass area targeting. The local conditions were characterised by modest topographic variations, small field parcels, low sediment connectivity via surface runoff and high connectivity via efficient subsurface drainage (Räsänen et al. 2023; Tähtikarhu et al. 2022), which likely contrast with many other regions in Europe. More comprehensive erosion assessment could benefit of improved empirical validation, in-depth uncertainty assessment and consideration of sediment connectivity via open ditches and streams. The work is described in more detail in a scientific manuscript (Tähtikarhu et al., submitted).

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Key messages of WP4

WP4 outlines key strategies for minimising uncertainty, standardising scaling procedures, and improving modelling approaches through sediment connectivity to enhance soil erosion and mitigation efforts.

Minimising uncertainty and communicating it

Uncertainty is an inherent part of the modelling procedure due to multiple factors such as dataset quality and process knowledge gaps. The impact of this uncertainty on the model outcome should be considered through uncertainty and sensitivity analysis and minimised correspondingly by improved model parameterisation. Open communication about the uncertainty of model predictions to stakeholders is crucial to enhance understanding and acceptance of soil erosion assessments through modelling.

Standardising up- and downscaling procedures in soil erosion modelling

Furthermore, knowing the impact of dataset quality, parameter methods and scale on the model outcome is vital for the validity of the resulting soil erosion risk assessment. Standardising up- and down-scaling procedures in soil erosion modelling is recommended to ensure consistency and comparability of model outcomes.

Connectivity approach improves our understanding of soil erosion and mitigation

Model scenarios can help identify soil erosion hotspots and optimise the location of ECMs in targeted mitigation strategies based on spatial variations. Soil erosion and mitigation scenario modelling can be improved by including a sediment connectivity approach. Different approaches to modelling of ECMs and connectivity are possible depending on the model. The ability of models to accurately represent ECMs and connectivity elements in their modelling procedure varies depending on model type. Most models can be altered to include these but it requires a lot of expertise from the model user and can be a laborious process. This may be a limiting factor in the development of successful soil erosion management scenarios. Therefore, further developments are needed to enhance the integration of sediment connectivity in modelling.

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2.5 Mitigation measures and decision support framework for stakeholders (WP5)

Work package 5 intended to build on the knowledge gathered in the previous work packages and provide decision support to soil erosion model users, practitioners and decision makers on the implementation of soil erosion mitigation measures at local level. Selected agricultural catchments within the project partner countries were described regarding erosion problems, modelling efforts and an evaluation of the social and economic barriers for implementation of soil erosion mitigation measures. The evaluation was done through local level cost estimation based on CAP subsidies and stakeholder focus group meetings.

2.5.1 Catalogue of catchments to develop mitigation plans with appraisal of erosion problems (WP5-D1)

This report presents a catalogue of 14 agricultural catchments in 8 European countries with various types of erosion and sediment connectivity problems and a need for implementation of mitigation measures against on- and off-site impacts of water erosion. Catchment selection was based on the experience and previous research of project partners, and should provide a representative sample of the variety of agricultural catchments present in the EU. The catchments include a wide range of catchment sizes (from 0.66 km^2 up to 449 km^2) and a variety of land uses, which were classified according to CORINE Land Cover 2018. The most dominant land use was non-irrigated arable land. Other land uses within individual catchments included forest, vineyards, olive groves and complex cultivation patterns.

The erosion issues encountered in the catchments included inter-rill erosion, rill erosion, gully erosion, landslides, calanchi, internal erosion through suffusion and subsurface drainage erosion. All catchments experienced inter-rill and rill erosion. Gully erosion was seen in all catchments except those in Denmark, Finland and France.

Almost all catchments had erosion estimations calculated by different soil erosion models. The types of soil erosion models applied included RUSLE, WaTEM/SEDEM, SWAT, MMF, MHYDAS, and RUSLE combined with an Index of Connectivity and Sediment Delivery.

Several of the catchments described in this deliverable were used in WP4 modelling scenarios and in the next tasks of WP5.

2.5.2 Catalogue of local costs for different mitigation measures across the study area (WP5-D2)

Several factors influence the success of soil erosion control measure (ECM) implementation, but farmers' willingness to adopt the recommended measures in their regular farm management

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is critical. The decision-making of farmers is influenced by many factors, where profitability of ECM implementation and associated additional costs are often of high importance. Thus, socio-economic information on soil protection is needed to guide decision-making on ECMs and inform policy incentives, in order to aid the promotion and implementation of sustainable land management practices at farm level. This deliverable provides an overview of available information regarding the implementation cost of certain ECMs in several project partner countries (Austria, Belgium-Flanders, Denmark, Finland, Spain).

The cost of the ECMs was estimated based on the agri-environmental payments farmers receive for implementing specific ECMs through the CAP. The data on cost were gathered by project partners consulting the national CAP Strategic Plans for 2023-2027, where the compensations for implementation of measures are detailed. Although these payments may not reflect the actual cost of ECM implementation, yield loss and associated additional costs, we use the CAP subsidies as a proxy for the real local cost. To analyse efficacy and cost efficiency the ECMs were grouped into five categories: soil management, vegetation management, buffering, water management and land use changes. The costs were analysed according to this grouping and presented for each individual country, as well as compared to literature values from other studies.

The analysis showed a variation in subsidy amounts between specific ECMs, management practices and countries. Generally, soil and vegetation management measures are most commonly subsidised and less costly, while water management measures show the greatest range in cost. To encourage a higher adoption of ECMs among farmers it may be worthwhile to establish more accurate, locally-based cost assessments to ensure effective financial support.

2.5.3 Report on prioritized plans of mitigation strategies at the catchment with end-users' feedback (WP5-D3)

Focus group meetings were held in catchments in Austria, Belgium (Flanders), Denmark, Finland and Spain to identify the perspectives of local stakeholders on soil erosion mitigation measures and evaluate the social and economic barriers hindering their implementation. The focus group meetings were mainly conducted with farmers to identify their opinions on the relevance and their perception of soil erosion risk and sediment transport, the usefulness of soil erosion models and maps to implement erosion mitigation measures and how to improve these tools. They were also requested to choose the most suitable measures to be implemented and the actions needed to overcome the barriers for wider adoption.

Farmers expressed different views on the risk of erosion. While there were farmers in the Austrian, Flemish and Spanish catchments who were aware of the impact of erosion on soil quality, crop yield and water quality, farmers from the Nordic countries did not perceive soil erosion as a significant threat.
In general, farmers possess a good knowledge of the erosion problem on their farms, however they distrust the erosion assessments based on erosion models and maps. Firstly, erosion assessments by models have a high degree of uncertainty, especially when used at farm scale.

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Most models used for erosion risk assessment are adequate at larger scales as they provide long-term, average results for a set of parameters. Farmers expect accurate model outputs for their specific farm management, which is not usually the case. Secondly, the farmers were apprehensive towards the model output, in case these inaccurate model assessments may result in excessive focus from authorities on their farm, in the form of regulatory restrictions or loss of subsidies. Instead, most farmers would advocate for more intensive field monitoring to obtain reliable and accurate data for specific farms.
The implementation of erosion control measures depends largely on farmers' experience, "tradition" and on profitability analysis. Subsidies were seen as a promising tool to encourage the adoption of new voluntary measures, but improving subsidy schemes, particularly by streamlining the administrative process, was identified as a priority.

In Flanders one focus group meeting with public servants connected with the agricultural and environmental sectors was also held. Their perception of the local soil erosion issues differed somewhat from the farmers'. The expert opinion (SCALE scientists) and farmers opinion on each catchment and its erosion problems also diverged, as the soil erosion experts saw a higher degree of issues with soil erosion than the farmers did.

As the views and opinions between farmers and other stakeholders may differ, there is a need for tailored mitigation strategies, which consider the different perceptions of the relationship between soil erosion, crop yield and the sustainability of farm systems, and the feasibility of implementing erosion mitigation measures. Particular attention should be paid to the relationship between science, modelling, and farm and landscape management. An improved participatory approach in the design and implementation of regulations and their technical specifications may be beneficial for ensuring targeted erosion control.

2.5.4 Guidelines for implementation of the mitigation measures with end-users adapted to local conditions (WP5-D4)

WP5-D4 offers guidelines for practitioners and decision-makers to identify, select, and propose locally suitable erosion control measures at the scale of agricultural catchments. The aim is to enhance the management of sediment connectivity in agricultural landscapes through the development of catchment-specific erosion control plans.

A representative sample of pilot catchments described in WP5-D1 and the modelling scenarios of WP4 was used to identify areas requiring mitigation measures against the impacts of water erosion, including soil loss, sedimentation, nutrient and organic carbon losses, impaired water quality, and increased flood risk due to high sediment loads. A catalogue of available mitigation measures was created, focusing on hydrological connectivity. This catalogue draws on extensive knowledge and experience in protecting soils from water erosion and reducing sediment transport and delivery. The efficiency of potential measures was evaluated using erosion simulation models, following an assessment of these models' capability and performance in simulating mitigation effects.

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The selection of the most applicable measures involved public participatory approaches. The adoption of erosion control measures by farmers hinges on their performance, economic viability, and perceived benefits. Economic evaluations considered potential mitigation measures included in the National Strategic Plan under the Common Agricultural Policy, using subsidies 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 that combines scientific, technical, and local knowledge helps to 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 that integrate different aspects and represent desired outcomes under each scenario can greatly facilitate discussion and negotiation processes.

2.5.5 Report with compilation of policy documents (WP5-D5)

WP5-D5 presents a decision support framework for soil erosion mitigation, integrating field-scale measures and catchment-scale sediment connectivity management. It summarises the main insights from WP5 into identified opportunities, main challenges and specific technical and administrative needs for improved soil erosion mitigation planning and appends this knowledge with the recommendations of the policy brief based on the results of WP1. It employs a participatory evaluation method, considering technical, economic and social barriers to implement optimal erosion control strategies. Key insights include cataloguing diverse erosion issues across the European catchments within the project, economic evaluations of mitigation measures and stakeholder engagement to develop locally adapted guidelines. The proposed framework guides decision-makers in assessing, selecting and implementing effective erosion control measures through comprehensive technical, economic, and social evaluations.

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Key messages of WP5

The variety in soil erosion issues in the described catchments, as well as the differences in the perception of erosion among stakeholders across Europe, show that tailored mitigation strategies and local adaptation is needed. Taking a more participatory approach to policy design and technical specifications of erosion mitigation measures may help to ensure targeted erosion control. Improved subsidy schemes with more effective financial support based on accurate, locally-based cost assessments and a more streamlined administrative process could encourage more farmers to adopt further voluntary measures. The relationship between science, modelling and farm and landscape management should be given particular attention. Hence, the key messages of WP5 are the follows:

Catalogue of catchments
A report catalogues 14 agricultural catchments across 8 European countries, detailing their erosion problems, land uses, and the application of various soil erosion models. The catalogue aims to represent the variety of agricultural catchments in the EU and includes a range of catchment sizes and types of erosion.

Local costs of mitigation measures
The cost of implementing soil erosion control measures (ECMs) in different countries using CAP subsidies as a proxy for real costs were examined. The study highlights the variation in subsidy amounts and costs between ECM types and countries, emphasising the need for accurate, localised cost assessments to encourage ECM adoption.

Stakeholder feedback
Focus group meetings with farmers and public servants in various countries identified differing perceptions of soil erosion risks and mitigation measures. Farmers generally distrust model-based erosion assessments and prefer intensive field monitoring. The study underscores the importance of tailored mitigation strategies that consider the views of different stakeholders.

Guidelines for local implementation
Guidelines for selecting and implementing locally suitable erosion control measures are provided. This involves using public participatory approaches, evaluating the economic viability of measures, and integrating scientific, technical, and local knowledge to enhance the management of sediment connectivity in agricultural landscapes.

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3 Conclusions

The SCALE project has significantly advanced our understanding of sediment connectivity and its crucial role in mitigating soil erosion across diverse European agricultural landscapes. By addressing the integration of sediment connectivity into erosion models and developing harmonised datasets and methodologies, the project has laid the groundwork for more effective and region-specific soil erosion control measures. The collaboration of 13 partners across 9 EU countries underscores the project's significance and its commitment to enhancing soil quality and protecting agricultural and ecological systems.

Key findings from each work package highlight the project's achievements:

- WP1 revealed that harmonising datasets and parameterisation across different erosion models is essential for consistent soil erosion assessments and improving management efficiency. Additionally, sediment connectivity should be a primary consideration in erosion risk modelling, particularly for policy and planning purposes.

- WP2's key findings include the development of a metadata scheme based on INSPIRE principles and a shared database that has improved data interoperability and facilitated sharing among project partners. It also stressed that accurate and reliable soil erosion modelling requires the standardisation of model-relevant parameters and input data consistency.

- WP3 emphasised the importance of standardising up- and downscaling procedures in soil erosion modelling to ensure consistency and comparability of model outcomes. Uncertainty and sensitivity analysis were also deemed crucial for understanding the impact of dataset quality and parameter methods on model outcomes.

- In WP4, the project identified that different approaches to modelling erosion control measures (ECMs) and connectivity are possible, but integration into models varies and requires substantial expertise and effort. Model scenarios were shown to help identify soil erosion hotspots and optimise the location of ECMs based on spatial variations.

- WP5 highlighted the necessity of tailored mitigation strategies and local adaptation to address the variety in soil erosion issues and stakeholder perceptions across Europe. It also noted that improved subsidy schemes and participatory approaches to policy design can encourage more farmers to adopt voluntary erosion control measures.

The project's findings and guidelines have been disseminated through various channels (as part of the tasks in WP6), ensuring that stakeholders are informed and can implement best practices.

Based on these findings, several recommendations for stakeholders have emerged. Policy makers and regulators should promote harmonisation of datasets and parameterisation across erosion models to ensure consistent assessments. Implementing region-specific erosion

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mitigation measures and incorporating sediment connectivity into erosion risk maps and policy frameworks can improve the accuracy and relevance of mitigation strategies. Farmers and land managers are encouraged to engage in participatory approaches to develop locally suitable erosion control measures. They should leverage subsidies and financial support schemes designed to mitigate soil erosion, ensuring these are based on accurate, local cost assessments. Enhanced collaboration with scientists and modellers is also recommended to integrate field monitoring data with model-based assessments. Researchers and modellers should continue developing and refining models to better integrate sediment connectivity and enhance their predictive accuracy. Standardising methods for up- and downscaling in soil erosion modelling will improve consistency, and conducting thorough uncertainty and sensitivity analyses will help understand the impact of data quality and parameter methods on model outcomes.

Future studies on connectivity research should focus on enhancing data quality and sharing by improving existing datasets and creating new, accurate datasets for specific parameters shared between multiple models. International collaborations should be fostered to ensure data interoperability and sharing, enhancing the overall quality and reliability of erosion models. Advanced modelling techniques, such as developing models that can more accurately represent ECMs and connectivity elements, should be explored to reduce the need for extensive expertise and effort in their integration. Innovative modelling approaches that incorporate real-time data and machine learning can also improve predictive capabilities. Establishing long-term monitoring campaigns to gather high-resolution data necessary for model calibration and validation is essential. Using empirical data to validate erosion risk maps and tailoring threshold values to regional conditions will ensure accuracy. These recommendations guide the path for stakeholders and researchers to contribute to more effective and sustainable soil erosion management practices, ultimately protecting agricultural productivity and environmental health across Europe.

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Deliverables

WP1-D1
Johannsen, L.L., & Schmaltz, E., 2022. Report on parameterisation of connectivity and mitigation strategies in the frequently-used soil erosion models. EJP SOIL project SCALE, Deliverable WP1-D1, 42 p.

WP1-D2
Thorsøe, M.H. & Heckrath, G., 2023. Report on implementation of soil erosion and mitigation strategies in national legal standards. EJP SOIL project SCALE, Deliverable WP1-D2, 35 p.

WP2-D1
Johannsen, L.L., Schmaltz, E., Lo Papa, G., Wawer, R., 2022. Description of common database including functionality and management. EJP SOIL project SCALE, Deliverable WP2-D1, 6 p.

WP2-D2
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WP3-D1
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WP3-D3
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WP4-D4
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WP4-D5
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WP5-D1
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