Author(s): Timo A. Räsänen, Mika Tähtikarhu, Jari Hyväluoma

Title: Exploring the RUSLE-based structural sediment connectivity approach for agricultural erosion management

Year: 2024

Version: Published version

Please cite the original version:

Timo A. Räsänen, Mika Tähtikarhu, Jari Hyväluoma, Exploring the RUSLE-based structural sediment connectivity approach for agricultural erosion management, CATENA, Volume 246, 2024, 108420, ISSN 0341-8162, https://doi.org/10.1016/j.catena.2024.108420 .

Catena 246 (2024) 108420

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Exploring the RUSLE-based structural sediment connectivity approach for agricultural erosion management

Timo A. Räsänen [*], Mika Tähtikarhu, Jari Hyväluoma

Natural Resources Institute Finland (Luke), Latokartanonkaari 9, 00790 Helsinki, Finland

ARTICLE INFO

Keywords:
RUSLE
Erosion
Sediment connectivity
Agriculture
Erosion management

ABSTRACT

Models play a crucial role in guiding agricultural erosion management, though their incorporation of sediment connectivity and management strategies varies. This study evaluated the RUSLE/IC/SDR model's potential for simulating agricultural erosion management at both the field scale and across two catchments. We tested the model's ability to simulate erosion management measures at a high spatial resolution (2 m × 2 m) across diverse topographies, assessed whether incorporating sediment connectivity improves RUSLE-based erosion management planning within catchments, and explored its capacity to tailor measures based on local connectivity characteristics. Our findings showed significant variability in sediment sources and connectivity. The simulation of no-till and buffer strip measures effectively demonstrated their varying effectiveness across fields and catchments. At the catchment scale, erosion management planning that incorporates sediment connectivity through the RUSLE/IC/SDR approach did not contribute to significant additional sediment delivery reduction compared to using RUSLE alone. However, at the field scale, RUSLE/IC/SDR offered improved opportunities for tailoring erosion management measures to local sediment connectivity characteristics. These simulations highlight both the potential and limitations of RUSLE/IC/SDR, advancing our understanding of its application for erosion management. In conclusion, while RUSLE/IC/SDR represents a valuable extension of RUSLE, further research is needed to fully realize its practical applications. Nonetheless, it shows promise for high-resolution simulation of sediment connectivity and erosion management at the field scale, across large catchments and regions.

1. Introduction

Mitigation of soil erosion by water is a persistent challenge in agricultural environments (Ulén et al., 2012). Erosion results in the loss of fertile topsoil, structural changes in the soil, and the transport of sediment, nutrients, and carbon to surface waters, with negative impacts on agricultural productivity, surface water quality, and aquatic ecosystems (Manninen et al., 2023; Ekholm and Lehtoranta, 2012; Bilotta and Brazier, 2008; Montgomery, 2007; McDowell et al., 2004; Henley et al., 2000; Pimentel et al., 1995). An effective mitigation of soil erosion and its negative impacts depends on understanding erosion, sediment transport, and deposition processes, as well as on effectively implementing erosion management measures tailored to local conditions.

Computational models provide an efficient means for studying and evaluating erosion management. They are widely used to support practical erosion management and decision-making (Schmaltz et al., 2024; Borrelli et al., 2021; Batista et al., 2019; Boix-Fayos et al., 2006). Models can be used to evaluate erosion management strategies at various scales, ranging from field to the catchment and regional levels. They effectively generalize and extend knowledge from local empirical measurements to different locations or regions, providing a cost-effective approach. The models, however, vary in their description of the erosion-transport-deposition process (e.g., Karydas et al., 2014; Merritt et al., 2003), as well as in their capacity to consider different erosion management measures (Schmaltz et al., 2024).

The most widely used erosion model is the Revised Universal Soil Loss Equation (RUSLE) (Borrelli et al., 2021; Renard et al., 1997). It is an empirical model, and it was originally developed for estimating soil loss on hill slopes, but is commonly used as a spatially distributed model where erosion is predicted across gridded computational units (Borrelli et al., 2021; Ghosal and Das Bhattacharya, 2020). The spatially distributed RUSLE, however, has a significant limitation as it does not consider sediment transport between the computational units. This limitation hinders the estimation of sediment delivery from the

---

* Corresponding author.
E-mail address: timo.rasanen@luke.fi (T.A. Räsänen).

https://doi.org/10.1016/j.catena.2024.108420
Received 13 May 2024; Received in revised form 13 August 2024; Accepted 20 September 2024

landscape to sinks (e.g., surface waters) and the incorporation of various erosion management measures and landscape features that affect sediment transport or connectivity in the simulations.

This limitation of RUSLE in spatially distributed computations has been addressed by at least two complementary approaches. The first approach utilizes the transport coefficient (T_C) approach to simulate sediment transport and has been implemented in USPED (Mitasova et al., 1996) and WATEM/SEDEM (Van Oost et al., 2000; Van Rompaey et al., 2001; Verstraeten et al., 2006), which are based on RUSLE factors. The second approach is based on the concept of connectivity (Hooke and Souza, 2021; Najafi et al., 2021; Baartman et al., 2020; Heckmann et al., 2018; Keesstra et al., 2018; Bracken et al., 2015; Bracken and Croke, 2007) and it utilizes connectivity indices to account for sediment transport (e.g., Hooke and Souza, 2021). A particularly promising approach is a structural sediment connectivity approach that is based on the Index of Connectivity (IC) (Borselli et al., 2008) and sediment delivery ratio (SDR) (Vigiak et al., 2012). In conjunction with RUSLE, it provides estimates of sediment delivery from source areas to sinks. The RUSLE/IC/SDR approach has been utilized at the catchment scale, for example by Hamel et al. (2017, 2015), Zhao et al. (2020), and Abebe et al. (2023), on the field scale by Tähtikarhu et al. (2022), and it is integrated as part of the InVest model (Hamel et al., 2015). Tähtikarhu et al. (2022) explored RUSLE/IC/SDR in the same study catchments as in our study, without validation against observed sediment delivery, and found the model to reveal variations in sediment connectivity characteristics between fields and that it consistently ranked fields by magnitude of sediment delivery despite different parametrizations. Applications that simulate erosion management measures and their effects on sediment yields at the field scale are limited, which is a limitation in the understanding of the potential of RUSLE/IC/SDR in supporting agricultural erosion management at the field scale.

Erosion management is often simulated using process-based erosion models, which provide more detailed description of the physical processes compared to empirical models (Pandey et al., 2016). These models typically allow for the consideration of a range of erosion management measures, although their capability to do so varies by model, and sometimes the users need to implement the measures into the model. Commonly used process-based models include WEPP (Laflen et al., 1991), SWAT (Arnold et al., 2021) and LiSEM (De Roo et al., 1996). However, our focus is on exploring the inclusion of sediment connectivity in the empirical RUSLE model, given its widespread use and the potential benefits for agricultural erosion management.

Our aim was to advance the understanding of the potential of RUSLE/IC/SDR for simulating agricultural erosion management. The specific objectives were:

a) To test how RUSLE/IC/SDR simulates erosion management measures on a field scale and at high spatial grid resolution across a range of fields with varying topography.
b) To evaluate whether considering sediment connectivity using RUSLE/IC/SDR can enhance RUSLE-based erosion management planning within catchments, particularly in allocating erosion management measures to individual fields to achieve higher sediment delivery reduction.
c) To test how RUSLE/IC/SDR can be used to tailor erosion management measures for individual fields according to local sediment connectivity characteristics.

To achieve these objectives, we simulated individual fields under different erosion management measures in two topographically differing agricultural catchments in southern Finland. The simulations employed a range of erosion management scenarios and focused on surface sediment delivery from individual fields to ditches and surface waters surrounding the fields. The simulations were exploratory and were not validated against sediment delivery observations. To our knowledge, RUSLE/IC/SDR has not been evaluated before with these specific objectives for agricultural erosion management.

2. Methodology

The simulations consisted of three parts, each corresponding to one of the three objectives. First, we implemented RUSLE/IC/SDR on the fields of two case study catchments with a spatial resolution of 2 m × 2 m. We simulated two erosion management measures with different sediment connectivity implications to evaluate how RUSLE/IC/SDR describes sediment delivery reduction under varying field conditions.

Second, we simulated scenarios where erosion management measures were allocated to individual field parcels based on RUSLE and RUSLE/IC/SDR approaches with different allocation rates. We evaluated whether considering sediment connectivity improves RUSLE-based erosion management planning by comparing the total sediment delivery reductions resulting from the two allocation approaches. In these scenarios, the erosion management measures were implemented uniformly across all fields without tailoring them to the sediment connectivity characteristics of individual fields. The scenarios also considered parameter uncertainty in SDR and the influence of different erosion and sediment delivery units in the allocation. These scenarios were developed for model evaluation purposes and did not reflect existing erosion management practices in the study areas.

Third, we simulated erosion management measures at two case study fields to evaluate the potential of RUSLE/IC/SDR for tailoring measures according to local sediment connectivity characteristics.

In all simulations the focus was on riparian fields. The sediment delivery from the fields was defined as the sum of sediments exiting the field from any side through surface transport, corresponding to sediment delivery to open ditches surrounding the fields or to surface water. Sediment transport outside of fields and potential sediment delivery through artificial subsurface drainage were not considered.

These simulations build upon earlier RUSLE-based erosion assessments (Räsänen et al., 2023) and the exploration of RUSLE/IC/SDR (Tähtikarhu et al., 2022) conducted in the same study areas. The methodology is described in detail in the following sections and summarized in Table A1 in Appendix A.

2.1. Study area

The RUSLE/IC/SDR simulations were conducted on riparian fields within the Aura and Mustio River sub-catchments in Southwestern Finland (Table 1). These sub-catchments (hereafter referred to catchments) are the lowest drainage areas of the coastal rivers that drain to the Baltic Sea situated within 80 km distance from each other. The study focused on riparian fields to account for erosion management measures typically implemented only in riparian fields, streamlining the analysis by limiting the number of fields.

The two catchments are intensive agricultural areas with nationally high erosion levels. They represent topographically different agricultural environments while experiencing similar climatic conditions (Räsänen et al., 2023). The topography of the Aura River catchment is generally flat, but with steep slopes near streams and rivers (Table 1 and Fig A1 in Appendix A). In the Mustio River catchment, the fields gently undulate with few or no steep slopes near streams and rivers. The soils of the agricultural lands in both catchments are dominated by clay soils (Vertic Luvic Stagnosols). However, Mustio River catchment also includes areas with siltic and loamic soils (Stagnic Regosols) and very small areas of muddier soils (Umbric Gleysols) (Lilja et al., 2017c). Annual precipitation averages in both catchments around 700 mm, with higher rates between June and January, according to the Finnish Meteorological Institute (Table 1). The area is covered by snow for an average of three to four months from December to March.

Agriculture is predominantly focused on spring and winter cereals (e.g., wheat, barley, and oats, covering 60 % of the field area) and perennial grass and hay crops according to data from Finnish Food

Table 1
Characteristics of the Aura and Mustio River catchments and their riparian fields.

	Aura River catchment	**Mustio River catchment**
Catchment area [km^2]	146.6	116.2
Catchment area [km^2]	146.6	116.2
Annual precipitation [mm]	690	710
Field area [%]	34	30
Topography	Generally flat, with steep slopes near rivers and streams	Gently undulating
Dominating soil types	Clay soil (Vertic Luvic Stagnosols)	Clay soil (Vertic Luvic Stagnosols), Siltic and loamic soils (Stagnic Regosols)
Riparian fields (pcs.) [-]	514	232
Average riparian field size (25th-75th percentile) [ha]	4.6 (1.1–5.8)	6.3 (1.7–8.5)
Average riparian field slope (25th-75th percentile) [°]	2.3 (0.9–2.9)	2.7 (1.5–3.8)

Authority. The spring crops are planted in April and May and harvested in August and September. Tillage is typically performed in the autumn after harvest using conventional moldboard plowing or reduced tillage. No-till and spring tillage are being increasingly used.

Most of erosion occurs outside the growing season, especially in spring, autumn, and early winter when the fields have less vegetation cover, and the soil is more exposed. Erosion is commonly managed by wintertime vegetation cover (e.g., stubble, winter crops), reduced tillage, and riparian grass buffer strips. The fields are typically drained by open ditches surrounding the fields and isolating them from each other in terms of surface runoff and sediment transport. The ditches effectively drain the field areas and transport sediments toward streams, rivers, and lakes. Artificial subsurface drainage is also a common practice.

Riparian fields were defined as those within a 10-meter distance from the main water bodies, such as lakes, rivers, and perennial streams (Finnish Environment Institute, 2010). The field borders were selected and defined from the Land Parcel Register of the Finnish Food Authority. This resulted in 514 and 232 riparian fields for the Aura and Mustio River catchments, respectively (Table 1, Fig. 1). The average size of the riparian fields is 4.6–6.3 ha.

2.2. *Simulation of sediment delivery reduction by erosion management measures*

2.2.1. *Revised Universal Soil Loss Equation (RUSLE)*

Erosion was estimated using the Revised Universal Soil Loss Equation (RUSLE) developed by Renard et al. (1997), an empirical model designed to predict sheet and rill erosion by water. RUSLE is a revised version of the Universal Soil Loss Equation (USLE) proposed by Wischmeier and Smith (1978). Initially developed for assessing soil loss at the field slope/plot scale, RUSLE has been widely applied as a spatially distributed model. The RUSLE equation is given by:

$$E = R \times K \times LS \times C \times P, \tag{1}$$

Here, E represents the annual average erosion (t ha^{-1} yr^{-1}), and the factors are defined as follows:

- *R:* Rainfall-runoff erosivity factor (MJ mm ha^{-1}h^{-1} yr^{-1})
- *K:* Soil erodibility factor (t ha h ha^{-1} MJ^{-1} mm^{-1})
- *LS*: Topographic factor (dimensionless)
- *C*: Cover-management factor (dimensionless)
- *P*: Support practice factor (dimensionless).

For a more detailed description of RUSLE factors, refer to Renard et al. (1997).

The original field slope/plot scale RUSLE predicts soil loss, or the amount of sediment transported to the end of the slope (Renard et al., 1997). In contrast, the spatially distributed RUSLE predicts soil loss at a spatially discrete computational unit, such as a grid cell, but does not account for sediment transport between the computational units. Therefore, the predictions of spatially distributed RUSLE over a

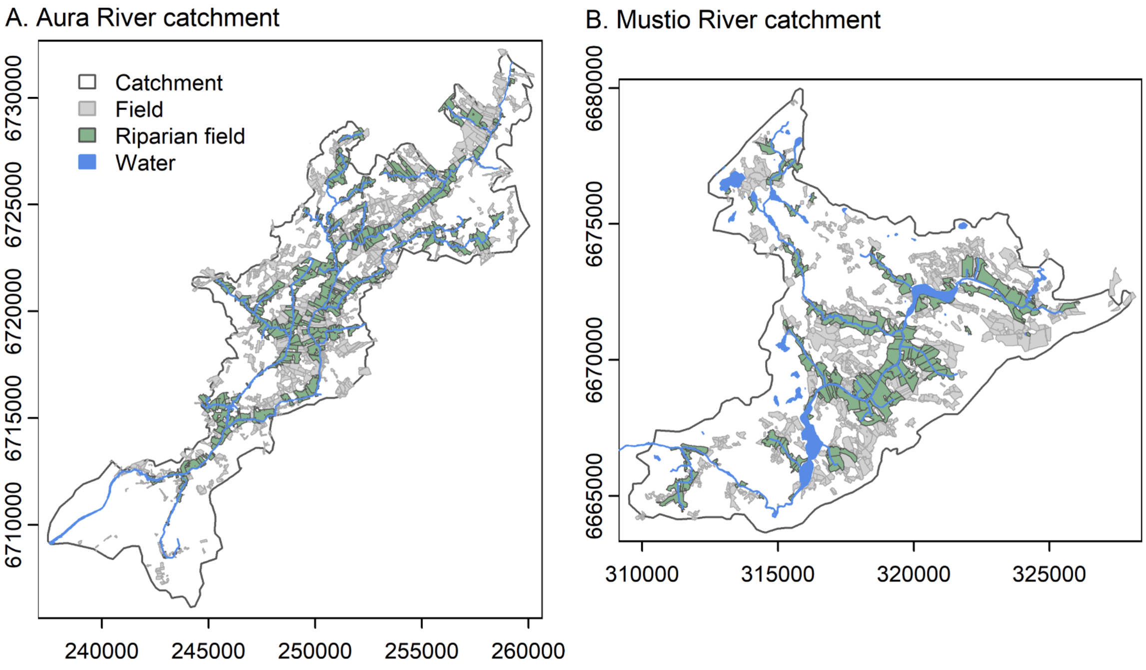


Fig. 1. A. Aura and B. Mustio River catchments and their riparian fields (axis units in meters, y-axis pointing north).

landscape are considered as gross erosion predictions. The spatial units are, however, connected in spatially distributed computation through the LS factor, which accounts for the effect of slope length and steepness on the erosion rate at each spatial unit.

2.2.2. Index of connectivity (IC) and sediment delivery ratio (SDR)

Sediment delivery was estimated by combining the IC and SDR following the methods of Borselli et al. (2008) and Hamel et al. (2017, 2015) with RUSLE (Renard et al., 1997), which is the structural sediment connectivity approach to estimate sediment delivery from the landscape to sinks (e.g. surface waters). The dimensionless IC is computed based on landscape structural elements, such as elevation and roughness, and is represented as

$$IC = log_{10}\left(\frac{D_{up}}{D_{down}}\right) \tag{2}$$

where D_{up} [m] and D_{down} [m] are the upslope and downslope factors, respectively. D_{up} is calculated as:

$$D_{up} = \overline{W}\overline{S}\sqrt{A} \tag{3}$$

where $\overline{W}$ [-] is the mean weighing factor of the upslope area, $\overline{S}$ [m m^{-1}] is the mean terrain slope (upslope area), and A [m^2] is the upslope area. D_{down} is calculated as:

$$D_{down} = \sum_{i=1}^{n}\frac{d_i}{W_iS_i} \tag{4}$$

where d_i [m] is the length of ith grid cell, W_i [-] is the weighing factor of ith cell, S_i [m m^{-1}] is the slope of ith cell along the downslope flow path, and n is the number of cells in the downslope path. w_i describe the effects of land use and vegetation (i.e., roughness) on the IC. In agricultural settings, $\overline{W}$ and W_i can be parameterized using RUSLE C factor values (Borselli et al., 2008). High and low IC values describe areas with a high and low degree of connectivity, respectively.

The sediment delivery ratio (SDR) from a grid cell to a sink is described by sigmoid-type function as

$$SDR_i = SDR_{max}\left(1 + \exp\left(\frac{IC_0 - IC_i}{K_{IC}}\right)\right)^{-1} \tag{5}$$

Here SDR_{max} [-] represents the maximum SDR (ranging from 0.0 to 1.0), IC_i [-] is the IC value of the ith grid cell, and IC_0 [-] and K_{IC} [-] are empirical parameters. SDR describes the share of eroded sediment that is transported over the soil surface from a grid cell to a specified sink.

Sediment delivery from the modelled area is then computed as

$$Q = \sum_{i=i}^{n}E_iSDR_i \tag{6}$$

where Q [t ha^{-1} yr^{-1}] is the total sediment delivery via surface transport, E_i [t ha^{-1} yr^{-1}] is the erosion (from RUSLE) in the ith grid cell, SDR_i [-] is the sediment delivery ratio in the ith grid cell, and n is the number of cells.

2.2.3. Erosion management measures

The erosion management measures were considered for spring cereal cultivation and comprised of:

- *No measure*: autumn moldboard tillage
- *No-till*: cultivation using a seed drill and wintertime stubble cover
- *Buffer strip*: autumn moldboard tillage and a 30-meter-wide riparian grass buffer strip with perennial grass cover that is mowed in the autumn

These measures were selected for simulations as they are commonly implemented and subsidized practices in Finland. From a connectivity simulation perspective, they present two distinct cases. "No-till" impact connectivity throughout the field, while buffer strips impact connectivity in specific areas of the field where they are located. The buffer strips also effectively reduce erosion at their own area. The selection of 30-meter buffer width aligns with Finland's CAP Strategic Plan (EU, 2022).

2.2.4. Estimation of erosion

Erosion in the riparian fields was estimated using RUSLE (Equation (1)). For the R, K, LS, and C factors of RUSLE, the same data was used as by Räsänen et al. (2023).

The R factor is derived from a 1 km resolution gridded European-scale dataset (Panagos et al., 2015), where the R for Finland was calculated using hourly precipitation data measured at 64 stations from 2007 to 2013. The R-values for the Aura and Mustio River catchments are 360 and 314 MJ mm ha^{-1} t^{-1} yr^{-1}, respectively.

The K factor is based on the Finnish Soil Database (Lilja et al., 2017c), supplemented with soil-specific K values (Lilja et al., 2017b, 2017a). The soil database contains a vector map (1:200,000) describing the Finnish soils according to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2022) with the smallest spatial feature being 6.25 ha. The dominant soils Vertic Luvic Stagnosol (clay soil) and Stagnic Regosol (siltic and loamic soils) in Aura and Mustio River catchments had values of 0.040 and 0.057 t ha h ha^{-1} MJ^{-1} mm^{-1}, respectively.

The LS is based on two-meter resolution digital elevation model derived from LiDAR measurements (National Land Survey of Finland, 2020). It was calculated for the field areas using Desmet and Govers (1996) method (rill/inter-rill erosivity ratio = 1 and stability = stable) and the multiple flow direction algorithm (Quinn et al., 1991). The average LS values for the agricultural lands of Aura and Mustio River catchments are 0.470 and 0.830, respectively.

The C factor values were taken according to the calibrated values for Finland (Räsänen et al., 2023). The C factor value for spring cereals (wheat, oat, and barley) with autumn moldboard plowing was 0.211, and for spring cereals (wheat, oat, and barley) with no-till it was 0.075. For the grassed area of buffer strips, we used a value of 0.065 of perennial grass. The P factor was not considered due to lack of adequate data on the subsurface drainage status of fields, their efficiency, and parametrization.

The resulting RUSLE data for riparian fields of Aura and Mustio River catchments had a 2 m × 2 m resolution. The average erosion rate for each field was calculated in kg ha^{-1} yr^{-1} and in kg yr^{-1} by multiplying the average rate in kg ha^{-1} yr^{-1} with the respective field area. The erosion estimates exclude the erosion reduction effect by potential subsurface drainage in the fields (see e.g., Räsänen et al., 2023). The erosion estimates by RUSLE are presented in the results section as average erosion rates for all fields and their buffer strip areas. Also, percentiles are calculated for average erosion rates of individual fields to describe the distribution of erosion rates between the fields.

The performance of RUSLE with the provided data was previously assessed against erosion measurements from seven experimental fields in Finland by Räsänen et al. (2023). The Nash-Sutcliffe efficiency (NSE) between predictions and estimates was 0.72 ($R^2 = 0.76$), with a mean absolute error of 190 kg ha^{-1} yr^{-1} and 90 % prediction errors ranging between −634 and 141 kg ha^{-1} yr^{-1}. These correspond to the typical performance of erosion models (Batista et al., 2019; Govers, 2011).

2.2.5. Estimation of sediment delivery and its reduction through erosion management measures

The sediment delivery through surface transport from each riparian field was estimated under no measure, no-till, and riparian buffer strip using the RUSLE/IC/SDR approach (Equation (6)). The approach has been used in the same study catchments earlier by Tähtikarhu et al. (2022), but it has not been evaluated against observations or used for simulation erosion management measures in these catchments. Therefore, we adopted a sensitivity-type approach for the most uncertain model parameters and a relative interpretation of simulation outputs, as explained below.

The sediment delivery was defined as the total amount of sediment exiting the field from any side, which closely corresponds to sediment delivered to open ditches surrounding the fields or adjacent surface water bodies. Sediment transport outside the field areas, as well as in ditches and streams, was not simulated. Sediment delivery through artificial subsurface drainage cannot be simulated with RUSLE/IC/SDR, and therefore potential subsurface drainage was not considered.

IC_i (Equation (2)) and SDR_i (Equation 5) were calculated for each grid cell of the fields using the same 2 m × 2 m resolution DEM (National Land Survey of Finland, 2020) as for the *LS* factor of RUSLE. The DEM was processed to address artificial sinks in order to prevent the fragmentation of flow paths by filling sinks up to 0.15 m, a fill level determined to be a realistic at the study areas (Tähtikarhu et al., 2022). The downslope flow path in the calculation of *IC* (Equation (4)) was defined from each grid cell to the edge of the field.

The IC_i and SDR_i were parameterized based on literature values as RUSLE/IC/SDR has not been calibrated against observations in Finland. W_i (Equation (4)) for spring cereals with autumn moldboard plowing, no-till, and buffer strips were parameterized using C values for RUSLE, as suggested by Borselli et al. (2008). Thus, the effect of no-till and buffer strips on sediment delivery was considered in W_i through the changes in vegetation cover (or roughness) in their respective areas.

Plausible parameter ranges for IC_0 and K_{IC} (in Equation 5) were estimated by applying three parameterizations: P1, P2, and P3. These were based on literature and earlier work by Tähtikarhu et al. (2022) in the same sub-catchments as in this study, and they are presented in Table 2. P1 is a commonly used parameterization in the literature (e.g., Hamel et al., 2015), P2 is the parameterization used by Hamel et al. (2017) and P3 is a parameterization suggested by Tähtikarhu et al. (2022) in the same catchments as our study. Tähtikarhu et al. (2022) explored a larger number of parametrizations. The parameterizations of SDR_i with different IC_0 and K_{IC} values are known to provide relatively consistent information about the relative differences between high and low sediment delivery areas and fields. however, the absolute magnitude of sediment delivery varies depending on the parametrization (Hamel et al., 2015; Tähtikarhu et al., 2022).

The P1, P2 and P3 values in our study were also selected so that the simulations provide sediment delivery rates that are within the range of what has been observed at experimental fields in Finland (Lilja et al., 2017a), while demonstrating the uncertainty in sediment delivery predictions resulting from the parameter uncertainty. The selected parameterizations also reflect different connectivity dynamics resulting in different shapes of the sigmoid function of the SDR equation (Equation 5).

The sediment delivery from the fields, denoted as Q (Equation (6)), was estimated using the RUSLE erosion estimates for no measure, no-till, and buffer strip, and the SDR_i (Eq. 5) for each field. *Q* values were calculated in kg ha^{-1} yr^{-1} and in kg yr^{-1}, similar to the erosion estimates.

Table 2
Parametrizations P1, P2 and P3 for IC/SDR.

Parameter	Description	Source
W	No measure: 0.211 No-till: 0.075 Buffer strip: 0.065	Räsänen et al. (2023)
SDR_{max}	1	Tähtikarhu et al. (2022)
IC_0	P1: 0.5 P2: 0.5 P3: −3.3	Tähtikarhu et al. (2022)Hamel et al. (2015) Hamel et al. (2017)
K_{IC}	P1: 2.0 P2: 3.5 P3: 1.0	Tähtikarhu et al. (2022)Hamel et al. (2015) Hamel et al. (2017)

The reduction in sediment delivery due to the erosion management measures at each field was calculated as the difference between sediment delivery under the erosion management measure and no measure (e.g., sediment delivery reduction by no-till = sediment delivery with no-till – sediment delivery with no measure). The sediment delivery reductions were reported as relative values due to the uncertainty in IC/SDR parameterization and resulting uncertainty in absolute values of sediment delivery reductions, as suggested by Oreskes et al. (1994) and Alewell et al. (2019). The absolute values of model outputs are generally more sensitive to uncertainties in model parameterization compared to the relative comparison of model outputs, such as between simulation scenarios. In the results section, the sediment delivery reductions are presented as average rates for all fields along with frequency distributions for individual fields.

All computations were performed using the standard algorithms of ArcMap 10.6.1 (ESRI, 2019) and the terra package (Hijmans et al., 2023) in the R software (R Core Team, 2022).

2.3. Evaluation of RUSLE/IC/SDR for erosion management planning

2.3.1. Planning of erosion management measures at catchments

The potential improvement brought by RUSLE/IC/SDR in RUSLE-based erosion management planning at catchment level, in terms of sediment delivery reduction, was evaluated through erosion management scenario simulations. In these scenarios, erosion management measures were allocated to individual fields of the two catchments using RUSLE (A) and RUSLE/IC/SDR (B) approaches. The resulting total sediment delivery reductions in the catchments were evaluated and compared to determine whether allocation with RUSLE/IC/SDR results in greater sediment delivery reduction than allocation with RUSLE alone.

In the RUSLE approach, erosion management measures were allocated to the highest-ranking fields according to estimated erosion rate under no measure. In the RUSLE/IC/SDR approach, the erosion management measures were allocated to the highest-ranking fields according to estimated sediment delivery reduction rate through erosion management measures. In the allocation, the fields were ranked in descending order (from largest to smallest) using two ranking units of kg ha^{-1} yr^{-1} and kg yr^{-1} based on the magnitude of field-specific erosion and sediment delivery reduction. In both approaches, no-till was allocated to the highest-ranking fields with rates of 20 %, 40 %, 60 %, and 80 % of the total riparian field area, while buffer strips were allocated to the highest-ranking fields with rates of 20 %, 40 %, 60 %, and 80 % of the total potential buffer strip area in the riparian fields. The potential buffer strip area was defined as the 30 m wide strip on the riparian side of a field, and they were allocated uniformly across all fields without tailoring their location or dimensions according local sediment connectivity characteristics. Three SDR parametrizations (P1, P2, and P3) were also used in these simulations to account for the parameter uncertainty in sediment delivery estimates, as previously described.

The allocation with the two approaches, the two ranking units, the four allocation rates, and the three parameterizations resulted in a total of 24 sediment delivery reduction scenarios for the RUSLE (A1-A24) and RUSLE/IC/SDR approaches (B1-B24) for each erosion management measure in both catchments. The scenarios are shown in detail in Table A2 in Appendix A, and they were developed solely for simulation purposes and to achieve our objectives; they do not reflect the actual allocation of the measures in the study catchments.

The differences in the catchment-scale total sediment delivery reduction resulting from the RUSLE and RUSLE/IC/SDR allocation approaches were evaluated by calculating the sediment delivery reduction difference between the simulation scenarios of the two approaches (e.g., Diff.1 = |A1| − |B1|, Diff.2 = |A2| − |B2|, see Table A2 in Appendix A). The total sediment delivery reductions from all scenarios were estimated with RUSLE/IC/SDR. The evaluation compares whether allocating erosion management measures to individual fields based on *estimated sediment delivery reduction by the erosion management measures* results in a greater total sediment delivery reduction in the catchment, compared to allocating based on *estimated erosion rate with no erosion management measures* at the fields.

2.3.2. Planning of erosion management measures at fields

The potential improvement brought by RUSLE/IC/SDR in RUSLE based-erosion management planning at field level, in terms of sediment delivery reduction, were evaluated at two individual fields. These fields were selected to represent different spatial distribution of high erosion areas and with different sediment transport pathways. The evaluation involved the comparison of three erosion management measures – no-till, buffer strip, and extended buffer strip – and their respective sediment delivery reductions. The extended buffer strip represent an erosion measure that were tailored to the fields according to local sediment connectivity characteristics to address sediment fluxes that were not captured by the conventional implementation of buffer strips. The width of the extended buffer strip was 30 m. We also calculated sediment flow accumulation rasters for both fields to visualize the sediment transport pathways using sediment delivery from individual grid cells ($Q_i = E_i{\cdot}SDR_i$) and standard flow accumulation algorithm of ArcMap 10.6.1 (ESRI, 2019).

3. Results

3.1. Erosion

According to RUSLE estimates, the riparian fields had average erosion rates of 1,939 kg ha^{-1} yr^{-1} (25.-75. percentiles for individual fields: 649–2,586) and 1,762 kg ha^{-1} yr^{-1} (783–2,176) with no measure at the Aura and Mustio River catchment, respectively (Fig. 2). At the potential buffer strip area, the erosion rate was 3,774 kg ha^{-1} yr^{-1} (924–5,572) and 1,715 kg ha^{-1} yr^{-1} (547–1,894) with no measure at the Aura and Mustio River catchments, respectively. Erosion was more pronounced near streams and rivers in the Aura River catchment due to steep slopes, while in the Mustio River catchment, erosion was generally more pronounced further away from streams and rivers due to undulating topography.

3.2. Sediment delivery reduction through erosion management measures

The assessment using RUSLE/IC/SDR and parameterization P1-P3 indicates that no-till has similar effect on sediment delivery in both catchments. No-till was found to reduce the sediment delivery of individual fields by an average of 71–83 % (P1-P3) in both catchments, and the differences between individual fields in the reduction were ≤ 7 percentage points (pp) (Fig. 3, Fig. 4).

The buffer strips were more effective in reducing sediment delivery at Aura than at the Mustio River catchment, with efficiency varying among fields. At Aura River catchment, riparian buffer strips reduced sediment delivery by an average of 39–55 % (P1-P3) for individual fields, with a quarter of the fields having lower reduction than 22–40 %

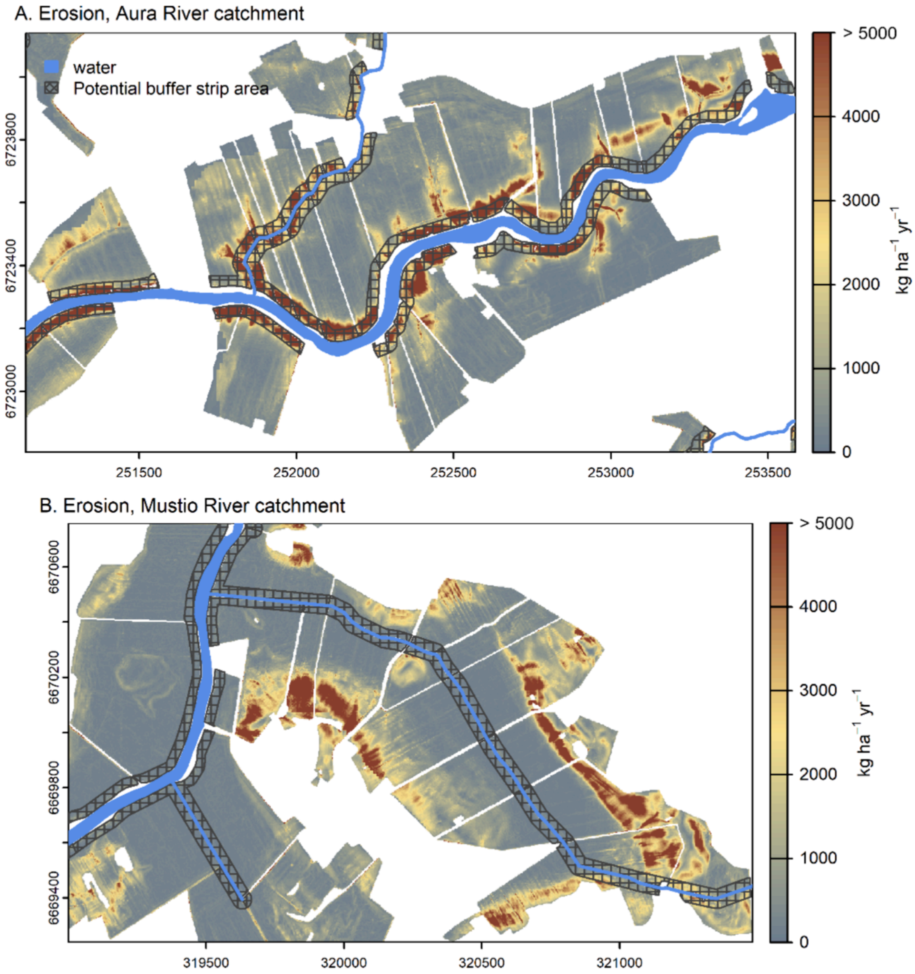


Fig. 2. A representative subset of the estimated erosion (kg ha^{-1} yr^{-1}) with no measures at riparian fields in the A. Aura and B. Mustio River catchments. The potential buffer strip areas (30 m wide) are also shown. (axis units in meters, y-axis pointing north).

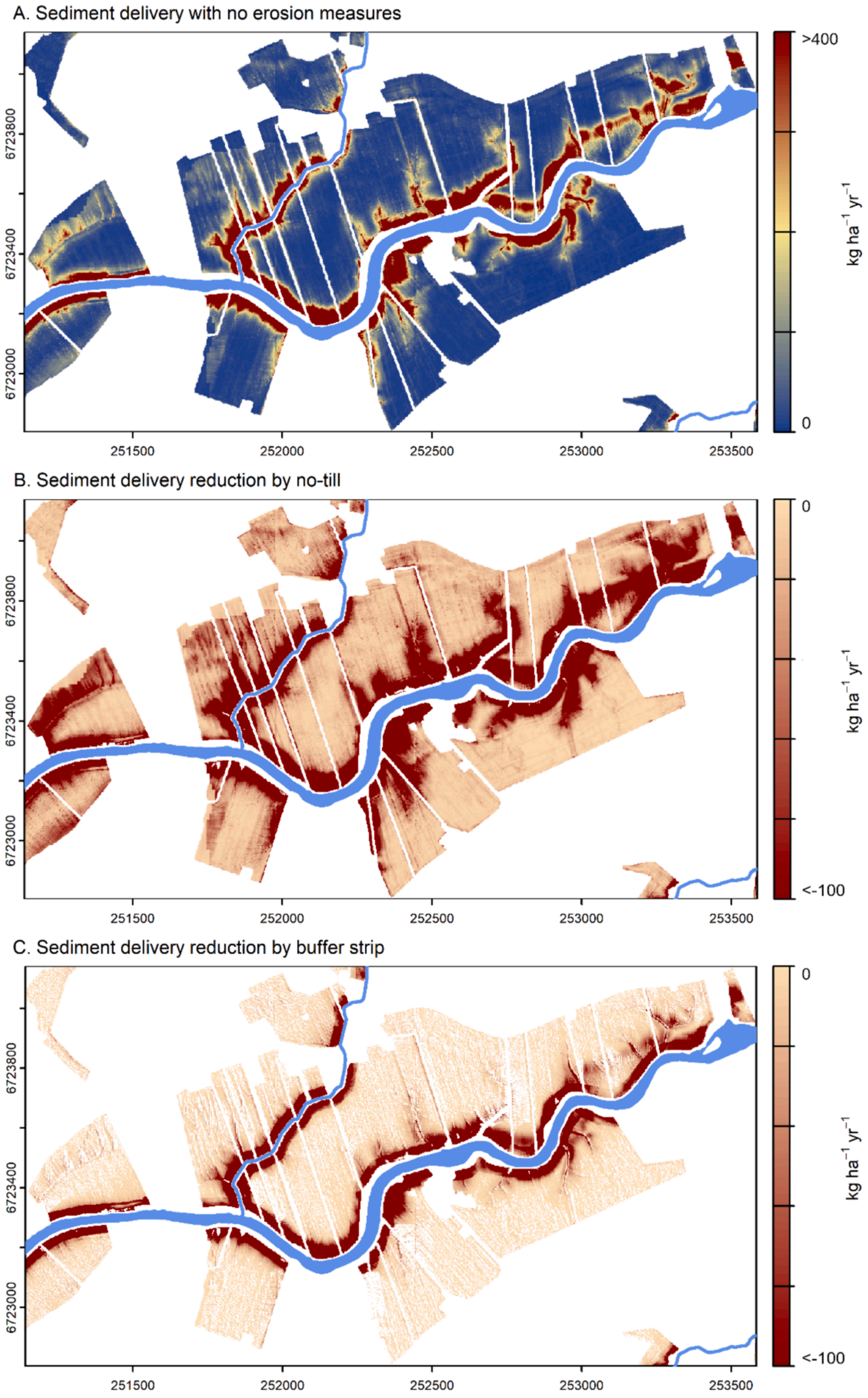


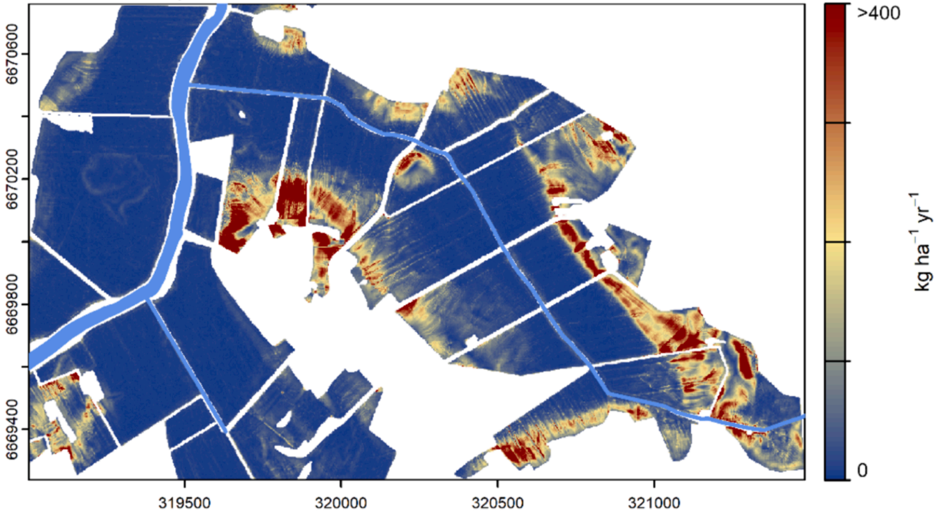
Fig. 5. Frequency distributions of estimated sediment delivery reduction by buffer strips and no-till practices at individual fields with parametrization P1-P3 at Aura (A-F) and Mustio (G-L) River catchments.

(P1-P3) (Table 3, Fig. 3). At Mustio River catchment, the reduction was on average 23–34 % (P1-P3) for individual fields, with a quarter of the fields having lower reduction than 7–13 % (P1-P3) (Table 3, Fig. 4).

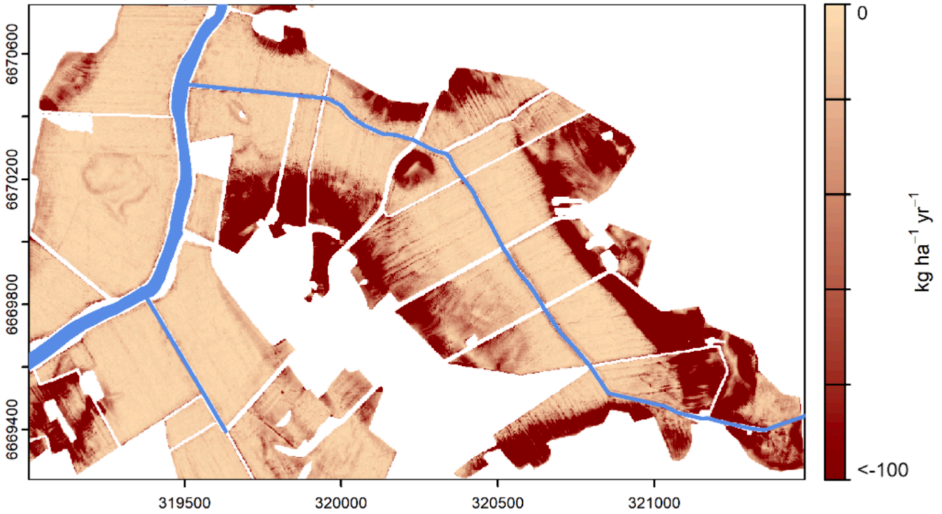
The parameterization P1-P3 influenced the magnitude and distribution of sediment delivery reduction rates at individual fields. Parameterization P3 generally resulted in the largest sediment delivery reductions, while P2 led to the lowest sediment delivery reductions with an average difference of 13 pp for individual fields (Fig. 5 and Table 3). In the case of buffer strips, the range of sediment delivery reduction rates is wide from below 10 % to above 80 % (Fig. 5). The frequency distributions for sediment delivery reduction rates at individual fields are also dissimilar between Aura and Mustio River catchments (Fig. 5). In the Aura River catchment, the distributions are more symmetric or skewed towards higher reduction rates, whereas at Mustio River Catchment, the distribution are heavily skewed towards lower reduction rates. In the case of no-till, the distributions are more similar between both catchments, but parameterization P3 shows greater variation in the sediment delivery reduction rates of individual fields compared to P1 and P2.

The surface sediment fluxes over the potential buffer strip areas were

A. Sediment delivery with no erosion measures



B. Sediment delivery reduction by no-till



C. Sediment delivery reduction by buffer strip

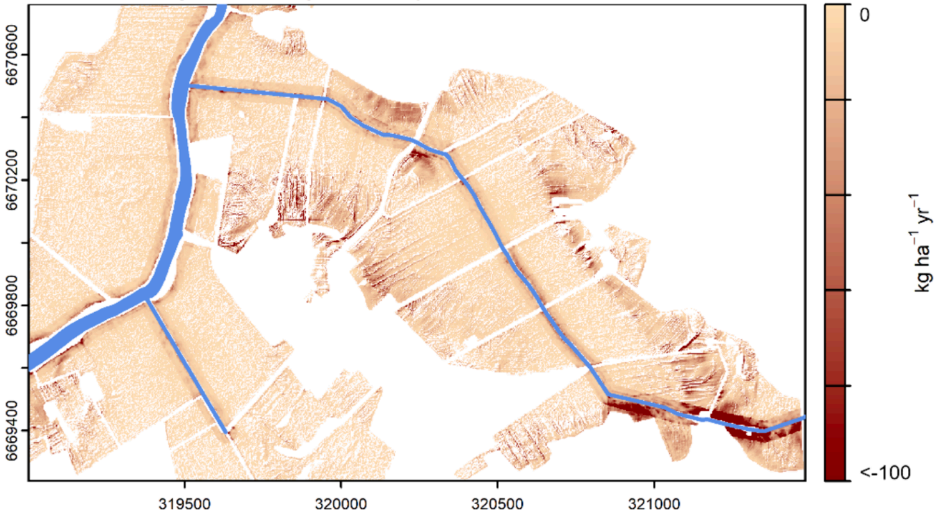


Fig. 3. Representative subsets of the estimated A. surface sediment delivery with no measures (kg ha^{-1} yr^{-1}), B. sediment delivery reduction with no-till (kg ha^{-1} yr^{-1}), C. sediment delivery reduction with buffer strips (kg ha^{-1} yr^{-1}) at the riparian fields in the Aura River catchment (SDR parameterization P1; axis units in meters, y-axis pointing north).

Table 3

Total catchment scale sediment delivery reductions by the erosion management measure allocation scenarios A1-A24 (RUSLE approach) and B1-B24 (RUSLE/IC/SDR approach) at Aura and Mustio River catchments. pp stands for percentage points.

		Aura River catchment								**Mustio River catchment**							
Ranking unit		kg ha^{-1} yr^{-1}				kg yr^{-1}				kg ha^{-1} yr^{-1}				kg yr^{-1}			
Allocation rate [%]		20	40	60	80	20	40	60	80	20	40	60	80	20	40	60	80
Erosion management measure: No-till																	
A. RUSLE: Total sediment delivery reduction (A1-A24)	P_1, %	-47	-66	-73	-75	-36	-58	-67	-72	-41	-57	-68	-74	-23	-42	-55	-68
	P_2, %	-41	-59	-66	-69	-32	-52	-61	-67	-34	-50	-61	-68	-21	-38	-51	-63
	P_3, %	-53	-73	-79	-81	-40	-64	-73	-78	-50	-66	-76	-81	-25	-46	-59	-74
	Range, pp	-12	-14	-13	-12	-8	-12	-12	-11	-16	-16	-15	-13	-4	-8	-8	-11
B. RUSLE/IC/SDR: Total sediment delivery reduction (B1-B24)	P_1, %	-47	-66	-73	-75	-37	-62	-72	-74	-42	-58	-68	-74	-32	-47	-61	-72
	P_2, %	-41	-58	-66	-69	-32	-54	-63	-68	-35	-50	-61	-68	-23	-40	-54	-65
	P_3, %	-54	-73	-80	-81	-44	-69	-79	-80	-51	-68	-76	-81	-40	-60	-71	-80
	Range, pp	-13	-15	-14	-12	-12	-15	-16	-12	-16	-18	-15	-13	-17	-20	-17	-15
Difference in sediment delivery reduction	P_1, %	0	0	0	0	-1	-4	-4	-2	-2	0	0	0	-9	-5	-7	-4
	P_2, %	0	1	0	0	0	-2	-2	-1	-1	0	0	0	-3	-2	-3	-2
	P_3, %	-1	0	0	0	-4	-5	-6	-2	-2	-1	-1	0	-15	-14	-12	-6
Erosion management measure: Buffer strip																	
A. RUSLE: Total sediment delivery reduction (A1-A24)	P_1, %	-27	-43	-49	-50	-27	-42	-47	-50	-14	-18	-22	-23	-8	-15	-19	-22
	P_2, %	-21	-34	-39	-40	-21	-33	-37	-40	-9	-13	-15	-16	-5	-10	-13	-16
	P_3, %	-33	-53	-59	-60	-33	-51	-56	-60	-20	-26	-30	-32	-11	-21	-26	-31
	Range, pp	-12	-19	-20	-20	-12	-18	-19	-20	-11	-13	-15	-16	-6	-11	-13	-15
B. RUSLE/IC/SDR: Total sediment delivery reduction (B1-B24)	P_1, %	-29	-43	-49	-50	-30	-44	-49	-50	-14	-19	-22	-23	-14	-19	-22	-23
	P_2, %	-22	-33	-39	-40	-23	-34	-39	-40	-9	-13	-15	-16	-10	-13	-15	-16
	P_3, %	-35	-52	-60	-61	-37	-53	-60	-60	-20	-27	-31	-32	-21	-27	-31	-32
	Range, pp	-13	-19	-21	-21	-14	-19	-21	-20	-11	-14	-16	-16	-11	-14	-16	-16
Difference in sediment delivery reduction	P_1, %	-2	0	0	0	-3	-2	-3	-1	0	-1	0	0	-7	-5	-3	-1
	P_2, %	-1	1	0	0	-2	-1	-2	-1	0	0	0	0	-5	-3	-2	-1
	P_3, %	-2	1	0	0	-4	-2	-3	-1	0	-1	-1	0	-10	-7	-4	-2

estimated to be, on average, 81–85 % and 64–66 % (P1-P3) of the total surface sediment flux from the riparian fields of Aura and Mustio River catchments, respectively. The rest of the sediments exited the field through other edges of the field. The drainage area of the buffer strips, in turn, was estimated to be on average 63 % and 69 % of the total field area in the Aura and Mustio River catchments.

The same allocation rates resulted in larger total sediment delivery reduction in the Aura than in the Mustio River catchments. For example, no-till with 40 % allocation rate reduced the total sediment delivery in the Aura River catchment by 52–73 %, and in the Mustio river catchment by 38–68 % (Table 3). Similarly, riparian buffer strips with 40 % allocation rate reduced the total sediment delivery in the Aura River catchment by 33–53 %, and in the Mustio River catchment by 10–27 % (Table 3).

The erosion management measures had the highest relative impact on total sediment delivery at lower allocation rates, and the impact of the measures did not increase considerably after 60 % allocation rate. For example, in the case of no-till, increasing allocation rate from 60 % to 80 % resulted in additional total sediment delivery reduction of 1–6 percentage points (pp) in the Aura River catchment and 4–15 pp in the Mustio River catchment (Table 3). In the case of buffer strips, increasing the allocation rate from 60 % to 80 % resulted in the additional total sediment delivery reduction of 1–3 pp in the Aura River catchment and 1–4 pp in the Mustio River catchment (Table 3).

The use of parameterization P1-P3 resulted in similar magnitude differences in total sediment delivery reductions at catchment scale compared to the field scale. The average difference in total sediment delivery reductions between P2 and P3 was 14 pp (Table 3).

3.3. *Planning of erosion management measures at catchments*

The allocation of erosion management measures using the RUSLE/IC/SDR approach resulted in small to modest differences in total sediment delivery reduction compared to the RUSLE approach. For no-till, allocation using the RUSLE/IC/SDR approach resulted in 0–6 and 0–15 pp (P_1-P_3, kg ha^{-1} yr^{-1} and kg yr^{-1}, allocation rates 20 %-80 %) larger total sediment delivery reduction than allocation using RUSLE approach in the Aura and Mustio River catchments, respectively (Table 3). In the case of buffer strip, allocation using RUSLE/IC/SDR approach resulted in 0–4 and 0–10 pp (P_1-P_3, kg ha^{-1} yr^{-1} and kg yr^{-1}, allocation rates 20 %-80 %) larger total sediment delivery reduction than allocation using RUSLE approach in the Aura and Mustio River catchments, respectively (Table 3). The level of improvement varied by field, ranking unit, allocation rate of erosion management measures, and the parameterization P1-P3 (Table 3).

The use of the ranking unit kg ha^{-1} yr^{-1} was generally found to result in larger or similar total sediment delivery reduction in the catchments than the use of the unit kg yr^{-1}. In the case of no-till, the use of unit kg ha^{-1} yr^{-1} resulted in 1–13 pp and 1–25 pp larger total sediment delivery reduction than the use of unit kg yr^{-1} in the Aura and Mustio River catchments, respectively (Table 3). In the case of buffer strip, the use of unit kg ha^{-1} yr^{-1} resulted at Aura River catchment in similar ($-2 - +3$ pp) and at Mustio River catchment in 0–10 pp larger total sediment delivery reduction than the use of unit kg yr^{-1} (Table 3). The differences in sediment delivery reduction between the two ranking units were generally higher with lower erosion management measure allocation rates. Two units also emphasized differently the size of fields in the of allocation of erosion management measures. The use of the unit kg yr^{-1} prioritized generally larger fields, whereas the unit kg ha^{-1} yr^{-1} did not

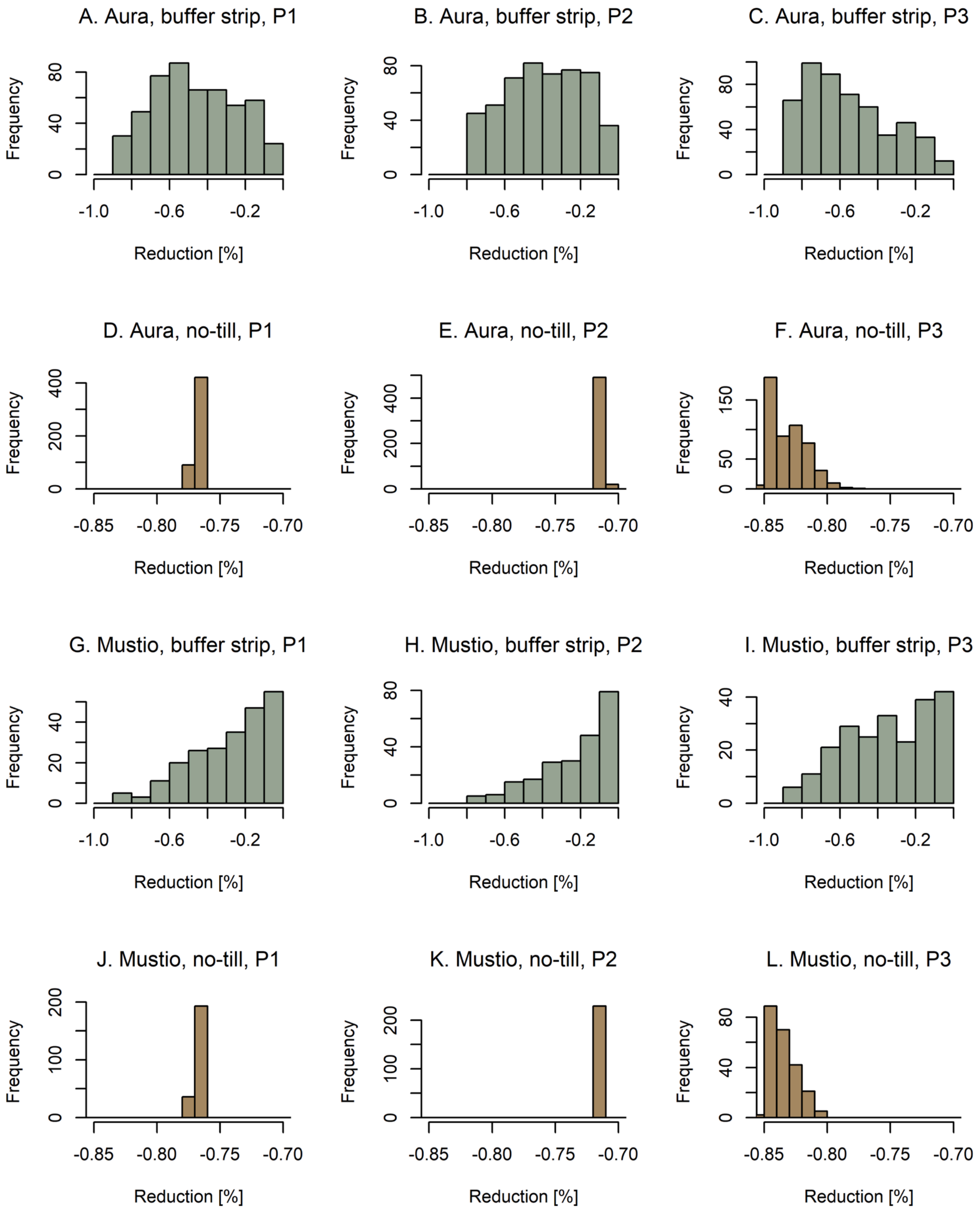


Fig. 4. Representative subsets of the estimated A. surface sediment delivery with no measures (kg ha^{-1} yr^{-1}), B. sediment delivery reduction with no-till (kg ha^{-1} yr^{-1}), C. sediment delivery reduction with buffer strips (kg ha^{-1} yr^{-1}) at the riparian fields in the Mustio River catchment (SDR parameterization P1; axis units in meters, y-axis pointing north).

consider the area sizes and accounted only for the average erosion or sediment delivery rate per surface unit.

The improvements of the RUSLE/IC/SDR allocation approach compared to the RUSLE approach varied based on the erosion management measure allocation rate, with generally higher improvements at lower allocation rates (Table 3).

Parameterizations P1-P3 of the SDR had only a marginal effect on the allocation of erosion management measures to fields, as the rankings were very similar across the different parameterizations. The Spearman rank correlations between the rankings were 0.97–1.00 ($p < 0.001$).

3.4. *Planning of erosion management measures at fields*

Both fields in the Aura and Mustio River catchments (Fig. 6) are large fields with high erosion rates, measuring 13.5 ha and 16.2 ha, respectively. The Aura field has an erosion rate of 2,970 kg ha^{-1} yr^{-1} with no measure, while the Mustio field has an erosion rate of 2,108 kg ha^{-1} yr^{-1} with no measure.

No-till had a similar effect on reducing sediment delivery at both fields, with reduction of 71–82 % (Table 4). However, the impact of buffer strips differed; at the Aura field, buffer strips reduced sediment delivery by 36–52 %, while at the Mustio field, the reduction was only 4–6 %.

In the Aura field, the presence of a large gully at the center of the field reduces the effectiveness of the buffer strips. Significant sediment fluxes (29–36 %, P1-P3) flow directly to the gully and the Aura River, bypassing the buffer strip (Fig. 5). To address this issue, the extended buffer strip provided an additional sediment delivery reduction of

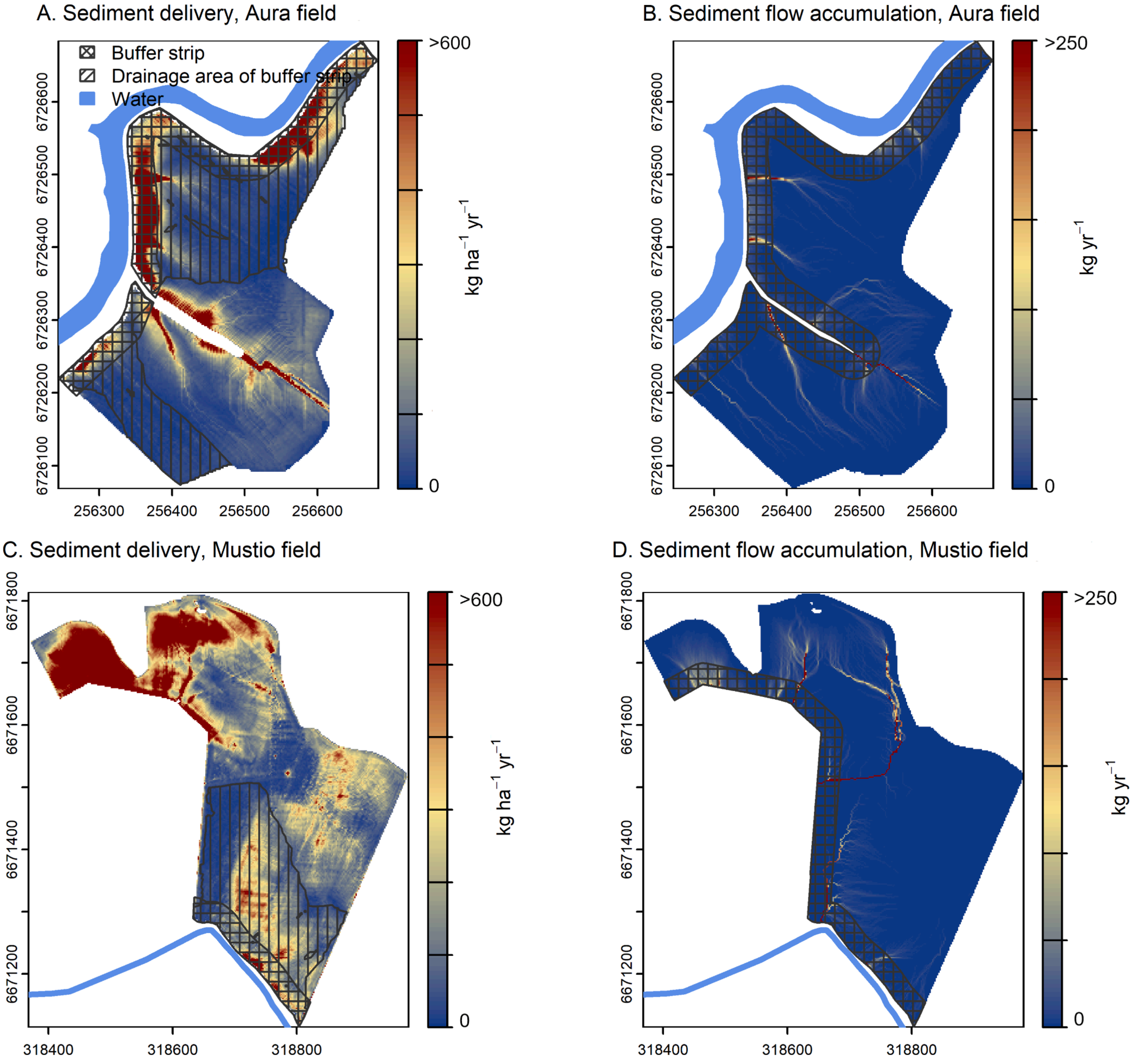


Fig. 6. Estimated A., C. sediment delivery via surface transport and B., D. surface sediment flow accumulation at Aura (13.5 ha) and Mustio fields (16.2 ha). The tiles A., C. show buffer strip areas and drainage areas of buffer strips (30 m wide), and the tiles B. and D. show extended buffer strip areas (30 m wide) (SDR parameterization P1; axis units in meters, y-axis pointing north).

13–17 pp (Table 4).

At the Mustio field, 29 % of the field area drains, and only 10–16 % (P1-P3) of sediments flow over the buffer strip area (Fig. 6). Moreover, high sediment source areas are located further away from the buffer strip. Sediments from these areas flow directly into a ditch and then into the tributary stream of the Mustio River, bypassing the buffer strip (Fig. 6). To address this issue, the extended buffer strip provided an additional sediment delivery reduction of 21–40 pp (Table 4).

Overall, the buffer strip results in 32–46 pp larger reduction in sediment delivery in the the Aura field than in the Mustio field. In the case of the extended buffer strip, the sediment delivery reduction is still 23–24 pp larger at the Aura field than at the Mustio field.

4. Discussion

4.1. Key findings

RUSLE/IC/SDR provided a significant expansion of the spatially distributed RUSLE by incorporating sediment connectivity for simulating sediment delivery and erosion management measures at the field and catchments levels. Previous studies using RUSLE/IC/SDR have primarily focused on sediment delivery at catchment scales (e.g., Abebe et al., 2023; Hamel et al., 2017, 2015; Zhao et al., 2020). There have been only a few studies focusing on field scale (e.g., Tähtikarhu et al., 2022), and even fewer studies that include erosion management measures in their field scale simulations. Our simulations provide an enhanced understanding of the potential and limitations of RUSLE/IC/SDR in simulating and assessing agricultural erosion management, as well as the role that sediment connectivity plays in RUSLE-based erosion management planning. Additionally, they also offer valuable insights

Table 4
Simulated reduction of erosion and sediment delivery through surface transport by no-till, buffer strip (30 m wide), and extended buffer strip (30 m wide) in the Aura (13.5 ha) and Mustio (16.2 ha) fields in the Aura and Mustio River catchments.

		Aura field Reduction [%]	**Mustio field** Reduction [%]
No-till	Erosion reduction	−64 %	−64 %
	Sediment delivery reduction, P1	−77 %	−77 %
	Sediment delivery reduction, P2	−71 %	−71 %
	Sediment delivery reduction, P3	−82 %	−82 %
Buffer strip	Erosion reduction	–32 %	−3 %
	Sediment delivery reduction, P1	−44 %	−6 %
	Sediment delivery reduction, P2	−36 %	−4 %
	Sediment delivery reduction, P3	−52 %	−6 %
Extended buffer strip	Erosion reduction	−41 %	−15 %
	Sediment delivery reduction, P1	−59 %	−36 %
	Sediment delivery reduction, P2	−49 %	−25 %
	Sediment delivery reduction, P3	−69 %	−46 %

into the effectiveness of erosion management measures under different topographical conditions.

Spring cereal cultivation with conventional autumn plowing, no-till, and grass buffer strips were successfully simulated in the fields of two topographically different catchments (Section 3.2). No-till measure had an average simulated reduction in sediment delivery of 71–83 % (P1-P3) at both catchments. Measurements from three experimental fields in Finland indicate a 36–75 % reduction in sediment delivery through surface transport by no-till (Honkanen et al., 2021; Kukkonen et al., 2004a; Puustinen et al., 2005). The measurements better consider the heterogeneity in soil and management conditions, while the RUSLE/IC/SDR simulations consider the accumulation of connectivity effects over larger areas than the experimental fields or plots. The reduction effect is known to be scale-dependent (García-Ruiz et al., 2015; Leys et al., 2010). Buffer strips, in turn, had average simulated reductions of 39–55 % and 23–34 % (P1-P3) at Aura and Mustio River catchments, respectively. Measurements from two experimental plots in Finland suggest 53–72 % reduction of sediment delivery through surface transport by 10–15 m wide grass buffer strips (Uusi-Kämppä and Jauhiainen, 2010; Puustinen et al., 2005). The measurements provide estimates of the effectiveness of buffer strips in well-controlled experimental plots, while the RUSLE/IC/SDR simulations reveal the effect of the heterogeneity in sediment connectivity characteristics between fields and catchments. For example, according to the simulations, a notable share of sediments are delivered to ditches on the sides of the fields, bypassing the buffer strips. This results in lower effectiveness of buffers strips compared to estimates from experimental plots where this phenomenon may not be present.

The sediment delivery reduction effect of no-till was relatively consistent across catchments and fields, with few pp higher reduction rates at Aura compared to the Mustio River catchment (Section 3.2). The variation between fields was on average less than 7 pp. The parameterization P3, however resulted in greater variation in the reduction rates than P1 and P2. The reduction of buffer strips, in turn, varied greatly by catchment and field, with 16–21 pp higher reduction rate at the Aura than at the Mustio River catchment, and 83 pp variation between fields. These highlight the potential of RUSLE/IC/SDR to simulate the impact of variable sediment connectivity characteristics on reducing sediment delivery through erosion management measures. The larger differences in sediment delivery reduction by buffer strips between catchments and fields compared to no-till are explained by the differences in the spatial distribution of high erosion areas and the nature of the two erosion management measures. The buffer strips were more effective in the Aura River catchment because they were located in high-erosion areas, effectively reducing erosion generation and sediment transport. In contrast, in the Mustio River catchment, the high-erosion areas were not commonly situated within the buffer strip areas. The buffer strips are also more sensitive to variations in local sediment connectivity characteristics because they are implemented only at one side of the field, and they do not capture sediment fluxes bypassing the buffer strips from other sides of the fields. In contrast, no-till measure has a more uniform effect on erosion generation and sediment transport across all areas of the field.

In the catchment level planning of erosion management measures to fields (Section 3.3), the RUSLE/IC/SDR approach (B) resulted in only small to modest additional sediment delivery reduction compared to the RUSLE approach (A). This unexpected result shows that allocating measures based on estimated erosion by RUSLE is almost as effective at the catchment scale as allocating based on the estimated effectiveness of erosion management by RUSLE/IC/SDR. The magnitude of erosion in the fields appears to be a strong indicator of erosion management outcomes, and the sediment connectivity characteristics did not vary significantly enough between the riparian fields to play a more substantial role in the allocation of erosion management measures. The outcome of this comparison could, however, be different if erosion management measures in the RUSLE/IC/SDR allocation approach were tailored according to the local sediment connectivity characteristics, similarly to the approach taken in the two case study fields, especially in the case of buffer strips. In the current comparison, the buffer strips were uniformly implemented on the riparian side of the fields without considering of the local sediment connectivity characteristics.

The improvements in sediment delivery reduction from RUSLE/IC/SDR approach were, however, slightly larger in the Mustio River catchment compared to the Aura River catchment and with the field ranking unit of kg yr^{-1} compared to the ranking unit of kg ha^{-1} yr^{-1}. This is likely due to the greater distances that sediments need to travel from high-erosion areas to the outlet of the fields at Mustio compared to the Aura River catchment, and that allocation with unit kg yr^{-1} considers the size of the fields, which related to sediment connectivity. This may imply that the improvements from RUSLE/IC/SDR allocation approach may be greater in conditions where fields are larger and high-erosion areas are located further away from field outlets.

The catchment-scale evaluation also revealed that the same allocation rates of erosion management measures resulted in higher total sediment delivery reductions at Aura than at the Mustio River catchment, attributed to the distribution of erosion across riparian fields. At the Aura River catchment, the highest erosion rates were concentrated to smaller number of fields, whereas at the Mustio River catchment, high-erosion rates were distributed more evenly among the fields. This indicates higher cost-effectiveness of erosion management measures at Aura than at Mustio River catchment.

The parameterizations P1-P3 of SDR were found to considerably influence the estimated absolute magnitude of sediment delivery, which was on average over three times higher with P3 and almost 2.5 times higher with P2 compared to P1. However, the parameterization had less effect on the estimated reduction effect of erosion management measures. The sediment delivery reduction was on average 22 % higher with P3 and 35 % times higher with P2 compared to P1. The parameterization P1-P3 also influenced the distribution of sediment delivery reduction rates at individual fields. This suggests that different parameterizations result in varying sediment connectivity characteristics in terms of how sediment is transported from source areas to sinks. However, the parameterization P1-P3 had very little effect on the ranking of fields in terms of sediment delivery reduction through erosion management measures. The correlations between rankings were 0.97–1.00, $p < 0.001$. The findings on the similarity of rankings with different parameterizations are consistent with earlier studies (Tähtikarhu et al., 2022; Hamel et al., 2015), and indicate that the RUSLE/IC/SDR approach provides consistent information for comparing relative sediment delivery reduction rates based on rank despite the uncertainty in parametrization.

In the planning of erosion management measures at individual fields (Section 3.4), the RUSLE/IC/SDR provided valuable opportunities for tailoring erosion management measures according to local sediment connectivity characteristics. RUSLE/IC/SDR revealed the source areas of sediment delivery and the connectivity characteristics within the fields, and it was able to consider the sediment transport-related effects of different configurations of erosion management measures. Whereas RUSLE was able to only reveal areas with high erosion rates and provide estimates on the impacts on gross erosion, but it could not provide information on sediment transport-related effects. In our case study fields, the consideration of local sediment connectivity characteristics in the implementation extended buffer strips to mitigate sediment fluxes bypassing the conventionally implemented buffer strip, resulted in an additional 13–40 pp reduction in sediment delivery. The consideration of local sediment connectivity characteristics can thus improve the effectiveness of erosion management.

4.2. Strengths, limitations, and ways forward

RUSLE/IC/SDR appears to be an efficient and valuable tool for screening sediment connectivity and effectiveness of erosion management measures at the field and catchments levels. RUSLE/IC/SDR provides a parallel empirical modeling framework to the more commonly utilized WaTEM/SEDEM (Van Oost et al., 2000; Van Rompaey et al., 2001) in practical applications. Both models provide predictions on the long-term average sediment delivery rates, or the structural sediment connectivity, and can be used to simulate various erosion management measures and landscape elements at the field scale in high grid resolution over large regions. The main strengths of RUSLE/IC/SDR are that it can be easily implemented as a post-processing method over existing RUSLE data with low data input, computational, and parameterization requirements. The IC/SDR can be computed using only DEM and three parameter values as the input data. The main limitations of RUSLE/IC/SDR compared to WaTEM/SEDEM are that it is less tested against empirical observations in different climatic, topographical, and soil conditions. Additionally, the development for incorporating different erosion management measures and different landscape elements is more limited compared to WaTEM/SEDEM. When compared to process-based models, RUSLE/IC/SDR provides a more cost-effective approach for screening large areas in high-resolution. Process-based models, in turn, provide a more detailed description of erosion-transport-deposition processes and erosion management measures. They often allow simulation of functional sediment connectivity in addition to structural sediment connectivity. Functional sediment connectivity typically provides better description of sediment delivery as sediment transport heavily depends on the temporal aspects of the rainfall-runoff process (Hooke and Souza, 2021). Implementing process-based models over large spatial scales can be more demanding due to high parameterization and computational requirements. Therefore, RUSLE/IC/SDR is particularly useful in situations where RUSLE data exists and there is a need for screening of erosion management over a large area. For instance, in evaluating the potential benefits of buffer strips across multiple large catchments.

Further evaluation and development of RUSLE/IC/SDR is, however, needed. Firstly, the sediment delivery estimates need further evaluation against observed sediment delivery rates to improve the parameterization and credibility of modeling approach. Evaluation has been performed in at least a few studies (e.g., Hamel et al., 2015; Zhao et al., 2020), but overall, the evaluation is not comprehensive. Secondly, the suitability of RUSLE/IC/SDR for various topographical climatic and soil conditions needs further evaluation. Very few studies have evaluated them. For example, Gay et al. (2016) noted different infiltration conditions between lowlands and hilly and mountainous environments. They adjusted the IC calculation to the lowland conditions in their study area and reported improvements compared to the original IC (Borselli et al., 2008). The infiltration is also influenced by other factors, such as winter conditions and artificial subsurface drainage. Currently, it is not clear how different infiltration conditions can be considered in the RUSLE/IC/SDR model structure, even though Borselli et al. (2008) metioned that infiltration could be factored into the weighting factor w_i (Eq. (4). Thirdly, RUSLE/IC/SDR was demonstrated to be able to simulate area-based erosion management measures that can be presented in raster grids. However, comprehensive evaluation of the implementation of different erosion measures and their parameterization is still lacking. Currently, area-based erosion management measures have mostly been implemented using the RUSLE C factor values to parameterize the weighting factor W_i (Eq. (3) and Eq. (4) in calculation of IC, following Borelli et al. (2008). We also did not evaluate in detail the implementation of erosion management measures in RUSLE/IC/SDR. For example, we did not evaluate the significance of flow convergence, which is known to influence sediment trapping by buffer strips (see e.g., Verstraeten et al., 2006). Fourthly, the model structure of RUSLE/IC/SDR currently does not enable the consideration sediment delivery via subsurface drainage, which is a significant limitation in various agricultural environments. For example, in Finland, artificial subsurface drainage is a common practice. Research shows that eroded sediments are transported from the soil surface to subsurface drains through cracks and macropores in the soil (Foster et al., 2003; Øygarden et al., 1997; Turunen et al., 2017; Uusitalo et al., 2001). A large share of the total sediment yield of a field can be through subsurface drainage flow, especially at clay soils (Finnish Environment Institute, 2019; Kukkonen et al., 2004b; Nurminen et al., 2018; Turtola et al., 2007; Turtola and Kemppainen, 1998; Warsta et al., 2014). The implementation of subsurface drainage in RUSLE/IC/SDR by partitioning the predicted erosion at each grid cell into surface and subsurface sediment fluxes and routing these fluxes separately to a sink would most likely be feasible.

In addition, the quality and spatial resolution of data significantly affect simulation outcomes. High-resolution DEMs are crucial for accurately describing erosion, sediment transport pathways, and sediment connectivity. However, all DEMs must be adjusted for artificial sinks to prevent errors in sediment connectivity. In our simulations, the K factor data from a 1:200,000 scale soil map limited erosion estimate detail (RUSLE), particularly within the fields, but did not impact sediment connectivity calculations (IC/SDR). The R factor data, though coarse (1 km^2), did not significantly influence erosion estimates due to the small, climatically similar catchments. Scenario-based simulations and their relative comparisons also reduced the impact of data inaccuracies.

Currently, we consider RUSLE/IC/SDR suitable for exploring sediment connectivity and erosion management at the field scale across catchments and regions. It can serve as an indicative tool, but due to the limitations discussed above, careful consideration is needed if it is used to estimate absolute values of sediment delivery rates or to support practical erosion management, especially in the Finnish context. Evaluation and development following the directions identified above can enhance the feasibility and credibility of RUSLE/IC/SDR for simulating agricultural erosion management.

Our simulations further indicate potential and a need to develop uncertainty management strategies beyond conventional calibration and validation, sensitivity analysis, and probabilistic approaches. In our simulations, the parameterization was based on literature, and the model outputs were not evaluated against observation. However, the simulations using the three different parameterizations (P1-P3) demonstrated that the parameterizations led to very similar rankings of fields in terms of sediment delivery reduction by erosion management measures. The relative sediment delivery reduction rates were not also very far from each other, despite significant differences in absolute sediment delivery reduction rates. These indicate that uncertainty can also be managed by testing the models against specific questions, simulation design, and a relative interpretation of model outputs. For example, in our case, the model outcomes with the three parameterizations and relative interpretations could have been evaluated against the question "At which fields the buffer strips are the most effective?“ and model outcomes would have provided very consistent answers to despite the parameterization uncertainty. This does not, however, reduce the uncertainties related to the model structure and whether it is suitable for the particular simulation. The simulation of absolute erosion and sediment delivery rates is inherently uncertain (Batista et al., 2019), and the relative interpretation of model outputs in scenario and system response analyses, as well as fit-for-purpose model evaluations can help to manage uncertainty in model simulations (Alewell et al., 2019; Batista et al., 2019; Guillaume et al., 2015; Oreskes et al., 1994).

4.3. *Implications of sediment connectivity for erosion management*

The simulations revealed spatial variability in sediment source hotspots, sediment connectivity, and effectiveness of erosion management measures. This indicates that practical erosion management can be improved through model-assisted planning that accounts for sediment connectivity. The RUSLE/IC/SDR simulations demonstrated how erosion management outcomes can potentially be improved by tailoring the erosion management measures according to local erosion and sediment connectivity characteristics.

The sediment connectivity was found to play an important role in the effectiveness of buffer strips, and most likely of other measures that aim to influence sediment fluxes from specific directions. The effectiveness of the buffer strips was influenced by the share of sediment fluxes bypassing the buffer strip area and flowing to the ditches on the sides of the field. The sediment fluxes were often found to be highly concentrated, which can further reduce the effectiveness of buffer strips (see e.g., Verstraeten et al., 2006). Additionally, artificial subsurface drainage provides an alternative transport pathway for sediments reducing the effectiveness of buffer strips. The buffer strips were, however, found to be most effective when located in the high erosion areas. They reduced erosion in those areas and trapped sediments transported from the upslope areas.

5. Conclusions

The RUSLE/IC/SDR approach enables the simulation of sediment connectivity and delivery by extending the spatially distributed RUSLE framework. Our simulations further advance the understanding of the feasibility of using RUSLE/IC/SDR for simulating erosion management measures at the field scale within catchments or regions, and of the potential and limitations of RUSLE/IC/SDR in enhancing the outcomes of RUSLE-based erosion management planning by considering sediment connectivity.

No-till and riparian buffer strip erosion management measures in spring cereal cultivation were successfully simulated using the RUSLE/IC/SDR modeling approach. The simulated sediment delivery reduction effects aligned with measurements from experimental fields, although the RUSLE/IC/SDR approach was parameterized based on literature and not against measured sediment delivery rates. The RUSLE/IC/SDR revealed the spatial variability in high sediment source areas and connectivity characteristics between the fields and the catchments. This had an important role in determining the effectiveness of erosion management measures between the fields and catchments, especially concerning buffer strips. These findings highlight the importance of local sediment connectivity characteristics in planning erosion management. RUSLE/IC/SDR provided valuable insights for this purpose.

At individual field level, RUSLE/IC/SDR provided a means for tailoring erosion management measures based on local erosion and sediment connectivity characteristics, thereby improving erosion management outcomes. Surprisingly, it did not lead to significant improvements in the catchment-scale allocation of erosion management measures to individual fields compared with allocation using RUSLE alone. The role of sediment connectivity simulated using RUSLE/IC/SDR appeared to be less important in catchment scale allocation, at least when erosion management measures were uniformly implemented across all fields without tailoring them according to local sediment connectivity characteristics of the fields.

For the practical application of RUSLE/IC/SDR in erosion management, greater attention must be given to model structure, parameterization, and prediction uncertainty than was done in our study. Specifically, the suitability of the model structure and the parameterization of RUSLE/IC/SDR across various climatological and soil conditions, as well as its performance against measured sediment delivery, require further evaluation. Additionally, research is needed to evaluate a wider range of erosion management measures and to account for sediment delivery through artificial subsurface drainage. Our simulations suggest that managing uncertainty in sediment delivery predictions can be enhanced through careful simulation design, relative interpretation of model outputs in different scenarios and system responses, and fit-for-purpose evaluations.

In conclusion, the RUSLE/IC/SDR model demonstrates significant promise for simulating sediment connectivity and evaluating the effectiveness of erosion management measures at the field scale. Its primary strengths include its ability to integrate with existing RUSLE data, offering high-resolution analysis across large areas with low data requirements and computational costs. By incorporating local sediment connectivity characteristics, RUSLE/IC/SDR has the potntial to substantially improve RUSLE-based erosion management planning.

CRediT authorship contribution statement

Timo A. Räsänen: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Mika Tähtikarhu:** Writing – original draft, Software, Methodology. **Jari Hyväluoma:** Writing – review & editing, Writing – original draft, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The work was done as part of the project 'Managing Sediment Connectivity in Agricultural Landscapes for reducing water Erosion impacts' (SCALE) within the European Joint Programme EJP SOIL and was funded by European Union's Horizon research and innovation programme (Grant agreement No 862695). The original text written by the authors was proofread using artificial intelligence by Wordwice AI.

Appendix A

Table A1
Summary of the methodology for exploring RUSLE/IC/SDR for erosion management planning at the field-scale in agricultural catchments.

Methodology	Description
1. Study area	**Aura River catchment in Southern Finland** Catchment area 146.6 km^2 514 riparian fields Topography generally flat with steep slopes near rivers and streams
	Mustio River catchment in Southern Finland Catchment area 116.2 km^2 232 riparian fields Topography gently undulating
2. Simulation of sediment delivery reduction by erosion management measures	**RUSLE** Empirical model for predicting long-term average erosion
	RUSLE/IC/SDR Structural sediment connectivity approach for predicting sediment delivery via surface transport
	Erosion management measures Spring cereal cultivation with No measure: Conventional autumn moldboard plowing No-till: no-tillage/seed drill/wintertime stubble cover Buffer strip: 30 m wide riparian grass buffer strips
	Estimation of erosion RUSLE Resolution 2 m × 2 m Erosion at the riparian fields under No measure No-till Buffer strip
	Estimation of sediment delivery via surface transport and its reduction by erosion management measures RUSLE/IC/SDR Resolution 2 m × 2 m Sediment delivery reduction from the riparian fields by No-till: difference between sediment delivery with no-till and sediment delivery with no measure Buffer strip: difference between sediment delivery with buffer strip and sediment delivery with no measure
3. Evaluation of RUSLE/IC/SDR for of erosion management planning	**Planning of erosion management measures at catchments** Approaches for allocating erosion management measures to fields: RUSLE approach (A): Allocation of erosion management measures to fields with highest erosion rate with no erosion measures RUSLE/IC/SDR approach (B): Allocation of erosion management measures to fields with highest sediment delivery reduction by erosion management measure Fields with highest erosion rate (A) and sediment delivery reduction by erosion management measures (B) were identified based on descending ranking of fields with ranking units kg ha^{-1} yr^{-1} and kg yr^{-1} Allocation of erosion management measures by four rates: 20 %, 40 %, 60 % and 80 % of field/potential buffer strip area Simulation with three IC/SDR parameterizations: P1, P2 and P3* Evaluation of allocation approaches A and B: Comparison of catchment scale total sediment delivery reductions resulting from the allocation approaches
	Planning of erosion management measures at fields The implementation of erosion management measures with RUSLE/IC/SDR was further evaluated at two case study fields with implementation of no-till, buffer strip, and extended buffer strip.

*Defined in Table 4.

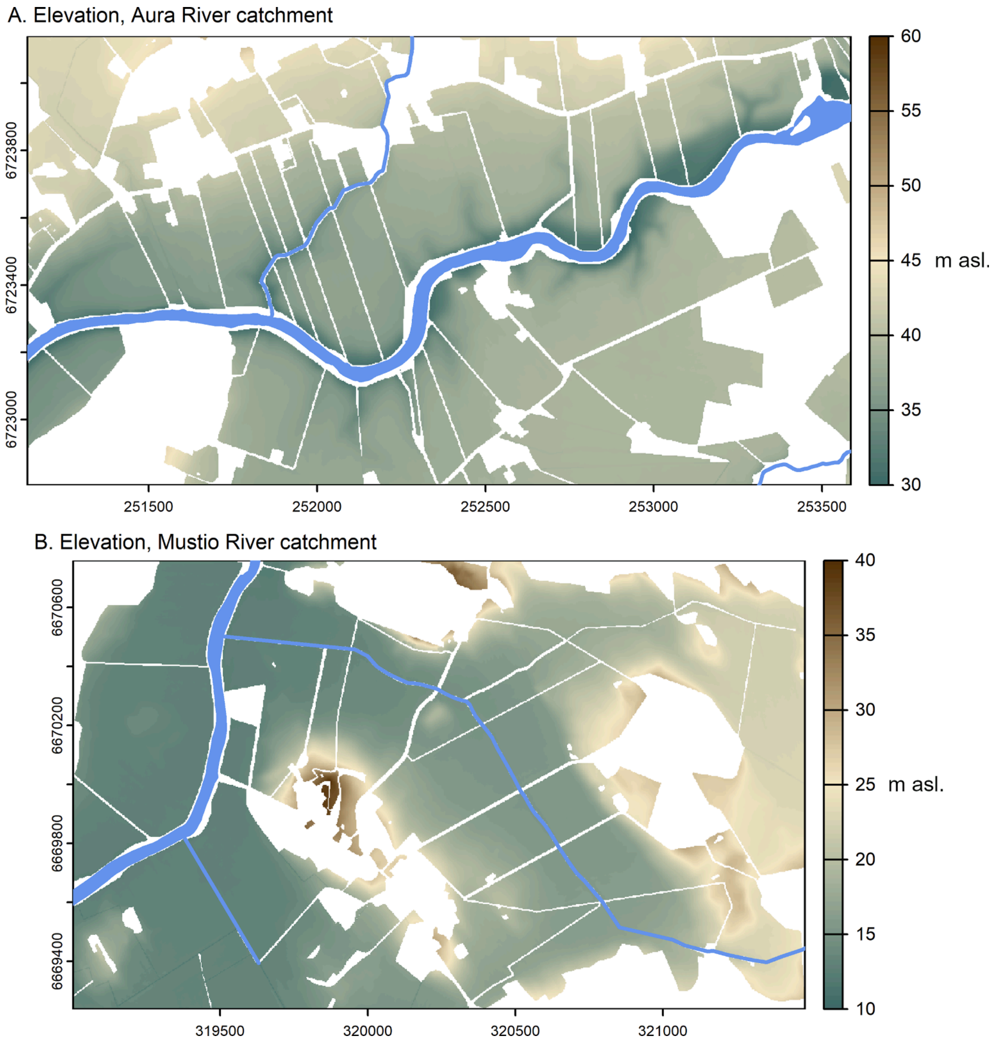


Fig. A1. A representative subset of elevation data (meters above sea level, m asl.) from the fields of A. Aura and B. Mustio River catchments. Note that the scale values vary in tiles, but their range remain consistent (axis units in meters, y-axis pointing north).

Table A2
Simulated total sediment delivery reduction scenarios for comparing the RUSLE (A) and RUSLE/IC/SDR (B) erosion management measure allocation approaches.

Allocation approach	Ranking unit (for ranking of the fields by erosion/sediment delivery reduction by erosion management measures)	Allocation rate of erosion management measures (for allocating the measures to highest ranking fields)	Parameterization of IC/SDR (for accounting the parameter uncertainty)	Total sediment delivery reduction scenarios (for comparing the allocation approaches at catchment scale)	
A. RUSLE (Allocation by erosion under no-measures) and B. RUSLE/IC/SDR (Allocation by sediment delivery reduction by erosion management measure)	kg ha^{-1} yr^{-1}	20 %	P1	A1	B1
			P2	A2	B2
			P3	A3	B3
		40 %	P1	A4	B4
			P2	A5	B5
			P3	A6	B6
		60 %	P1	A7	B7
			P2	A8	B8
			P3	A9	B9

(continued on next page)

Table A2 (*continued*)

Allocation approach	Ranking unit (for ranking of the fields by erosion/sediment delivery reduction by erosion management measures)	Allocation rate of erosion management measures (for allocating the measures to highest ranking fields)	Parameterization of IC/SDR (for accounting the parameter uncertainty)	Total sediment delivery reduction scenarios (for comparing the allocation approaches at catchment scale)	
		80 %	P1	A10	B10
			P2	A11	B11
			P3	A12	B12
	kg yr^{-1}	20 %	P1	A13	B13
			P2	A14	B14
			P3	A15	B15
		40 %	P1	A16	B16
			P2	A17	B17
			P3	A18	B18
		60 %	P1	A19	B19
			P2	A20	B20
			P3	A21	B21
		80 %	P1	A22	B22
			P2	A23	B23
			P3	A24	B24

References

Abebe, N., Eekhout, J., Vermeulen, B., Boix-Fayos, C., de Vente, J., Grum, B., Hoitink, T., Baartman, J., 2023. The potential and challenges of the 'RUSLE-IC-SDR' approach to identify sediment dynamics in a Mediterranean catchment. Catena 233, 107480. https://doi.org/10.1016/j.catena.2023.107480.

Alewell, C., Borrelli, P., Meusburger, K., Panagos, P., 2019. Using the USLE: chances, challenges and limitations of soil erosion modelling. Int. Soil Water Conserv. Res. 7, 203–225. https://doi.org/10.1016/j.iswcr.2019.05.004.

Arnold, J.G., Moriasi, D.N., Gassman, P.W., Abbaspour, K.C., White, M.J., Srinivasan, R., Santhi, C., Harmel, R.D., van Griensven, A., Van Liew, M.W., Kannan, N., Jha, M.K., 2021. SWAT: model use, calibration, and validation. Trans. ASABE 55. https://doi.org/10.13031/2013.42256.

Baartman, J.E.M., Nunes, J.P., Masselink, R., Darboux, F., Bielders, C., Degré, A., Cantreul, V., Cerdan, O., Grangeon, T., Fiener, P., Wilken, F., Schindewolf, M., Wainwright, J., 2020. What do models tell us about water and sediment connectivity? Geomorphology 367, 107300. https://doi.org/10.1016/j.geomorph.2020.107300.

Batista, P.V.G., Davies, J., Silva, M.L.N., Quinton, J.N., 2019. On the evaluation of soil erosion models: are we doing enough? Earth Sci. Rev. 197, 102898. https://doi.org/10.1016/j.earscirev.2019.102898.

Bilotta, G.S., Brazier, R.E., 2008. Understanding the influence of suspended solids on water quality and aquatic biota. Water Res. 42, 2849–2861. https://doi.org/10.1016/j.watres.2008.03.018.

Boix-Fayos, C., Martínez-Mena, M., Arnau-Rosalén, E., Calvo-Cases, A., Castillo, V., Albaladejo, J., 2006. Measuring soil erosion by field plots: understanding the sources of variation. Earth Sci. Rev. 78, 267–285. https://doi.org/10.1016/j.earscirev.2006.05.005.

Borrelli, P., Alewell, C., Alvarez, P., Anache, J.A.A., Baartman, J., Ballabio, C., Bezak, N., Biddoccu, M., Cerdà, A., Chalise, D., Chen, S., Chen, W., De Girolamo, A.M., Gessesse, G.D., Deumlich, D., Diodato, N., Efthimiou, N., Erpul, G., Fiener, P., Freppaz, M., Gentile, F., Gericke, A., Haregeweyn, N., Hu, B., Jeanneau, A., Kaffas, K., Kiani-Harchegani, M., Villuendas, I.L., Li, C., Lombardo, L., López-Vicente, M., Lucas-Borja, M.E., Märker, M., Matthews, F., Miao, C., Mikoš, M., Modugno, S., Möller, M., Naipal, V., Nearing, M., Owusu, S., Panday, D., Patault, E., Patriche, C.V., Poggio, L., Portes, R., Quijano, L., Rahdari, M.R., Renima, M., Ricci, G.F., Rodrigo-Comino, J., Saia, S., Samani, A.N., Schillaci, C., Syrris, V., Kim, H.S., Spinola, D.N., Oliveira, P.T., Teng, H., Thapa, R., Vantas, K., Vieira, D., Yang, J.E., Yin, S., Zema, D.A., Zhao, G., Panagos, P., 2021. Soil erosion modelling: a global review and statistical analysis. Sci. Total Environ. 780, 146494. https://doi.org/10.1016/j.scitotenv.2021.146494.

Borselli, L., Cassi, P., Torri, D., 2008. Prolegomena to sediment and flow connectivity in the landscape: a GIS and field numerical assessment. Catena 75, 268–277. https://doi.org/10.1016/j.catena.2008.07.006.

Bracken, L.J., Croke, J., 2007. The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems. Hydrol. Process. 21, 1749–1763. https://doi.org/10.1002/hyp.6313.

Bracken, L.J., Turnbull, L., Wainwright, J., Bogaart, P., 2015. Sediment connectivity: a framework for understanding sediment transfer at multiple scales. Earth Surf. Proc. Land. 40, 177–188. https://doi.org/10.1002/esp.3635.

De Roo, A.P.J., Wesseling, C.G., Ritsema, C.J., 1996. Lisem: a single-event physically based hydrological and soil erosion model for drainage basins. I: theory, input and output. Hydrological Processes 10, 1107–1117. https://doi.org/10.1002/(SICI)1099-1085(199608)10:8<1107::AID-HYP415>3.0.CO;2-4.

Desmet, P.J.J., Govers, G., 1996. A GIS procedure for automatically calculating the USLE LS factor on topographically complex landscape units. J. Soil Water Conserv. 51, 427–433.

Ekholm, P., Lehtoranta, J., 2012. Does control of soil erosion inhibit aquatic eutrophication? J. Environ. Manage. 93, 140–146. https://doi.org/10.1016/j.jenvman.2011.09.010.

ESRI, 2019. ArcGIS Desktop: Release 10.6.1. Environmental Systems Research Institute, Redlands, CA.

EU, 2022. Finland – CAP Strategic Plan [WWW Document]. Agriculture and rural development, European Commission. URL https://agriculture.ec.europa.eu/cap-my-country/cap-strategic-plans/finland_en (accessed 10.20.23).

Finnish Environment Institute, 2010. Ranta10 - rantaviiva 1:10 000 - SYKE [WWW Document]. URL https://ckan.ymparisto.fi/dataset/%7BC40D8B4A-DC66-4822-AF27-7B382D89C8ED%7D (accessed 3.25.21).

Finnish Environment Institute, 2019. Sediment and nutrient loading to surface waters in 3 different scales [WWW Document]. Finnish Environment Institute (SYKE). URL https://metasiirto.ymparisto.fi:8443/geoportal/catalog/search/resource/details.page?uuid=%7B15893DD0-0193-40AD-9E21-452D271DB791%7D (accessed 1.25.21).

Foster, I.D.L., Chapman, A.S., Hodgkinson, R.M., Jones, A.R., Lees, J.A., Turner, S.E., Scott, M., 2003. Changing suspended sediment and particulate phosphorus loads and pathways in underdrained lowland agricultural catchments; Herefordshire and Worcestershire, U.K. The Interactions between Sediments and Water 119–126. DOI: 10.1007/978-94-017-3366-3_17.

García-Ruiz, J.M., Beguería, S., Nadal-Romero, E., González-Hidalgo, J.C., Lana-Renault, N., Sanjuán, Y., 2015. A meta-analysis of soil erosion rates across the world. Geomorphology 239, 160–173. https://doi.org/10.1016/j.geomorph.2015.03.008.

Gay, A., Cerdan, O., Mardhel, V., Desmet, M., 2016. Application of an index of sediment connectivity in a lowland area. J. Soil. Sediment. 16, 280–293. https://doi.org/10.1007/s11368-015-1235-y.

Ghosal, K., Das Bhattacharya, S., 2020. A review of RUSLE model. J. Indian Soc. Remote Sens. 48, 689–707. https://doi.org/10.1007/s12524-019-01097-0.

Govers, G., 2011. Misapplications and misconceptions of erosion models. In: Morgan, R.P.C., Nearing, M.A. (Eds.), Handbook of Erosion Modelling. Blackwell Publishing Ltd, Chichester.

Guillaume, J.H.A., Kummu, M., Räsänen, T.A., Jakeman, A.J., 2015. Prediction under uncertainty as a boundary problem: a general formulation using iterative closed question modelling. Environ Model Softw. 70, 97–112. https://doi.org/10.1016/j.envsoft.2015.04.004.

Hamel, P., Chaplin-Kramer, R., Sim, S., Mueller, C., 2015. A new approach to modeling the sediment retention service (InVEST 3.0): Case study of the Cape Fear catchment, North Carolina, USA. Sci. Total Environ. 524–525, 166–177. https://doi.org/10.1016/j.scitotenv.2015.04.027.

Hamel, P., Falinski, K., Sharp, R., Auerbach, D.A., Sánchez-Canales, M., Dennedy-Frank, P.J., 2017. Sediment delivery modeling in practice: comparing the effects of watershed characteristics and data resolution across hydroclimatic regions. Sci. Total Environ. 580, 1381–1388. https://doi.org/10.1016/j.scitotenv.2016.12.103.

Heckmann, T., Cavalli, M., Cerdan, O., Foerster, S., Javaux, M., Lode, E., Smetanová, A., Vericat, D., Brardinoni, F., 2018. Indices of sediment connectivity: opportunities, challenges and limitations. Earth Sci. Rev. 187, 77–108. https://doi.org/10.1016/j.earscirev.2018.08.004.

Henley, W.F., Patterson, M.A., Neves, R.J., Lemly, A.D., 2000. Effects of sedimentation and turbidity on lotic food webs: a concise review for natural resource managers. Rev. Fish. Sci. 8, 125–139. https://doi.org/10.1080/10641260091129198.

Hijmans, R.J., Bivand, R., Forner, K., Ooms, J., Pebesm, E., 2023. terra: Spatial Data Analysis. R package version 1.7-29 [WWW Document]. The Comprehensive R Archive Network. URL https://CRAN.R-project.org/package=terra (accessed 10.13.23).

Honkanen, H., Turtola, E., Lemola, R., Heikkinen, J., Nuutinen, V., Uusitalo, R., Kaseva, J., Regina, K., 2021. Response of boreal clay soil properties and erosion to ten years of no-till management. Soil Tillage Res. 212, 105043. https://doi.org/10.1016/j.still.2021.105043.

Hooke, J., Souza, J., 2021. Challenges of mapping, modelling and quantifying sediment connectivity. Earth Sci. Rev. 223, 103847. https://doi.org/10.1016/j.earscirev.2021.103847.

IUSS Working Group WRB, 2022. World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps. 4th edition. International Union of Soil Sciences (IUSS), Vienna, Austria.

Karydas, C.G., Panagos, P., Gitas, I.Z., 2014. A classification of water erosion models according to their geospatial characteristics. Int. J. Digital Earth 7, 229–250. https://doi.org/10.1080/17538947.2012.671380.

Keesstra, S., Nunes, J.P., Saco, P., Parsons, T., Poeppl, R., Masselink, R., Cerdà, A., 2018. The way forward: Can connectivity be useful to design better measuring and modelling schemes for water and sediment dynamics? Sci. Total Environ. 644, 1557–1572. https://doi.org/10.1016/j.scitotenv.2018.06.342.

Kukkonen, M., Niinioja, R., Puustinen, M., 2004a. Viljelykäytäntöjen vaikutus ravinnehuuhtoutumiin Liperin koekentällä Pohjois-Karjalassa. Abstract: Leaching of nutrients under different cultivation in the Liperi test field in North Karelia, Finland., Alueelliset ympäristöjulkaisut 367. Pohjois-Karjalan ympäristökeskus, Joensuu, Finland.

Kukkonen, M., Niinioja, R., Puustinen, M., 2004b. Viljelykäytäntöjen vaikutus ravinnehuuhtoutumiin Liperin koekentällä Pohjois-Karjalassa. Abstract: Leaching of nutrients under different cultivation in the Liperi test field in North Karelia, Finland., Alueelliset ympäristöjulkaisut 367. Pohjois-Karjalan ympäristökeskus, Joensuu, Finland.

Laflen, J.M., Lane, L.J., Foster, G.R., 1991. WEPP: A new generation of erosion prediction technology. J. Soil Water Conserv. 46, 34–38.

Leys, A., Govers, G., Gillijns, K., Berckmoes, E., Takken, I., 2010. Scale effects on runoff and erosion losses from arable land under conservation and conventional tillage: the role of residue cover. J. Hydrol. 390, 143–154. https://doi.org/10.1016/j.jhydrol.2010.06.034.

Lilja, H., Uusitalo, R., Yli-Halla, M., Nevalainen, R.,Väänänen, R., Tamminen, P., Tuhtar, J., 2017c. Suomen maannostietokanta: Käyttöopas versio 1.1 (Finnish Soil Database: Manual, version 1.1) (No. 6), Luonnonvara- ja biotalouden tutkimus. Luonnonvarakeskus (LUKE) (Natural Resources Institute Finland).

Lilja, H., Hyväluoma, J., Puustinen, M., Uusi-Kämppä, J., Turtola, E., 2017a. Evaluation of RUSLE2015 erosion model for boreal conditions. Geoderma Reg. 10, 77–84. https://doi.org/10.1016/j.geodrs.2017.05.003.

Lilja, H., Puustinen, M., Turtola, E., Hyväluoma, J., 2017b. Suomen peltojen karttapohjainen eroosioluokitus (Map-based classificication of erosion in agricultural lands of Finland). Natural Resources Institute Finland (luke) 36.

Manninen, N., Kanerva, S., Lemola, R., Turtola, E., Soinne, H., 2023. Contribution of water erosion to organic carbon and total nitrogen loads in agricultural discharge from boreal mineral soils. Sci. Total Environ. 905, 167300. https://doi.org/10.1016/j.scitotenv.2023.167300.

McDowell, R.W., Biggs, B.J.F., Sharpley, A.N., Nguyen, L., 2004. Connecting phosphorus loss from agricultural landscapes to surface water quality. Chem. Ecol. 20, 1–40. https://doi.org/10.1080/02757540310001626092.

Merritt, W.S., Letcher, R.A., Jakeman, A.J., 2003. A review of erosion and sediment transport models. Environ. Model. Software Model. Hydrol. Syst. 18, 761–799. https://doi.org/10.1016/S1364-8152(03)00078-1.

Mitasova, H., Hofierka, J., Zlocha, M., Iverson, L.R., 1996. Modelling topographic potential for erosion and deposition using GIS. Int. J. Geogr. Inf. Syst. 10, 629–641. https://doi.org/10.1080/02693799608902101.

Montgomery, D.R., 2007. Soil erosion and agricultural sustainability. PNAS 104, 13268–13272. https://doi.org/10.1073/pnas.0611508104.

Najafi, S., Dragovich, D., Heckmann, T., Sadeghi, S.H., 2021. Sediment connectivity concepts and approaches. Catena 196, 104880. https://doi.org/10.1016/j.catena.2020.104880.

National Land Survey of Finland, 2020. Elevation model 2 m [Data set] [WWW Document]. URL https://www.maanmittauslaitos.fi/en/maps-and-spatial-data/expert-users/product-descriptions/elevation-model-2-m (accessed 5.29.20).

Nurminen, J., Paasonen-Kivekäs, M., Äijö, H., 2018. Tuotantosuunnan muutoksen vaikutus savipellolta tulevaan ravinne- ja kiintoainekuormitukseen, Gårdskullan kartanon mittaustulokset 2008–2017 (No. 34), Tiedote. Salaojituksen tutkimusyhdistys ry.

Oreskes, N., Shraderfrechette, K., Belitz, K., 1994. Verification, validation, and confirmation of numerical-models in the earth-sciences. Science, 263(5147), 641e646. Science 263(5147). DOI: DOI: 10.1126/science.263.5147.641.

Øygarden, L., Kværner, J., Jenssen, P.D., 1997. Soil erosion via preferential flow to drainage systems in clay soils. Geoderma 76, 65–86. https://doi.org/10.1016/S0016-7061(96)00099-7.

Panagos, P., Ballabio, C., Borrelli, P., Meusburger, K., Klik, A., Rousseva, S., Tadić, M.P., Michaelides, S., Hrabalíková, M., Olsen, P., Aalto, J., Lakatos, M., Rymszewicz, A., Dumitrescu, A., Beguería, S., Alewell, C., 2015. Rainfall erosivity in Europe. Sci. Total Environ. 511, 801–814. https://doi.org/10.1016/j.scitotenv.2015.01.008.

Pandey, A., Himanshu, S.K., Mishra, S.K., Singh, V.P., 2016. Physically based soil erosion and sediment yield models revisited. Catena 147, 595–620. https://doi.org/10.1016/j.catena.2016.08.002.

Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., Crist, S., Shpritz, L., Fitton, L., Saffouri, R., Blair, R., 1995. Environmental and economic costs of soil erosion and conservation benefits. Science 267, 1117–1123. https://doi.org/10.1126/science.267.5201.1117.

Puustinen, M., Koskiaho, J., Peltonen, K., 2005. Influence of cultivation methods on suspended solids and phosphorus concentrations in surface runoff on clayey sloped fields in boreal climate. Agr. Ecosyst. Environ. 105, 565–579. https://doi.org/10.1016/j.agee.2004.08.005.

Quinn, P., Beven, K., Chevallier, P., Planchon, O., 1991. The prediction of hillslope flow paths for distributed hydrological modelling using digital terrain models. Hydrol. Process. 5, 59–79. https://doi.org/10.1002/hyp.3360050106.

R Core Team, 2022. R: A Language and Environment for Statistical Computing (https://www.R-project.org/). R Foundation for Statistical Computing, Vienna, Austria.

Räsänen, T.A., Tähtikarhu, M., Uusi-Kämppä, J., Piirainen, S., Turtola, E., 2023. Evaluation of RUSLE and spatial assessment of agricultural soil erosion in Finland. Geoderma Reg. https://doi.org/10.1016/j.geodrs.2023.e00610.

Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K., Yoder, D.C., 1997. Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE). Agricultural Handbook 703. US Department of Agriculture, Washington, DC, pp. 404.

Schmaltz, E.M., LJohannsen, L., Thorsøe, M., Tähtikarhu, M., Räsänen, T.A., Darboux, F., Strauss, P., 2024. Connectivity elements and mitigation measures in policy-relevant soil erosion models: A survey across Europe. CATENA 234, 107600. DOI: 10.1016/j.catena.2023.107600.

Tähtikarhu, M., Räsänen, T., Oksanen, J., Uusi-Kämppä, J., 2022. Exploring structural sediment connectivity via surface runoff in agricultural lands of Finland. Acta Agriculturae Scandinavica, Section B — Soil & Plant Science 72, 957–970. https://doi.org/10.1080/09064710.2022.2136583.

Turtola, E., Alakukku, L., Uusitalo, R., 2007. Surface runoff, subsurface drainflow and soil erosion as affected by tillage in a clayey Finnish soil. Afsci 16, 332–351. https://doi.org/10.2137/145960607784125429.

Turtola, E., Kemppainen, E., 1998. Nitrogen and phosphorous losses in surface runoff and drainage water after application of slurry and mineral fertilizer to perennial grass ley. Agric. Food Sci. Finland 7, 569–581. https://doi.org/10.23986/afsci.5614.

Turunen, M., Warsta, L., Paasonen-Kivekäs, M., Koivusalo, H., 2017. Computational assessment of sediment balance and suspended sediment transport pathways in subsurface drained clayey soils. Soil Tillage Res. 174, 58–69. https://doi.org/10.1016/j.still.2017.06.002.

Ulén, B., Bechmann, M., Øygarden, L., Kyllmar, K., 2012. Soil erosion in Nordic countries – future challenges and research needs. Acta Agriculturae Scandinavica, Section B — Soil & Plant Science 62, 176–184. https://doi.org/10.1080/09064710.2012.712862.

Uusi-Kämppä, J., Jauhiainen, L., 2010. Long-term monitoring of buffer zone efficiency under different cultivation techniques in boreal conditions. Agric. Ecosyst. Environ. Special Section Harvested Perennial Grasslands: Ecol. Models Farming's Perennial Future 137, 75–85. https://doi.org/10.1016/j.agee.2010.01.002.

Uusitalo, R., Turtola, E., Kauppila, T., Lilja, T., 2001. Particulate phosphorus and sediment in surface runoff and drainflow from clayey soils. J. Environ. Qual. 30, 589–595. https://doi.org/10.2134/jeq2001.302589x.

Van Oost, K., Govers, G., Desmet, P., 2000. Evaluating the effects of changes in landscape structure on soil erosion by water and tillage. Landsc. Ecol. 15, 577–589. https://doi.org/10.1023/A:1008198215674.

Van Rompaey, A.J.J., Verstraeten, G., Van Oost, K., Govers, G., Poesen, J., 2001. Modelling mean annual sediment yield using a distributed approach. Earth Surf. Proc. Land. 26, 1221–1236. https://doi.org/10.1002/esp.275.

Verstraeten, G., Poesen, J., Gillijns, K., Govers, G., 2006. The use of riparian vegetated filter strips to reduce river sediment loads: an overestimated control measure? Hydrol. Process. 20, 4259–4267. https://doi.org/10.1002/hyp.6155.

Vigiak, O., Borselli, L., Newham, L.T.H., McInnes, J., Roberts, A.M., 2012. Comparison of conceptual landscape metrics to define hillslope-scale sediment delivery ratio. Geomorphology 138, 74–88. https://doi.org/10.1016/j.geomorph.2011.08.026.

Warsta, L., Taskinen, A., Paasonen-Kivekäs, M., Karvonen, T., Koivusalo, H., 2014. Spatially distributed simulation of water balance and sediment transport in an agricultural field. Soil Tillage Res. 143, 26–37. https://doi.org/10.1016/j.still.2014.05.008.

Wischmeier, W., Smith, D., 1978. Predicting rainfall erosion losses: a guide to conservation planning. Agricultural Handbook No. 537. Washington DC, USA: U.S. Department of Agriculture.

Zhao, G., Gao, P., Tian, P., Sun, W., Hu, J., Mu, X., 2020. Assessing sediment connectivity and soil erosion by water in a representative catchment on the Loess Plateau, China. Catena 185, 104284. https://doi.org/10.1016/j.catena.2019.104284.