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Title: Evaluation of RUSLE and spatial assessment of agricultural soil erosion in Finland

Year: 2023

Version: Published version

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Please cite the original version:

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 Regional 32, e00610. https://doi.org/10.1016/j.geodrs.2023.e00610

Geoderma Regional 32 (2023) e00610

Contents lists available at ScienceDirect

Geoderma Regional

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

Evaluation of RUSLE and spatial assessment of agricultural soil erosion in Finland

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ARTICLE INFO

Keywords:
Soil erosion
RUSLE
Agriculture
Water protection
Finland
Stagnosols
Gleysols
Regosols
Podzols
Histosols

ABSTRACT

Agricultural soil erosion has negative effects on surface water quality and aquatic ecosystems. A major impediment to agricultural erosion management in Finland has been the lack of high-resolution country-scale data on the spatial distribution of erosion. As a result, erosion mitigation measures have been targeted with limited information. Therefore, we evaluated the performance of the widely used RUSLE model against measurements from experimental fields, used the model to produce a two-metre resolution crop and management independent erosion estimate for all agricultural lands of Finland, and analysed erosion over different spatial scales. RUSLE showed skill ($R^2 = 0.76$, NSE = 0.72) in estimating the observed erosion at experimental fields (55–2100 kg ha^{-1} yr^{-1}) but with large errors (mean: −134 kg ha^{-1} yr^{-1}, 90% range: −711 and 218 kg ha^{-1} yr^{-1}). The evaluation, however, suggests that RUSLE performs similarly in Finland as elsewhere. The analysis of the developed country-scale data, in turn, revealed high erosion regions, and it showed how erosion varies between sub-catchment and between and within field parcels. For example, high-erosion areas concentrated in the proximity of water bodies were identified at the sub-catchment and within-field parcel scales. Altogether, the results demonstrate the predictive skill of RUSLE in high-latitude conditions, fill the earlier data gap in country-scale erosion, provide information for targeting erosion mitigation measures, and considerably improve the understanding of the spatial distribution of erosion in Finland.

1. Introduction

Agricultural soil erosion has considerable negative impacts on surface waters in Northern Europe (Ulén et al., 2012). Erosion leads to eutrophication, siltation, and increased turbidity, which are all detrimental to water quality and aquatic ecosystems. A key issue is the transport of soil-bound phosphorus from agricultural lands to surface waters, as it is a significant contributor to eutrophication (Röman et al., 2018).

Soil erosion by water is a hydrologically driven phenomenon where soil particles are detached from the soil surface by several processes, including the kinetic energy of raindrops and surface runoff, slaking, swelling, and dispersion (Bissonnais, 2016; Ulén et al., 2012; Jarvis et al., 1999; Wicks and Bathurst, 1996), and it is affected by multiple connected factors, including hydrometeorological conditions, the soil's physical characteristics and chemical conditions, varying particle detachment mechanisms, topographical factors, and farming practices (Turunen et al., 2017; Bechmann, 2012; Ulén et al., 2012; Turtola et al., 2007; Øygarden et al., 1997). The variation in these factors leads to high spatial variability in erosion and further affects the transport and deposition of eroded soil material (Röman et al., 2018; Ulén et al., 2012).

The erosion process in Finnish agricultural lands (2.3 million ha, which is 7.6% of the total land area) is dominated by sheet and rill erosion, and long-term average erosion rates are observed to vary at the field parcel scale from 55 to 2100 kg ha^{-1} yr^{-1} (Lilja et al., 2017a; Puustinen et al., 2010). On the country scale, modelling studies suggest an average agricultural erosion of 420–490 kg ha^{-1} yr^{-1} (Lilja et al., 2017b; Panagos et al., 2015e; Puustinen et al., 2010). The erosion processes in Finland are affected by the temporal distribution of rainfall-runoff erosivity, a short growing period (140–180 days) and long winter, and cropping and tillage practices. The main erosion periods are the rainy autumn and early winter months as well as the spring snowmelt periods when the fields have less vegetation cover or they have been autumn-tilled (Puustinen et al., 2007). The crops are dominated by spring cereals (42% according to data from the Finnish Food Authority for 2019), and the fields have been traditionally tilled in the autumn, but the extent of winter-time vegetation cover (e.g. stubble) has increased.

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https://doi.org/10.1016/j.geodrs.2023.e00610
Received 1 August 2022; Received in revised form 13 January 2023; Accepted 18 January 2023

The agricultural areas in Finland are largely concentrated in coastal areas of southern and western Finland, as shown in Fig. 1.

Agricultural erosion management in Finland is guided by the EU's Common Agricultural Policy (European Commission, 2021) and Water Framework Directive (European Commission, 2020), and it is implemented through national programmes (e.g., Ministry of Agriculture and Forestry, 2014) and national and regional authorities. Erosion mitigation measures (such as the riparian buffer strips, winter-time vegetation cover, and reduced tillage) are encouraged through the payment of subsidies to farmers, and they have been targeted based on broad regional classifications over Finland (Ministry of Agriculture and Forestry, 2014), including the eight river basin districts (Alahuhta et al., 2010). Recently, the potential of soil amendments in erosion reduction has also been investigated (Rasa et al., 2021; Valkama, 2018). Despite the significant efforts, the success in reducing the loading to surface waters on the country scale has been limited (Räike et al., 2020; Tattari et al., 2017), and further developments are needed for improving agricultural erosion management. A clear limitation has been the lack of country-scale data on the spatial distribution of erosion to support the targeting of erosion mitigation measures, which may have undermined the cost-effectiveness of the implemented measures. Spatially consistent high-resolution erosion data over the whole country would potentially benefit erosion management in Finland.

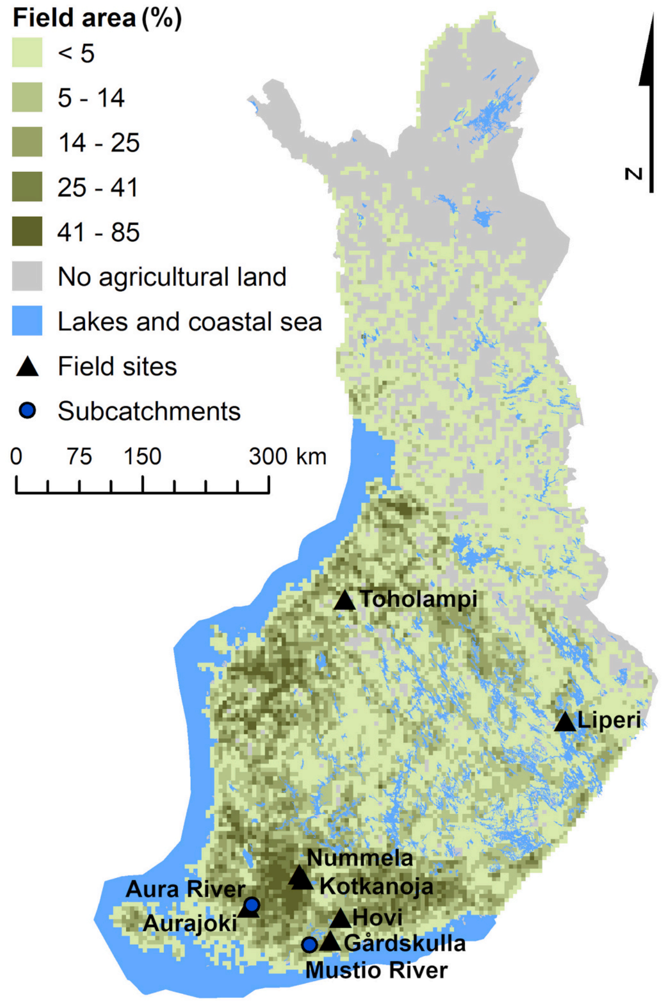

Fig. 1. Spatial distribution of agricultural lands of Finland, including the locations of the seven field sites (Aurajoki, Gårdskulla, Hovi, Kotkanoja, Liperi, Nummela, Toholampi) used in the evaluation of RUSLE and the two subcatchments (Aura and Mustio River) used in the spatial analysis of erosion on local scales. Areas with no agricultural land are shown in grey. The field area data is shown in 5 × 5 km grid resolution.

The erosion process and the spatial distribution of erosion can be studied and estimated using different types of models. Process-based computational models have shown a reasonable capability to describe the erosion and sediment transport process dynamics at monitored sites and catchments (e.g., Borrelli et al., 2021; Turunen et al., 2017; Warsta et al., 2013; Bärlund et al., 2007; Jarvis et al., 1999; Wicks and Bathurst, 1996), but they can be infeasible for large-scale modelling due to extensive requirements for input data, parameterisation, and computational resources. By contrast, empirical models that estimate erosion based on a few dominating factors provide efficient means to estimate the spatial distribution of erosion over large scales and in high resolution. These include models such as the empirical Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) and the revised USLE (RUSLE) (Renard et al., 1997), which have been widely applied in different regions and shown to be capable of reproducing measured erosion loads at the field parcel scale under different vegetation, management, topographic, and hydrometeorological conditions (Borrelli et al., 2021; Alewell et al., 2019; Batista et al., 2019). RUSLE is generally considered to be suitable for ranking erosion-prone areas over larger spatial scales when high-quality data are available for their parameterisation, but their validation on larger scales is a challenge as suitable observational validation data for is rarely available (Batista et al., 2019).

Thus, the overall objective of this research was to develop a spatially consistent high-resolution erosion estimate for identifying high erosion source areas to support agricultural erosion management in Finland. For the modelling method, we chose RUSLE since it is the most widely applied model (Alewell et al., 2019; Borrelli et al., 2021), its performance is similar to other commonly used models in reproducing long-term average erosion loads (Batista et al., 2019; Govers, 2011), it is well-suited for spatially distributed high-resolution modelling, the input data requirements are modest, and the first evaluation of RUSLE at experimental fields in Finland was promising (Lilja et al., 2017a).

To achieve our objective, RUSLE factor data were first prepared for all agricultural lands in Finland, and the RUSLE was calibrated and evaluated at seven experimental field sites. Next, a high-resolution crop- and management-independent erosion estimate was calculated for all agricultural lands, which excludes the effects of temporal changes in crop composition, management, and support practices and allows for a spatially consistent comparison of erosion areas. Finally, the erosion estimates were analysed over several spatial scales to provide an improved understanding of the spatial distribution of agricultural erosion.

2. Methodology

First, the RUSLE factors were prepared and developed in two-metre resolution for all agricultural lands in Finland, including seven experimental field sites used for calibration and evaluation of RUSLE. Second, RUSLE was calibrated at the seven field sites under different crop and management conditions against year-round erosion measurements. Third, the performance of the calibrated RUSLE was then evaluated using standard metrics and by developing a preliminary probability-based error distribution. Finally, RUSLE was used to calculate a crop- and management-independent erosion estimate for all agricultural lands in Finland in two-metre resolution, and the spatial variability of erosion of agricultural lands was analysed over different scales relevant to erosion management. These steps are explained below in more detail together with a general introduction to RUSLE.

2.1. Revised Universal Soil Loss Equation (RUSLE)

RUSLE (Eq. (1)) is an empirical model for estimating soil loss due to sheet and rill erosion by water (Renard et al., 1997). It is the revised version of USLE (Wischmeier and Smith, 1978). The RUSLE equation is (Eq. (1)):

$$A = R \times K \times LS \times C \times P \quad (1)$$

where A is the annual average erosion (t ha^{-1} yr^{-1}). R is the rainfall-runoff erosivity factor (MJ mm ha^{-1} h^{-1} yr^{-1}), which describes the effect of rainfall and run-off on erosion and is defined by the energy intensity of rainfall events. K is the soil erodibility factor (t ha h ha^{-1} MJ^{-1} mm^{-1}), which describes the propensity of soil to detach by the energy of the rainfall; it is affected by soil properties, including particle size fractions, organic matter content, soil structure, soil permeability, and soil freezing. LS is the topographic factor (dimensionless), which describes the effect of slope length (L) and steepness (S) on erosion. C is the cover-management factor (dimensionless), which considers the effects of different cropping and tilling practices on erosion; it is described by the energy intensity of rainfall, prior land use, canopy cover, surface cover, and surface roughness. P is the support practice factor (dimensionless), which accounts for the effect of various support practices on erosion, including contouring, strip cropping, terracing, and subsurface drainage.

2.2. RUSLE data

2.2.1. R factor

The R factor was taken from 1 km resolution gridded European scale data based on observational data (Panagos et al., 2015a). In the data, the R for Finland is calculated from hourly precipitation data measured at 64 stations during the years 2007–2013. Based on this, the average R-value for Finland is 273 MJ mm ha^{-1} t^{-1} yr^{-1} (the European average is 722 MJ mm ha^{-1} t^{-1} yr^{-1}) with an annual average precipitation of 660 mm. The R factor was resampled to a two-metre resolution using bilinear interpolation.

2.2.2. K factor

The K factor was based on the Finnish Soil Database (Lilja et al., 2017c; Lilja and Nevalainen, 2006), which was supplemented with soil-specific K values. The soil map in the database is vector data (1:200,000) describing the Finnish soils according to the classification of the World Reference Base for Soil Resources (IUSS Working Group WRB, 2015) with the smallest spatial feature being 6.25 ha. The K values for the soil in the soil map were established by Lilja et al. (2017a, 2017b) and are supported by earlier work in Finland (Rekolainen and Posch, 1993; Bärlund and Tattari, 2001; Rankinen et al., 2001; Bärlund et al., 2009). The soil-specific K values are shown in Table A1 in Appendix A.

The K-value-supplemented soil map was then rasterised to a two-metre resolution by using the nearest neighbour interpolation method. The rasterised K-factor data were also extrapolated with the nearest neighbour interpolation method to account for the finer details of shorelines of water bodies, as the scale of the soil map does not describe the shorelines in detail.

2.2.3. LS factor

The LS factor was calculated from a two-metre resolution LiDAR-based digital elevation model (DEM) of Finland (National Land Survey of Finland, 2020) using the SAGA-GIS Module LS Factor (Conrad, 2003) and the method of Desmet and Govers (1996) with the default settings (rill/inter-rill ratio = 1). The LS calculation was performed at the same resolution as the source DEM.

The agricultural land was defined in the DEM according to field parcel data from the Finnish Food Authority, which contains over one million vectorised field parcels and accounts for almost all agricultural land in Finland. The field borders in the field parcel data were used in the LS calculation to account for the effects of discontinuity elements (mainly open ditches) on surface runoff, as recommended by Desmet and Govers (1996). In Finland, the fields are typically surrounded by open ditches that isolate the field parcels in terms of surface runoff. However, adjacent field parcels that shared the same parcel border were treated in the calculation as a single field parcel since such fields can be uniform in management and drainage.

The DEM was not treated for sinks before calculating the LS factor. The DEMs typically contain artificial depressions, but agricultural lands also have real depressions. It was observed that partially filling sinks (0.05, 0.1, 0.15, 0.2, and 0.25 m) had a minor effect on the calculated LS factor, and the effects were mainly restricted to flat areas with local sinks where erosion rates are low and real depressions may occur.

2.2.4. C factor

The C factors for the experimental field sites with different crop and management cases were established with a calibration approach, as the data for calculating location-specific C factors according to Renard et al. (1997) were not available for this study and are generally limited in Finland. The C factor is known to be one of the largest sources of uncertainty in RUSLE (Estrada-Carmona et al., 2017), and the calibration is shown to improve the RUSLE erosion estimates (Batista et al., 2019).

In the calculation of country-scale erosion data, the C factor was given a value of 1 for all agricultural lands, which corresponds to 'clean-tilled continuous fallow conditions' (Renard et al., 1997). This approach excludes the effects of temporally and spatially varying crops, management, and support practices and results in crop- and management-independent erosion data for a spatially consistent comparison of spatial erosion patterns on agricultural lands. The erosion estimates with a C value of 1 are, however, likely to be higher compared to the erosion under the prevailing farming practices.

2.2.5. P factor

At the experimental field sites, the effect of subsurface drainage on erosion was considered in the P factor. We used the P factor value of 0.6 suggested by Renard et al. (1997) and used earlier in Finland by Lilja et al. (2017a). According to several studies from different climatic conditions, subsurface drainage is found to reduce erosion by 16 to 84% (Bengtson et al., 1988, 1984; Bengtson and Sabbagh, 1990; Bottcher et al., 1981; Formanek et al., 1987; Grazhdani et al., 1996; Istok and Kling, 1983; Schwab et al., 1980, 1977). A study in Finland showed that substituting poorly functioning old drainage pipes and trenches with new ones reduced erosion by up to 15% on gently sloping (2.6%) clay soil (Turtola and Paajanen, 1995). The erosion reduction effect of subsurface drainage was attributed in these studies to reduced surface runoff, increased soil infiltration, changes in soil moisture, and increased crop yield.

When calculating the country-scale erosion estimate, the subsurface drainage was not considered, and the P factor was given a value of 1 to provide a spatially consistent erosion estimate.

2.3. RUSLE calibration and evaluation

2.3.1. Field sites

The seven experimental field sites for calibration and evaluation of RUSLE were Aurajoki, Gårdskulla, Hovi Liperi, Kotkanoja, Nummela, and Toholampi. The Gårdskulla and Hovi sites are single field areas in normal agricultural use, and the rest have multiple plots. The field sites have varying soil and topographical conditions, and all except the Aurajoki site were fully subsurface-drained during the measurement campaigns. The locations of the field sites are shown in Fig. 1, and their characteristics are summarised in Table 1.

The field sites had year-round measurements of erosion loads via surface runoff and subsurface drain discharge, and the fields were under different crop and management practices during the erosion measurements used for this study. These included spring cereals (wheat, oat, barley) with conventional autumn ploughing, shallow autumn stubble tillage, autumn cultivator tillage, no autumn tillage (winter-time stubble), and direct sowing (winter-time stubble); winter cereals (wheat, rye); perennial grass; and perennial pasture. The data from these sites provided 20 crop and management cases, with each having three to ten years of measurements that were classified into six cases of cropping and

Table 1
The characteristics of the seven field sites used in the calibration and evaluation of RUSLE.

Field	Location, site description, data period	More detailed field description / data source
Aurajoki	Southwestern Finland (60.4815°N 22.3678°E), slope 7.0%, Stagnosol (clay), experimental field with 12 plots (each 18 × 51 m), data period 1989–2002	Puustinen et al. (2005) / Finnish Environment Institute (2019)
Gårdskulla	Southern Finland (60.1766°N, 24.1726°E), slope 5.0%, Stagnosol (clay), single field (4.7 ha), sub-surface drained, data period 2011–2020	Turunen et al. (2017) / The Field Drainage Research Association
Hovi	Southern Finland (60.4232°N, 24.3711°E), slope 1.7%, Stagnosol (clay), a section of a larger field (12 ha), sub-surface drained, data period 1990–2001	Bengtsson et al. (1992) / Finnish Environment Institute (2019)
Kotkanoja	Southern Finland (60.8157°N, 23.5110°E), slope 2.6% Stagnosol (clay), experimental field with 4 plots (each 33 × 132 m), sub-surface drained, data period 1993–2010	Uusitalo et al. (2018)/ Finnish Environment Institute (2019)
Liperi	Eastern Finland (62.5297°N, 29.3669°E), slope 1.0%, Stagnosol (silt), experimental field with 4 plots (each 20 × 126 m), sub-surface drained, data period 1989–1999	Kukkonen et al. (2004) / Puustinen et al. (2010)
Nummela	Southern Finland (60.8660°N, 23.4300°E), slope 0.8%, Stagnosol (clay), experimental field with 4 plots (total area 9 ha), sub-surface drained, data period 2007–2016	Äijö et al. (2018) / Field Drainage Research Association
Toholampi	Central western Finland (63.8209°N, 24.1598°E), slope 1.0%, Regosol (sand), experimental field with 16 plots (each 16 × 100 m), sub-surface drained, data period 1997–2009	Turtola and Kemppainen (1998) / Finnish Environment Institute (2019)

management practices for calibration and evaluation: cereals with autumn ploughing, cereals with reduced autumn tillage, cereals with winter-time stubble, winter cereals, perennial grass, and perennial pasture (Table 2).

2.3.2. *Calibration*

C factors were calibrated for the six crop and management cases of the seven experimental field sites: cereals with autumn ploughing, cereals with reduced autumn tillage, cereals with winter-time stubble, winter cereals, perennial grass, and perennial pasture. C factors were calibrated by optimizing the C value by minimising the error between the erosion estimate of RUSLE and the measured average annual soil loss of the measurement periods at the field sites, including the sum load via surface runoff and subsurface drainage. The optimization was done individually for each crop and management case using the least squares method. Separate validation could not be performed due to the small number of field sites and the short measurement periods.

The inclusion of subsurface load was necessary for considering the total erosion load from soil surface processes and comparing the estimated and measured total erosion. Measurements in Finland have shown that the erosion material in subsurface drainage flow originates from the erosion processes in the surface soil (Uusitalo et al., 2001) and that the sediment load via subsurface drainage varies at least from 50 to 90% of the total load (Finnish Environment Institute, 2019; Turunen et al., 2017; Warsta et al., 2014, 2013; Turtola et al., 2007). A modelling study in Finland supports the findings of the origin of the erosion material in subsurface drainage (Turunen et al., 2017), and studies from Norway (Øygarden et al., 1997) and the United Kingdom (Foster et al., 2003) report findings similar to Finland. According to these studies, the soil material was transported to subsurface drains via cracks and macropores in the soil matrix.

Since RUSLE does not include a specific description for sediment transport via subsurface drainage, a simplified inclusion of subsurface load was used. It was assumed that the eroded soil material from the soil surface is transported via the soil cracks, macropores, and tile drains to the outlet of the subsurface drainage system, and that in the subsurface domain, the long-term sediment mass balance is at equilibrium, meaning that the sediment mass entering the subsurface domain equals the sediment mass exiting the subsurface domain via subsurface drainage.

The calibrated C values represent the average values of the most common crop and management cases in the southern half of Finland, and they do not consider possible differences in location-specific cropping and management schedules and the intra-annual distribution of rainfall erosivity. The potential inaccuracies in the C factors can lead to

Table 2
Measured and estimated erosion for the different crop and tillage management cases at the seven field sites. The measurements include the average erosion (sum via surface runoff and subsurface drainage discharge) of the measurement periods and the range of annual erosion (in brackets).

Crop and tillage management	Field	Treatment	Duration (yr)	Measured ($kg\ ha^{-1}\ yr^{-1}$)	Estimate ($kg\ ha^{-1}\ yr^{-1}$)	Error ($kg\ ha^{-1}\ yr^{-1}$)	Relative error (%)
Cereals with autumn ploughing	Aurajoki	Normal ploughing	9	2100 (980–4640)	2213	113	5%
	Liperi	Normal ploughing	10	125 (67–163)	146	21	16%
	Toholampi	Normal ploughing	10	380 (88–661)	329	−51	−13%
	Kotkanoja	Normal ploughing	10	968 (435–1996)	489	−479	−49%
	Hovi	Normal ploughing	12	640 (198–1858)	638	−2	0%
Cereals with reduced autumn tillage	Aurajoki	Shallow stubble tillage	4	1420 (650–2930)	1699	279	20%
	Aurajoki	Cultivator	5	1760 (1120–3330)	1699	−61	−3%
	Kotkanoja	Shallow stubble tillage	5	987 (552–1313)	379	−608	−62%
	Nummela	Cultivator	7	1246 (324–2330)	125	−1121	−90%
Winter cereals	Aurajoki	Winter wheat	9	1555 (780–3540)	1566	11	1%
	Liperi	Winter rye	3	90 (49–130)	103	13	14%
Cereals with winter-time stubble	Aurajoki	No autumn till	9	790 (270–1500)	754	−36	−5%
	Liperi	No autumn till	4	80 (33–98)	50	−30	−38%
	Toholampi	No autumn till	4	195 (76–456)	112	−83	−43%
	Aurajoki	Direct Sowing	5	620 (430–950)	754	134	22%
	Kotkanoja	Direct sowing	3	541*	168	−373	−69%
Perennial grass	Aurajoki	Grass ley	4	570 (500–620)	571	1	0%
	Liperi	Grass ley	8	55 (17–160)	38	−17	−32%
	Kotkanoja	Grass ley	6	631 (383–1239)	262	−369	−58%
Perennial pasture	Gårdskulla	Pasture	9	720 (137–1151)	720	0	0%

[*] Measured range not available due to missing data and the short measurement period.

errors in erosion predictions, and these possible errors were considered in the model evaluation.

2.3.3. *Evaluation*

Model performance was estimated against the measured erosion rates at the seven field sites described above (Section 2.2.1) by using standard metrics and estimating the probability distribution for the model errors. The standard metrics included coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE), mean absolute error (MEA), root mean square error (RMSE), and mean bias error (MBE). Error distribution was estimated by fitting known distributions to the observed errors using the maximum likelihood method.

Model uncertainties are commonly evaluated by analysing the uncertainty in individual model parameters by using approaches such as forward propagation error analysis (see e.g. Batista et al., 2021) and the Monte Carlo method (Metropolis and Ulam, 1949), but for the present study, the data on RUSLE factors were inadequate for using such approaches.

2.4. *Erosion at agricultural lands*

2.4.1. *Calculation of erosion data*

The erosion estimate was calculated for all agricultural lands in Finland at a two-metre resolution by using the R, K, and LS data, and a value of 1 for the C and P factors in all agricultural areas, as explained in Section 2.2. The calculation was performed in the same two-metre raster resolution as the LS factor by multiplying the R, K, and LS data in the high-performance computing environment of the CSC – IT Center for Science using R (R Core Team, 2022). The resulting data is spatially consistent, independent of variations in crop, management and erosion mitigation practices, and it represents erosion under 'clean-tilled continuous fallow conditions' (Renard et al., 1997).

2.4.2. *Spatial analysis of erosion*

The developed erosion estimate was analysed to reveal high erosion source areas and how erosion varies within different spatial scales. The scales were selected to provide new and meaningful insights for erosion management. They included the whole country in 5 × 5 km grid resolution, as well as sub-catchment, field parcel, and 2 × 2 m grid resolution scales. The sub-catchment scale involved an analysis of erosion near water bodies, which was based on a calculation of the ratio of average erosion near water bodies ($<$ 50 m) to the average erosion in the respective sub-basin. The ratio values above (below) 1 indicate a higher (lower) erosion rate near a water body than the average in the sub-catchment. For the analyses, the sub-basin borders and the water bodies (i.e., sea, lakes, rivers, and streams) were taken from the Finnish Environment Institute (Finnish Environment Institute, 2010). The spatial distribution of erosion at the field parcel and 2 × 2 m scales were exemplified using two topographically differing case study areas, the Aura River and Mustio River sub-catchments (locations shown in Fig. 1). We report erosion rates in kg ha^{-1} yr^{-1} and on a country-scale 5 × 5 km resolution analysis also in t yr^{-1} by multiplying the former rate with the field area (ha) of the 5 × 5 km area and by converting kilograms to tonnes. The t yr^{-1} describes the total amount of erosion occurring in a specific area.

Additionally, the role of the R, K, and LS factors in the erosion estimate was analysed by calculating statistical correlations between the factors and the erosion estimate.

3. Results

3.1. *Model calibration and evaluation at the field parcel scale*

The erosion estimates of the calibrated RUSLE corresponded well with the measurements at the five fields – Aurajoki, Gårdskulla, Hovi, Liperi, and Toholampi. But at the two heavy clay field sites – Kotkanoja and Nummela – erosion was clearly underestimated, as shown in Table 2. The R^2 for the 20 crop management cases was 0.76 (p-value $<$0.000) (Fig. 2), NSE was 0.72, the mean absolute error (MEA) was 190 kg ha^{-1} yr^{-1}, and the root mean square error (RMSE) was 336 kg ha^{-1} yr^{-1}. The calibrated C factor values for the evaluated crop and management cases are shown in (Table 3) together with the field site-specific R, K, LS, and P factor values.

The average error of the RUSLE prediction for the 20 crop and tillage management cases was −133 kg ha^{-1} yr^{-1}, and the 5th and 95th percentiles of the errors were − 634 and 141 kg ha^{-1} yr^{-1}, respectively. The errors were skewed, and according to the Shapiro-Wilk test, the errors were not normally distributed (p-value = 0.0005488). Therefore, the Weibull, gamma, and log-normal distributions were evaluated for the error distribution. The gamma distribution provided the best fit to the observed errors (Table A2 and Fig. A2 in Appendix A), and the resulting error distribution had an average of −134 kg ha^{-1} yr^{-1}. The 5th and 95th percentiles of the error distribution were − 711 and 218 kg ha^{-1} yr^{-1}, respectively.

3.2. *Spatial distribution of erosion on agricultural lands*

The average erosion on agricultural lands in Finland under clean-tilled continuous fallow conditions (C = 1) was estimated to be 3760 kg ha^{-1} yr^{-1}, and the spatial variation was large, as shown in Fig. 3A. On the field parcel scale, the average erosion varied from 500 to 15,890 kg ha^{-1} yr^{-1} (95% range) by parcel, with 90% of the field parcels below 8390 kg ha^{-1} yr^{-1}.

On the country scale, the analysis of erosion data in Fig. 3 reveals varying spatial patterns. Two large regions with high erosion in kg ha^{-1} yr^{-1} were identified, one in central southern Finland and the other in the coastal area in southwestern Finland (Fig. 3A). A large region with relatively low erosion was identified in the upper western coastal area.

In terms of t yr^{-1} at 5 × 5 km resolution, the distribution of erosion in Fig. 3B resembles the distribution of agricultural lands in Fig. 1. The major area of agricultural erosion is in the coastal areas of the south and southwest, but more localised erosion areas are also observed, for example near many of the rivers draining into the Baltic Sea on the western coast. A larger inland area with high erosion (t yr^{-1}) can also be observed in central Finland.

The analysis of the role of the R, K, and LS factors (Fig. 4A-C) in the calculated erosion estimate revealed that the topography of the fields, as described by the LS factor, was the most influential factor on the country scale in the estimation of erosion. The linear correlation between the LS

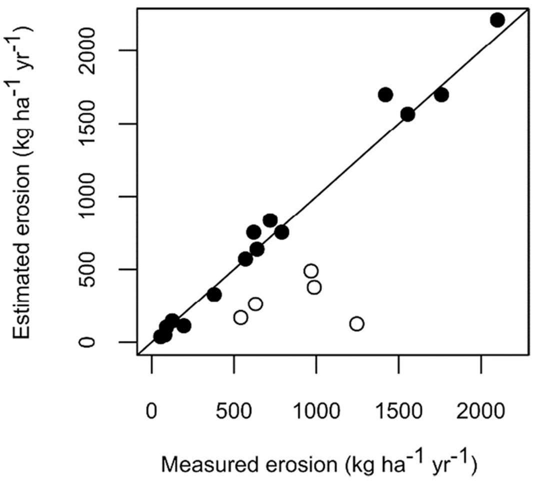

Fig. 2. RUSLE's performance at the seven experimental field sites. The cases of clear model underestimations from two fields (Kotkanoja and Nummela) are shown by empty circles. The R^2 and NSE between estimated and measured erosion rates are 0.76 (p-value$<$0.001) and 0.72, respectively.

Table 3
The R, K, LS, C, and P factor values used for the seven field sites. R is from Panagos et al. (2015a), K is from Lilja et al. (2017a, 2017b) and P is from Renard et al. (1997), LS and C were estimated in the current study.

Field site	R (MJ mm ha^{-1} h^{-1} yr^{-1})	K (t ha h ha^{-1} MJ^{-1} mm^{-1})	LS (−)	C (−)	P (−)
Aurajoki	356	0.04	0.80	0.211[1]/0.162[2]/ 0.075[3]/0.149[4]/ 0.065[5]	1
Gårdskulla	322	0.04	1.00	0.097[6]	0.6
Hovi	301	0.04	0.42	0.211[1]	0.6
Kotkanoja	324	0.04	0.30	0.211[1]/0.162[2]/ 0.075[3]/0.065[5]	0.6
Liperi	238	0.04	0.12	0.211[1]/0.075[3]/ 0.149[4]/0.065[5]	0.6
Nummela	302	0.04	0.11	0.162[2]	0.6
Toholampi	287	0.057	0.16	0.211[1]/ 0.075[3]	0.6

[1] Cereals with autumn ploughing.
[2] Cereals with reduced autumn tillage.
[3] Cereals with winter-time stubble.
[4] Winter cereals.
[5] Perennial grass.
[6] Perennial pasture.

factor and the erosion at the 5 × 5 km grid scale was 0.58 (p-value $<$0.000), whereas for soil erodibility (K), it was 0.51 (p-value $<$0.000), and for rainfall erosivity, it was (R) 0.36 (p-value $<$0.000).

The LS was also a major contributing factor in the two major regions identified as having high erosion: one in central southern Finland and the other in the coastal area in southwestern Finland. The LS factor in Fig. 4C shows larger values in these regions. Similarly, the lower LS factor values on the western coast contributed to the lower erosion in the upper western coastal area. According to the K factor of agricultural lands, large areas of erosive soils are situated in the southwest, more on the western coast and in some inland areas, as shown in Fig. 4B. The areas with the highest rainfall erosivity were found on the western coast of southern Finland, as shown in Fig. 4A.

On the country scale, the erosion was also found to be distributed differently within different sub-catchments. Higher erosion rates near water bodies ($<$ 50 m distance) were observed in several sub-catchments, as indicated by the erosion ratio values between erosion near water bodies and erosion in the catchment (shown in Fig. 5). Two broader regions with considerably higher erosion near the water bodies were identified, and both are situated by the coast of the Baltic Sea. The largest one is in southwest Finland, and the smaller one is in South Finland. Southeast Finland, in turn, has a large region where the erosion ratio is more uniform in all agricultural areas and where lakes form a large proportion of the area. In northern Finland, with a low proportion of agricultural land, the situation is mixed. Altogether, the erosion near water bodies is on average 1.6 times the erosion of all agricultural lands.

A comparison at the sub-catchment level at the Aura and Mustio rivers highlights further differences in the erosion distribution between the sub-catchments and field parcels (Fig. 6). At the Aura River sub-catchment, the average erosion of field parcels under a clean-tilled continuous fallow condition (C = 1) was estimated to be 5800 kg ha^{-1} yr^{-1} (95% range: 67–25,440 kg ha^{-1} yr^{-1}), and the high-erosion field parcels were concentrated largely along the mainstream, as shown in Fig. 6. At the Mustio River sub-catchment, the average erosion of field parcels under a clean-tilled continuous fallow condition (C = 1) was estimated to be 7910 kg ha^{-1} yr^{-1} (95% range:140-–27,340 kg ha^{-1} yr^{-1}), and the field parcels with the highest erosion were more scattered in the landscape. Also, a small concentration of high-erosion field parcels was found at the northern part of the Mustio River sub-catchment, as shown in Fig. 6. The average erosion rates of the field parcels of the Aura and Mustio sub-catchments were 1.5 and 2.1 times higher, respectively, than the country average.

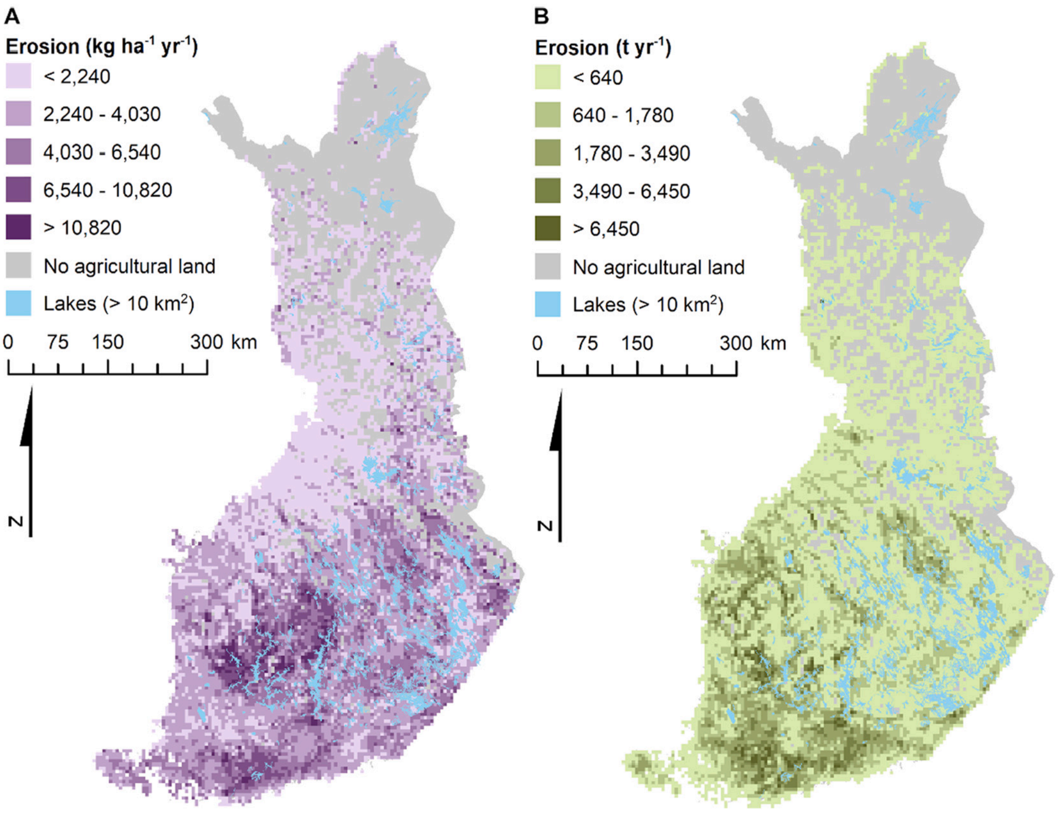

Fig. 3. Estimated erosion of agricultural lands under clean-tilled continuous fallow conditions (C = 1) in (A) kg ha^{-1} yr^{-1} and (B) t yr^{-1}. The calculated erosion estimate is in 2 × 2 m resolution but is presented in the figure in a 5 × 5 km grid resolution. Areas with no agricultural land are shown in grey.

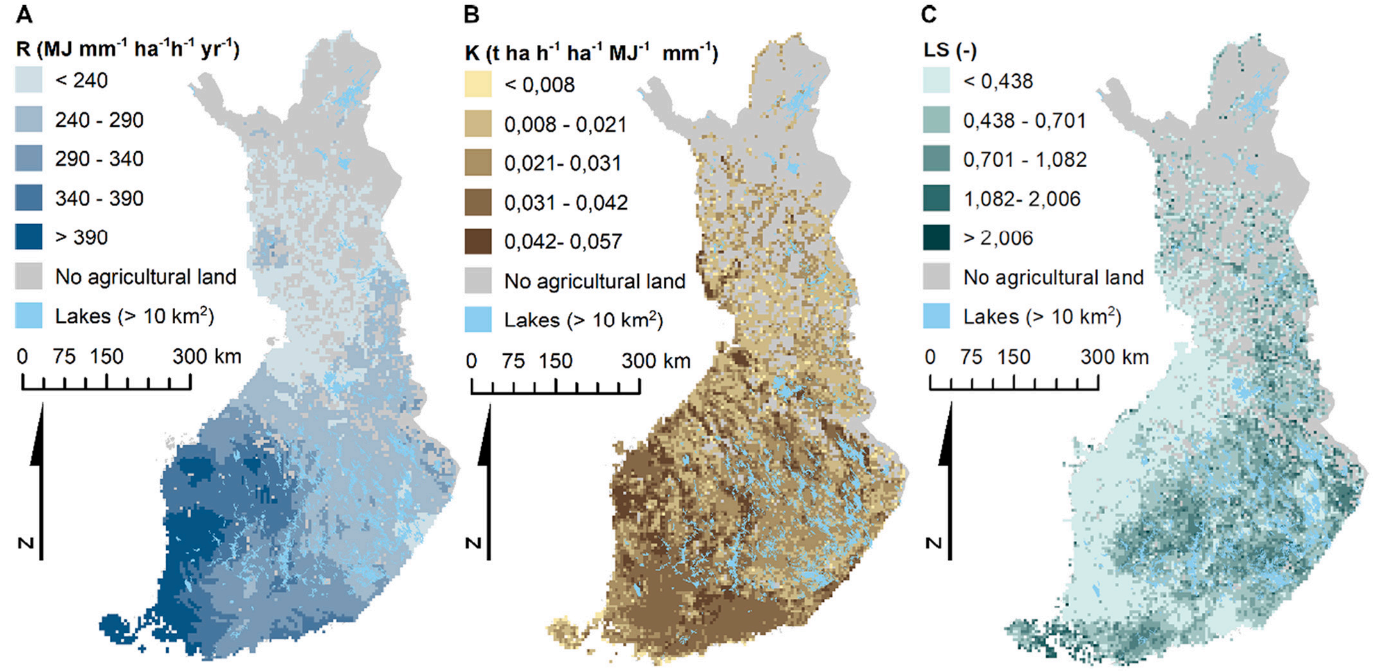

Fig. 4. The RUSLE factors for the erosion data of agricultural lands at 5 × 5 km grid resolution: (A) the rainfall erosivity factor (R) (calculated from Panagos et al., 2015a); (B) the soil erodibility factor (K) (calculated from Lilja et al., 2017a, 2017b); and (C) the slope length and steepness factor (LS) estimated in this study. Areas with no agricultural land are shown in grey.

On a more local scale, we also found a high variation in erosion distribution within the field parcels. The analysis of the two-metre resolution erosion data in Fig. 7 shows how the high erosion source areas at the Aura River sub-catchment are largely located on the river side of the field parcels. And at the Mustio River sub-catchment, they are often located on the opposite side of the field parcels and further away from the rivers and streams. However, individual field parcels with high erosion source areas on the stream side were also observed at the Mustio River sub-catchment. These differences are largely explained by topography. At the Aura River sub-catchment, the landscape is mainly gently sloping with steep slopes near the rivers and streams, whereas at the Mustio River sub-catchment, the landscape is more undulating with less steep slopes near the rivers and streams. At the Aura River sub-catchment, the erosion near water bodies (<50 m distance) is estimated to be 5.5 larger than the average in the basin. And at the Mustio River sub-catchment, the erosion near water bodies is lower than the average in the basin with a ratio of 0.77.

4. Discussion

4.1. Evaluation of RUSLE

The results indicate that at the field parcel scale as compared to the measured erosion, RUSLE is skilled in predicting erosion ($R^2 = 0.76$, NSE = 0.72) and differentiating between different crop and management types in the Finnish boreal condition. However, RUSLE underpredicted erosion at two out of seven fields, and the predictions have a large uncertainty interval (mean = -134 kg ha^{-1} yr^{-1}; 5th and 95th percentiles = -711 and 218 kg ha^{-1} yr^{-1}, respectively) according to the estimated error distribution.

The field parcel scale results are similar to an earlier evaluation in Finland by Lilja et al. (2017a) and broader model comparisons in the literature. Batista et al. (2019) reviewed model performances of several models (MMF, RUSLE, USLE USLE-M, WEPP), and the NSE value of the calibrated RUSLE in the present study (NSE = 0.72) corresponds to the average performance of the calibrated models in the review (NSE = 0.74). The average performance of the reviewed non-calibrated models was lower and had a wider performance range than the calibrated models. Also, according to the review by Govers (2011), for the R^2 value, the performance of the calibrated RUSLE in the current study is typical for erosion models in general. However, at larger landscape scales, the evaluation of a spatially distributed RUSLE is a challenge as the model produces gross erosion estimates and suitable evaluation data is rarely available on such scales. The absolute erosion estimates of spatially distributed erosion models are known to be large, but they are nevertheless considered capable of ranking erosion-prone areas (Alewell et al., 2019; Batista et al., 2019).

The current work expanded the earlier RUSLE evaluation in Finland (Lilja et al., 2017a) by including new field sites in the assessment, considering the loads from subsurface drainage, and providing a probabilistic uncertainty estimate for RUSLE predictions. The estimated C factor values correspond to values by Lilja et al. (2017a) and also the values by Panagos et al. (2015c) with minor differences, as shown in Table 4. In particular, Lilja et al. (2017a) estimated a C value of 0.12 for spring cereals, whereas we estimated a value of 0.211, which is close to the value estimated by Panagos et al. (2015c). This difference is likely a result of a different selection of field sites and the exclusion of subsurface loads by Lilja et al. (2017a). The probabilistic uncertainty estimate for RUSLE predictions in turn is a useful measure for understanding the uncertainties of RUSLE in future studies in Finland. It also enables the estimation of uncertainties of larger spatial scale estimates (e.g. catchment scale erosion) through an accumulation of uncertainties of individual field parcels. The probabilistic uncertainty estimate is, however, to be taken as preliminary, given the limited data used for its estimation.

Given that the calibrated C values correspond to the literature, it is expected that the *P* value of 0.6 used for the subsurface is also appropriate, although uncertainties remain due to limited empirical data. The same value was suggested by Renard et al. (1997) to be used in RUSLE, and it was used for Finland by Lilja et al. (2017a). However, the literature suggests possible *P* values ranging from at least 0.16 to 0.84 (Bengtson et al., 1988, 1984; Bengtson and Sabbagh, 1990; Bottcher et al., 1981; Formanek et al., 1987; Grazhdani et al., 1996; Istok and Kling, 1983; Schwab et al., 1980, 1977).

The six C factors calibrated in this study (Table 3) also provide

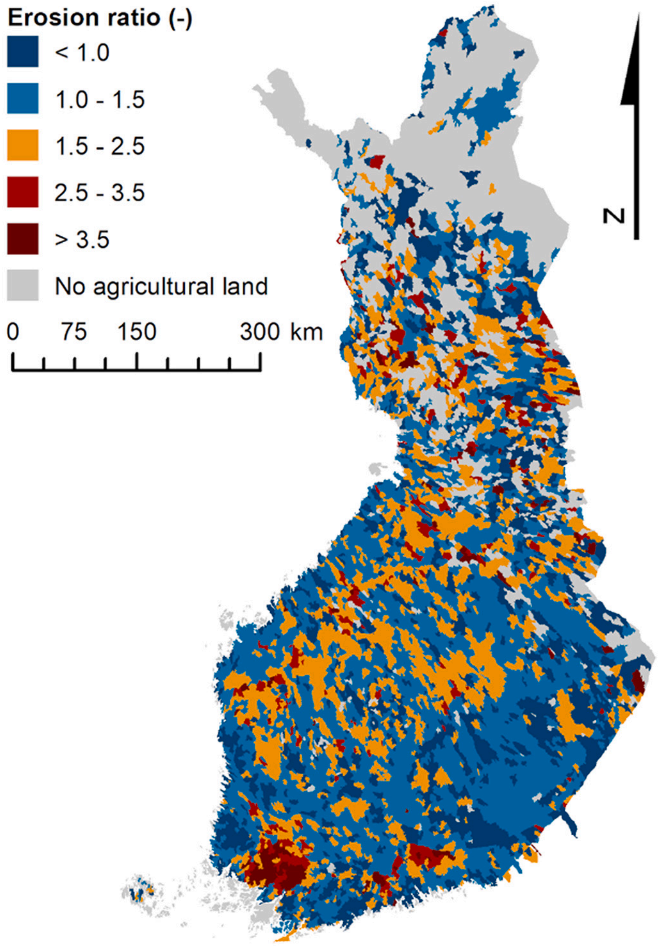

Fig. 5. High erosion areas near water bodies by sub-catchments. The erosion ratio values above (below) one indicate higher (lower) erosion near water bodies (< 50 m) than on average in the respective sub-catchment.

estimates of the average effect of crop and management on erosion. In cereal cultivation, winter-time stubble is estimated to reduce erosion by 64%, reduced autumn tillage by 23%, and winter cereals by 29% compared to conventional autumn ploughing. The perennial grass, in turn, had on average 69% lower erosion than the spring cereals with conventional autumn ploughing. According to the measurements, winter-time stubble (no-till, spring till) is reported to reduce erosion by 42–70%, reduced tillage (cultivation, shallow stubble tillage) by 16–32%, winter cereals by 25–26%, and perennial grass by 59–73% compared to cereals with autumn ploughing (Honkanen et al., 2021; Puustinen et al., 2005; Kukkonen et al., 2004).

Preliminary estimates for actual average erosion rates of different crop and management types can also be derived from the calibrated C factors and the estimated average erosion. For example, by using the estimated average erosion of 3760 kg ha^{-1} yr^{-1} under a clean-tilled continuous fallow condition (C = 1) (Section 3.2) and by assuming that the calibrated C factor values and the used P value for subsurface drainage (Section 3.1) are representative average values for Finland, it can be estimated that the country-scale average erosion rate of spring cereals (C = 0.211) with conventional autumn ploughing would be 793 kg ha^{-1} yr^{-1}, and with subsurface drainage, it would be 476 kg ha^{-1} yr^{-1} ($P = 0.6$). Similarly, the average erosion rate for perennial grass (C = 0.065) would be 244 kg ha^{-1} yr^{-1} and 147 kg ha^{-1} yr^{-1} with subsurface drainage. These values may, however, be underestimated and contain uncertainty, given that the evaluation of RUSLE at the seven field sites suggested a mean bias error of −133 kg ha^{-1} yr^{-1}, and the uncertainty estimate at the individual field was large (Section 3.1).

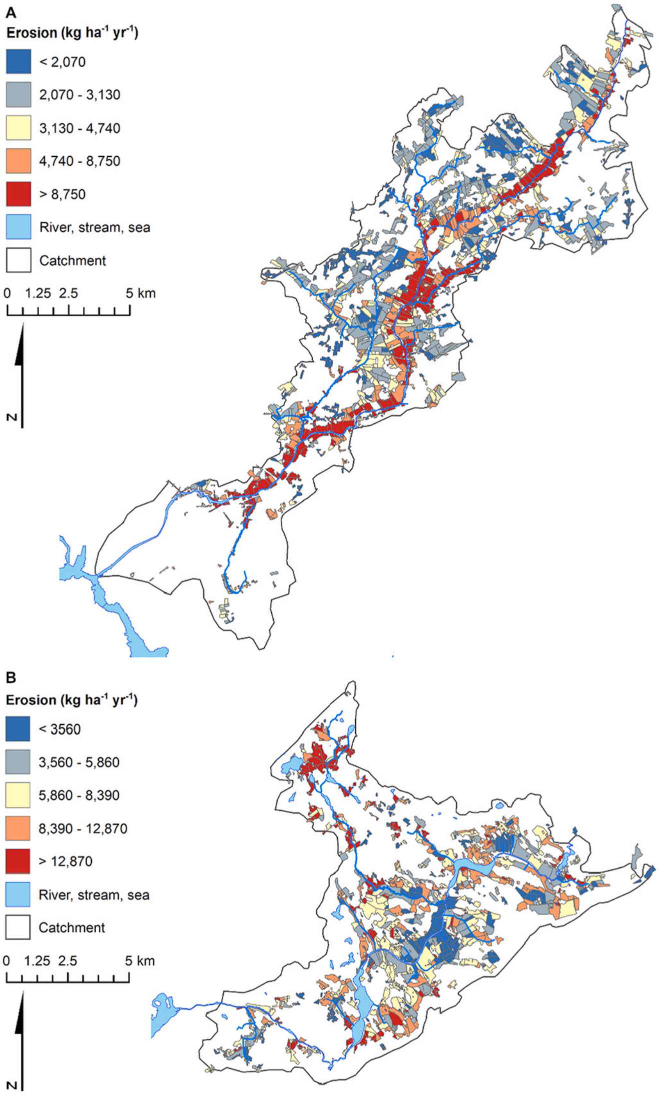

Fig. 6. Estimated erosion of field parcels of the (A) Aura River and (B) Mustio River sub-catchments under clean-tilled continuous fallow conditions (C = 1). Each (coloured) group in the legend contains 20% of the field parcels in the sub-catchments.

4.2. Spatial distribution of erosion

The present study provides the first high-resolution country-scale view on the spatial distribution of agricultural erosion in Finland (Section 3.2), while previously, the country-scale view was provided by a 100 m resolution RUSLE 2015 estimate from Panagos et al. (2015e). These two estimates have several differences in addition to the spatial resolution. Most importantly, for deriving the K factor, we used national soil survey data and a soil map with a scale of 1:200000, whereas Panagos et al. (2014) used European LUCAS soil survey data, a cubist regression method, and remote sensing data to interpolate a European K factor map at 500 m resolution. For the calculation of the LS factor, the same method was used in both studies. But we used a national 2 m resolution DEM, whereas Panagos et al. (2015b) used a European 25 m resolution DEM. Also, we estimated crop and management independent erosion of agricultural lands and set the C and P factor values to 1, whereas Panagos et al. (2015c) developed C factors based on literature for broad NUTS regions and considered grass margins in the P factor (Panagos et al., 2015d).

The comparison of these two erosion estimates in Fig. 8 shows that Panagos et al. (2015e) identify roughly the same major high-erosion

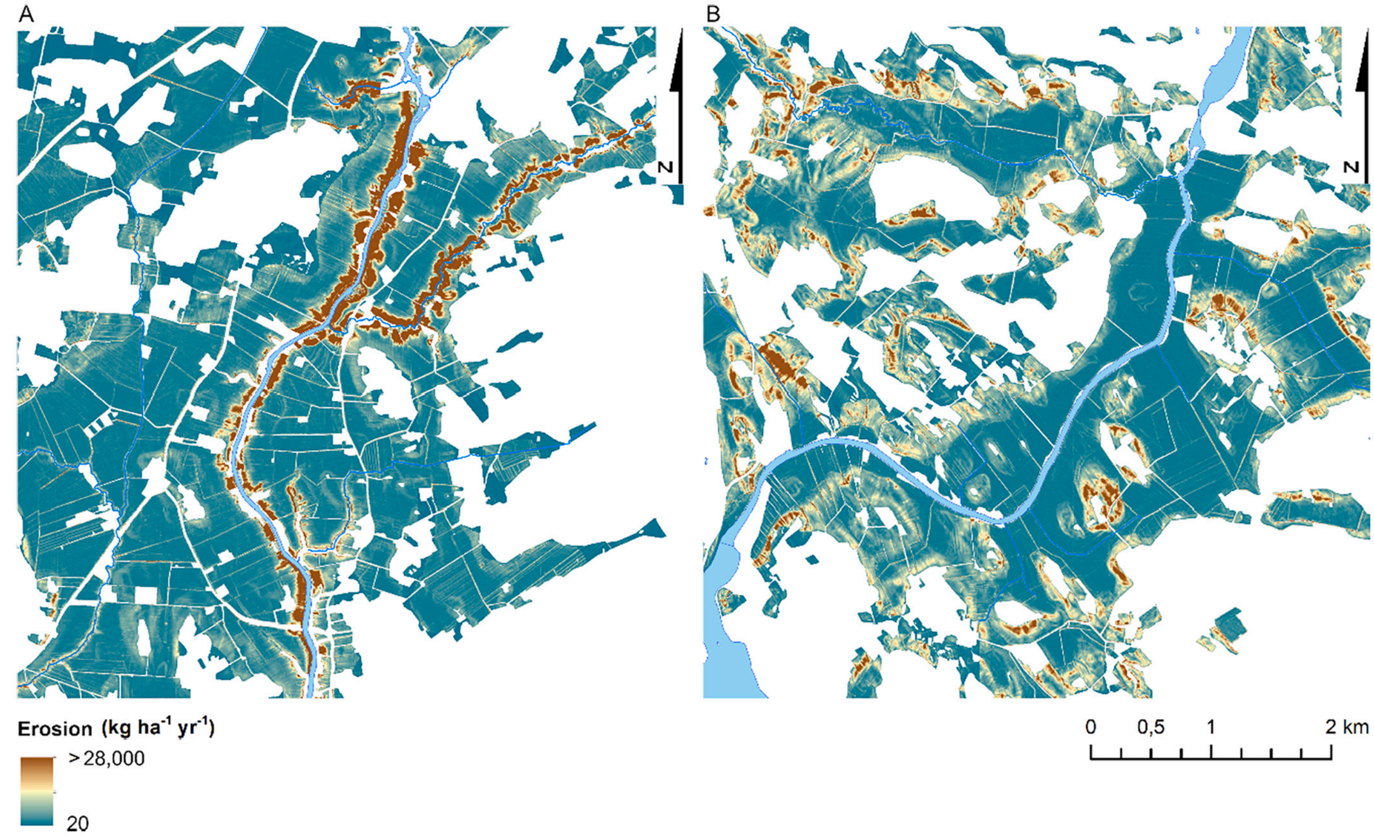

Fig. 7. Estimated erosion under clean-tilled continuous fallow conditions (C = 1) in two-metre resolution at the (A) Mustio River and (B) Aura River sub-catchments in the coastal area of southwestern Finland (see locations in Fig. 1).

Table 4
Comparison of the C factor values estimated in this study to the values by Lilja et al. (2017a) and Panagos et al. (2015c).

Crop and tillage management	Estimated in this study	Lilja et al. (2017a)	Panagos et al. (2015c)
Cereals with autumn ploughing	0.211	0.12	0.2
Cereals with reduced autumn tillage	0.162	0.149	0.166
Cereals with winter-time stubble	0.075	0.065	0.05
Perennial grass	0.065	0.038	0.027

areas as identified in this study but with differences. For example, the high erosion area in the coastal area of southern Finland is larger in Panagos et al. (2015e), and in the western part of southern Finland, it is smaller (Fig. 8) than in our estimated erosion map. The linear correlation for these two erosion estimates at 5 km × 5 km resolution (as in Fig. 8) is 0.59 (p-value <0.01), and at 100 m resolution, it is 0.32 (p-value <0.01).

The differences between the two data sets are thus considerable, and they are expected to result largely from differences in the K and LS factors, given their differences between the two studies. The description of spatial distribution of soil types and their parametrisation in the K factor, as well as the resolution of the DEM in LS calculation are both well-known sources of uncertainties in erosion estimates (see e.g., Michalopoulou et al., 2022; Rompaey and Govers, 2002). The differences due to the C factors between the two studies are expected to be small as the C factor estimates of Panagos et al. (2015c) specified single C values for each of the four NUTS regions in Finland, and in the main agricultural areas, these C values are similar. The differences due to the P factor are also expected to be small, given the small effect of support practices in Finland estimated by Panagos et al. (2015d). Both studies used the same R data.

The absolute erosion magnitudes of the two estimates could not be fully compared as they reflect different crop and management conditions. However, we believe that in future, the inclusion of national field parcel scale crop and management (Finnish Food Authority) data and subsurface drainage status data (Finnish Field Drainage Association) in the C and P factors in our present erosion estimate will provide locally more relevant and accurate estimates than those by Panagos et al. (2015e).

Our result further revealed new information on the drivers of spatial variations in soil erosion in Finland. We found statistical evidence that the variation was driven more by variation in topography (LS) and soil type (K) than in rainfall (R) (Section 3.2). This was visible also in the estimated erosion maps, for example, the high and low erosion regions identified on the country scale in Fig. 3 coincided with high and low LS factor values (Fig. 4C), respectively. The soil type, in turn, contributed to higher erosion rates in large areas of clay soil (Vertic Luvic Stagnosols) in Southwest Finland and more localised areas of highly erodible silty and loamy soils (Stagnic Regosols) (Fig. 4B).

On more local scales at the Aura River and Mustio River sub-catchments, the spatial variation in erosion was driven even more by topography, as the soil types in the catchments varied less than on the country scale. For example, at the Aura River sub-catchment with relatively flat terrain and steep slopes near water bodies, the high erosion areas were concentrated near water bodies. And at the Mustio River sub-catchment with its undulating topography, the high erosion areas were more scattered in the landscape (Fig. 7). The high erosion rates near water bodies were also observed to be linked to soil type in some regions. For example, in several river basins on the western coast, more erodible soils were concentrated near water bodies.

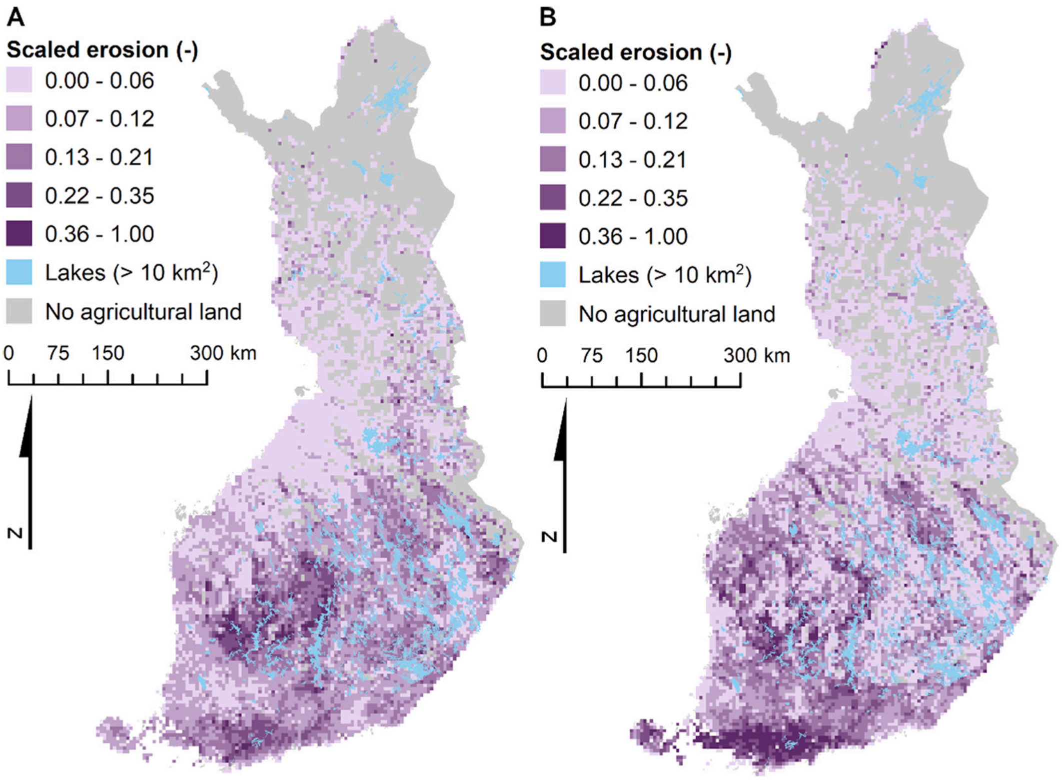

Fig. 8. Comparison of scaled erosion estimates for agricultural lands by (A) this study and (B) Panagos et al. (2015e) at 5 km × 5 km grid resolution. The erosion (kg ha^{-1} yr^{-1}) was scaled to a range of 0 to 1 using min-max normalisation for improved visual comparison. Areas with no agricultural land are shown in grey. Also note that the erosion estimate in A corresponds to clean-tilled continuous fallow conditions ($C = 1$), while the erosion estimate in B includes the C factor estimates according to European NUTS regions (Panagos et al., 2015c).

4.3. *Implications for erosion management*

The developed erosion estimate and the findings of the spatial analysis suggest that erosion management can be improved by targeting erosion mitigation measures to high erosion areas according to high-resolution erosion data. This is an important improvement in Finland, where erosion mitigation measures have been targeted based on broad regions (Ministry of Agriculture and Forestry, 2014) without spatially explicit data on high erosion areas. For example, on the country scale, the erosion management resources could be allocated differently to different regions according to the magnitude of the erosion (Fig. 3). At the sub-catchment scale, vegetated riparian buffer strips could be emphasised where erosion magnitudes near water bodies are high (Fig. 5, Fig. 7). At the field parcel scale, the high erosion field parcels can be identified, and erosion management resources can be targeted accordingly (Fig. 6). At the 2 × 2 m grid resolution scale, the most appropriate and effective erosion management measures (e.g. winter-time vegetation cover, reduced tillage, riparian buffer strips, grassed water ways) can be selected and implemented according to the magnitude and spatial distribution of erosion within the field parcels (Fig. 7). Altogether, the developed erosion estimate provides new and more informed possibilities for planning of erosion management in Finland. However, the applicability of the high-resolution data for improving erosion management needs to be further improved and studied with quantitative scenario analyses (see e.g. Ricci et al., 2020).

An example of a specific region, where erosion mitigation could be emphasised according to the results, is the southwestern coastal area where multiple rivers drain into the archipelago in the Baltic Sea, and where the nutrient loading is already known to be high (Räike et al., 2020; Huttunen et al., 2016). The area has intensive agriculture (Fig. 1), the total amount of erosion is high (Fig. 3B), and the high erosion areas are concentrated near water bodies (Fig. 5) and in relatively confined areas (Fig. 6). In such an area, the erosion and its negative effects could be reduced in a cost-effective way through well-targeted riparian buffer zones and winter-time vegetation cover.

4.4. *Limitations and ways forward*

The large-scale implementation of RUSLE also revealed challenges. In this regard, the erosion assessment with RUSLE can be further developed in Finland, particularly by developing the country-scale K and C factor data. The current K factor data are based on coarse-scale (1:200,000) soil data (Lilja et al., 2017c; Lilja and Nevalainen, 2006), and the variation in K values within soil types could be further investigated. It is also hypothesised that the heavy clay soils may not be presented well enough in the current K factor, given the underestimated erosion at the two clay soil field sites.

The inclusion of location-specific effects of crops and management on erosion in the C factor on the country scale was not feasible at this point. The estimation of C factors requires spatially varying soil loss ratios (SLR) (see Renard et al., 1997), which were not available for this study, and the data for deriving them are generally limited in Finland. The development of C factor data for agricultural lands would be a considerable task, given that there are over 200 crop and vegetation cover types in the whole country (Finnish Food Authority). A potential approach could be based on a combination of new measurements and remote sensing (Phinzi and Ngetar, 2019), and it is also likely that new monthly R factor data need to be developed as well.

The consideration of winter conditions in the R and C factors is also an increasingly important issue as the climate is changing rapidly in Finland. Winters are experiencing more liquid precipitation, and the snow-covered period is getting shorter (Luomaranta et al., 2019), which in turn is expected to result in increased erosion, given that the fields have less vegetation cover during the winter and are more prone to erosion by rainfall and runoff.

Other improvements include the investigation of the role of subsurface drainage and its inclusion in RUSLE as well as the development of improved data on implemented sub-surface drainage within the country. The development of new RUSLE factor data should also consider the need for uncertainty assessment, as appropriately developed factor data would allow for more robust and comprehensive uncertainty assessments than was possible to perform in this study.

5. Conclusions

The RUSLE showed skill in estimating erosion rates observed at experimental fields. Its evident strength was its capacity to produce large-scale and high-resolution erosion data with relatively modest data inputs. However, the uncertainty in the absolute erosion estimates was large. The erosion rates were substantially underestimated at two of the seven field sites, which may indicate a tendency to underestimate the erosion rates also at larger spatial scales, particularly with clay soils. RUSLE's performance was, however, similar to RUSLE applications elsewhere and erosion models in general, and the remaining uncertainties can potentially be reduced by further development of the underlying factor data. The observed uncertainties further suggest that thus far, RUSLE is best used for the identification of high erosion areas and for a relative comparison of erosion rates (for example in system response and scenario analyses) instead of an accurate estimation of absolute erosion rates.

The developed high-resolution erosion estimate for agricultural lands fills an existing data gap in the spatial distribution of erosion in Finland, and it provides a transparent and systemic approach to analyse and discuss erosion distribution and mitigation. While the erosion estimate describes erosion under clean-tilled continuous fallow conditions and excludes the effects of temporal changes in crop composition, management, and support practices, it allows a spatially consistent and crop- and management-independent identification and analysis of high erosion source areas over various spatial scales. For erosion estimates under prevailing crop and management conditions, the erosion estimate needs to be scaled down with appropriate C and P factors.

The spatial analysis of the erosion, in turn, provided a new view of the spatial distribution of agricultural erosion in Finland. It showed high erosion regions in the country and that erosion is distributed differently between and within catchments and field parcels. These findings can inform the targeting of erosion mitigation measures, such as winter-time vegetation cover, reduced tillage, and riparian grass buffer zones. The comparison of the developed erosion estimate with a European-scale erosion estimate in turn, demonstrated that using calculations on different spatial scales and with different input data can result in variable insights into spatial erosion patterns.

Altogether, the results demonstrate the predictive skill of RUSLE in northern boreal conditions, fill the earlier data gap, provide a new approach for targeting erosion measures, open new avenues for erosion modelling research, and considerably improve the understanding of the spatial distribution of erosion in Finland.

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

The developed 2 × 2 m erosion data for all agricultural lands in Finland are publicly available at: http://urn.fi/urn:nbn:fi:att:fdb14fe3-dd2d-499f-81a5-e1e799d8db8a.

Acknowledgements

The work was funded by the Ministry of Agriculture and Forestry of Finland, European Union's Horizon 2020 research and innovation programme (Grant agreement No 862695) and by Natural Resources Institute Finland. The authors also want to acknowledge the work of Harri Lilja on the application of RUSLE in Finland, as it provided the basis for the work presented in this paper; Anders Munck at the Finnish Food Authority for preparing and providing the field parcel data; Helena Äijö and Jyrki Nurminen from the Finnish Field Drainage Association/Field Drainage Research Association for preparing and providing the measurement data for the Gårdskulla and Nummela fields; and the CSC – IT Center for Science, Finland, for computational resources; and, especially, Kylli Ek for technical support.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geodrs.2023.e00610.

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