Improving the agricultural erosion management in Finland through high-resolution data

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Abstract. Soil erosion reduces the sustainability of agricultural sector by loss of productive soil and through negative impacts on surface waters. In Finland, considerable efforts have been made to reduce soil erosion, but the suspended sediment loads to surface waters have not markedly reduced. A major limitation has been the lack of high-resolution data on erosion risk for efficient targeting of the erosion management efforts. In this study, by using the Revised Universal Soil Loss Equation 10 (RUSLE) a two-meter resolution erosion risk data was developed and consequently the spatial distribution of the erosion risk of Finnish agricultural land was analysed. With agricultural management practices of 2019, the average erosion of agricultural land was estimated to be 430 kg ha^{-1} yr^{-1}, and it varied at the municipality scale from 100 to 1290 kg ha^{-1} yr^{-1}. At more local scales the erosion risk had even greater variability, and areas with high erosion risk were differently located in terms distances to water bodies. The results also suggest that the past erosion management efforts have not been well-targeted according to the 15 actual erosion risk. Altogether, the results indicate that erosion mitigation measures can be improved by inclusion of high-resolution data in the planning and implementation of the measures, by considering the spatial variability of the erosion risk over multiple spatial scales, and by implementation of location specific erosion reduction measures.

1 Introduction

Soil erosion has a central role in the sustainability of agricultural sector, as it has significant negative impacts on soil 20   productivity, surface water quality and aquatic ecosystems (Wuepper et al., 2020; Borrelli et al., 2017; Montgomery, 2007; Pimentel et al., 1995). It contributes to eutrophication, and to increased turbidity and siltation of surface waters (Ulén et al., 2012). Erosion causes harmful structural changes in the soil surface, and in the long-term, it can reduce soil fertility through loss of the most fertile top soil (Pimentel et al., 1995). Soil erosion is also linked to climate regulation through transport and storage of carbon (Lugato et al., 2018) and altogether, it is a cross cutting issue in the land use sector (Montanarella and 25   Panagos, 2021).

The key process causing soil erosion is hydrological, and soil particles are detached from the surface by the kinetic energy of rain drops and surface runoff causing slaking, swelling and dispersion (Bissonnais, 2016; Ulén et al., 2012; Jarvis et al., 1999; Wicks and Bathurst, 1996). This process is affected by multiple connected factors, including hydrometeorological conditions, varying particle detachment mechanisms, farming practices, soil physical characteristics and chemical conditions

30   (Turunen et al., 2017; Bechmann, 2012; Ulén et al., 2012; Turtola et al., 2007; Øygarden et al., 1997) leading to high spatial variability in erosion and further in the transport of suspended sediment loads from different sites and catchments (Röman et al., 2018; Ulén et al., 2012).

In Finland, the total area of agricultural land is 2.3 million ha (7.6 % of total land area) and the main crops are cereals (45% of total area) and grass type crops (31%) (data of Finnish Food Authority for 2019). The erosion process is affected by short

35   growing period (140-180 days) and long winter, with highest erosion during rainy autumn months and spring snowmelt (Puustinen et al., 2007). Experimental studies have estimated the average erosion from fields to vary from 55 to 2100 kg ha-1 yr-1 (Lilja et al., 2017a; Puustinen et al., 2010) and earlier modelling approaches have estimated the average erosion of all agricultural lands to be 418-485 kg ha-1 yr-1 (Lilja et al., 2017b; Puustinen et al., 2010). These Fig.s are relatively low in global and European scales (Borrelli et al., 2017; Panagos et al., 2015c), however, in respect to the ecological state of water

40   bodies in northern latitudes, they result in significant negative impacts in surface waters and in the Baltic Sea (Ulén et al., 2012), particularly through transport of phosphorus along with the eroded soil particles (Röman et al., 2018).

The management of environmental impacts of agriculture in Finland is guided by the EU's Common Agricultural Policy (CAP) (European Commission, 2021) and the Water Framework Directive (European Commission, 2020) and is implemented through national programmes, such as the Rural Development Programme (Ministry of Agriculture and Forestry, 2014). The

45   management focuses largely on the main agricultural areas in southern and western Finland (Ministry of Agriculture and Forestry, 2014), where major river basins drain to the Baltic Sea, and includes targeting of erosion mitigation measures, such winter-time vegetation cover, reduced soil tillage, vegetated buffer zones along streams and rivers, and perennial grass type vegetation covers. The targeting of these measures is implemented through natural constraint and environment payments to the farmers.

50   Despite the considerable management efforts, the agricultural loading to surface waters has not reduced substantially (Räike et al., 2020; Tattari et al., 2017). In the case of erosion, a major limitation has been the lack of spatial data on distribution of erosion risk, which have led to formulation of agricultural policies and programmes with limited knowledge on spatial variability of erosion risk. For example, the current targeting of mitigation measures is based on broad regions of eight river basin districts (Alahuhta et al., 2010) with less consideration of local conditions. The modest achievements in the erosion

55   control are also partially influenced by changes in climate and weather (Räike et al., 2020), and it is likely that the erosion rates will be further influenced by the climate change (Panagos et al., 2021). These highlight the importance of improving the erosion management, and a country-wide understanding of spatial distribution of erosion risk through high-resolution data is paramount in such efforts.

Local erosion risk can be reliably estimated with various methods but generating reliable and spatially extensive erosion

60   data is still a challenge. Direct empirical measurement campaigns provide the most accurate information on erosion and sediment loads but are costly and infeasible for production of large-scale data. Process-based computational models have shown reasonable capability to describe the erosion and sediment transport process dynamics at monitored sites (e.g. Borrelli et al., 2021; Turunen et al., 2017; Warsta et al., 2013; Jarvis et al., 1999; Wicks and Bathurst, 1996), but they are also infeasible

for large scale data production due to high computational requirements. In contrast, simplified models, which aim to estimate

65   erosion based on a few dominating factors, provide efficient means to estimate large scale spatial distribution of erosion. 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 have shown capability to reproduce annual loads in different land-use, topographic and hydrometeorological conditions (Batista et al., 2019; Estrada-Carmona et al., 2017), including the high-latitude boreal conditions (Lilja et al., 2017a).

70   Based on the above premises, the goal of this study was to produce a publicly available high-resolution erosion risk data for agricultural lands of Finland, and thereby to demonstrate the importance of considering the variability of the erosion risk for achieving effective erosion management outcomes. The goal was achieved by 1) estimating erosion risk at two-meter resolution using RUSLE, 2) analysing spatial variability of erosion risk and its management over different spatial scales, and finally 3) providing recommendations for policy development and future research. This work was well in line with targets of

75   the national programme on enhancing the effectiveness of water protection (Ministry of the Environment, 2021), and with the targets of EU's Common Agricultural Policy (European Commission, 2021), Water Framework Directive (European Commission, 2020), and the European Green Deal (Montanarella and Panagos, 2021).

2 Methodology

The estimation of agricultural erosion was based on the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997;

80   Wischmeier and Smith, 1978), and three different types of average erosion estimates were calculated for the Finnish agricultural lands, based on average weather during 2007-2013 (Fig. 1):

- *Erosion susceptibility (kg ha⁻¹yr⁻¹)* of all land areas, which describes the erosion risk according to rainfall erosivity, topography and soil erodibility, excluding the effects of vegetation cover and soil management
- *Potential erosion risk (kg ha⁻¹yr⁻¹)* of agricultural lands, which describes the highest potential erosion corresponding

85   to bare fallow land without sub-surface drainage.

- *Actual erosion risk (kg ha⁻¹yr⁻¹)* of agricultural lands, which describes the erosion under agricultural practices of the year 2019, including the prevailing sub-surface drainage

These estimates were derived through a modelling framework consisting of calculation of soil erosion susceptibility in two-meter resolution for all land areas (A, Fig. 1), calibration of RUSLE at seven experimental fields (B), testing of calibrated

90   RUSLE at five small catchments and at fourteen large river basin (C), estimation of potential erosion risk for all arable lands (D), and estimation of the actual erosion risk of all arable lands (E). In addition, an *Erosion Management Index (EMI) (-)* was developed and used to estimate the effectiveness of erosion mitigation measures.
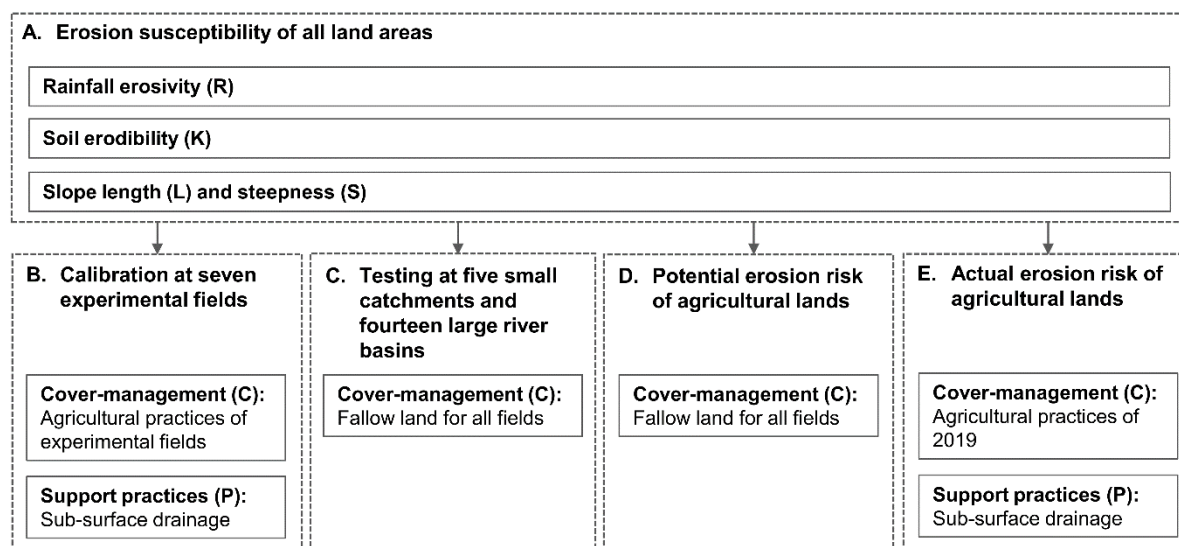
Figure 1: The RUSLE modelling framework. See Tab. 1 for description and sources of data needed for the different RUSLE factors R, K, L, S, C and P.

The resulting data were then analysed spatially. The potential erosion risk was analysed at sub-basin scale, to identify differences in erosion risks within the landscape. The actual erosion risk and the EMI were analysed at municipal level to provide administratively relevant information for managing erosion.

The following sections provide general introduction to RUSLE and a detailed explanation of the modelling framework and the used data. Additional information is presented in supplementary material.

2.1 Revised Universal Soil Loss Equation (RUSLE)

The RUSLE (Eq. 1) is an empirical model for estimating soil loss due to water erosion (Renard et al., 1997; Wischmeier and Smith, 1978). The RUSLE equation is (Eq. 1)

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

where E is the annual average erosion (t ha^{-1} yr^{-1}), R is the rainfall erosivity factor [MJ mm ha^{-1} h^{-1} yr^{-1}], K is the soil erodibility factor (t ha h ha-1 MJ-1 mm-1), L is slope length factor (dimensionless) and S is the slope steepness factor (dimensionless), C is the cover-management factor, and P is the support practices factor which accounts for erosion control practices, such as buffer zones, contour tillage and sub-surface drainage. The dimensionless C and P factors vary from near 0 to 1.

While the other factors are described with single factor values, the cover-management factor (C) consists of sub-factors (Eq. 2),

$$C = C_{crop} \times C_{management} \tag{2}$$

where C_{crop} accounts for the influence of crops on erosion, and $C_{management}$ accounts for the influence of management practices on erosion (Panagos et al., 2015b). The C_{crop} and $C_{management}$ sub-factors are dimensionless and vary from near 0 to 1.

The $C_{management}$ is further divided to sub-factors (Eq. 3)

115 $\quad C_{management} = C_{tillage} \times C_{residues} \times C_{cover}$, $\hspace{6cm}$ (3)

where $C_{tillage}$, $C_{residues}$ and C_{cover} quantify the effects of tillage, plant residues and cover crops on erosion, respectively (Panagos et al., 2015b). In this study, the $C_{residues}$ was not considered due to lack of data.

2.2 Erosion susceptibility

The erosion susceptibility is described with the R, K, L, S factors, and their values were set for all land areas of Finland at two-

120 meter scale using spatial data as described below. The calculated erosion susceptibility was used in calibration at experimental fields, testing at catchments and river basins, and in estimation of the potential and actual erosion data (Fig. 1).

The R factor was taken from a 1 km resolution gridded European scale dataset that is based on observational data (Panagos et al., 2015a). For Finland, R is calculated from hourly precipitation data measured at 64 stations covering a period of 2007-2013. The average R-value for Finland is 273 MJ mm ha^{-1} t^{-1}yr^{-1} with annual average precipitation of 660 mm, while the

125 European average is 722 MJ mm ha^{-1} t^{-1}yr^{-1}.

The K factor was taken from Finnish Soil Database (Lilja et al., 2017c; Lilja and Nevalainen, 2006) supplemented with soil specific K values (Lilja et al., 2017a, 2017b). The soil database is a vector data with scale of 1:200 000 and the smallest feature in the data is 6,25 ha. The K values are based on calibration of ICECREAM model for Finnish soils (Rekolainen and Posch, 1993), except for clay soils. For the clay soils, the K value is derived from field studies in Poland (Lilja et al., 2017a;

130 Święchowicz, 2012). The soils of Finnish Soil database and the soil specific K values are shown in Tab. S1.

The L and S factors were calculated in this study from a two-meter resolution LiDAR-based digital elevation model (DEM) of Finland (National Land Survey of Finland, 2020). A combined LS-factor was calculated with SAGA-GIS Module LS Factor (Conrad, 2003) using the method of Desmet and Govers (1996) with default settings. The DEM was used as such and it was not treated for sinks, as it would have introduced more errors. For example, filling of sinks would fill fields up to the level of

135 nearby roads, and breaching would create artificial erosion areas in the fields. For the LS calculations Finland was divided in 301 units and these were based on river basins, sub-basin groups (Finnish Environment Institute, 2010), and in offshore areas on groups of multiple islands (Fig. S1).

The R factor was resampled, and the K factor was rasterised to the same two-meter resolution as the LS factor data using bilinear (R) and nearest neighbour (K) interpolation methods. The rasterised K-factor data was also extrapolated (nearest

140 neighbour method) to account for finer details of shorelines of water bodies, as the scale of the Finnish Soil Database does not describe the shorelines in detail.

The erosion susceptibility for all land areas of Finland was then calculated by multiplying the R, K and LS factor data. The erosion susceptibility data for agricultural areas was thereafter extracted using the field parcel data from Finnish Food Authority. The calculations were done in high-performance computing environment (CSC - IT Center for Science, Finland)

145 using RSAGA (Brenning et al., 2018) and terra (Hijmans et al., 2021) libraries of the R (R Core Team, 2020). The used data is summarized in Tab. 1.

Table 1: Summary of the data used for RUSLE factors R, K, LS, C and P.

Data	Description and source
Rainfall erosivity (R)	European rainfall erosivity data with 1 km resolution (Panagos et al., 2015a). Data for Finland is calculated using 60 min precipitation data from 64 stations over the period 2007-2013.
Soil erodibility (K)	A Finnish soil database (Lilja et al., 2017c; Lilja and Nevalainen, 2006) with soils classified according to World Reference Base for soil Resources (IUSS Working Group WRB, 2015) and with soil specific K factor values (Lilja et al., 2017a, 2017b) (Tab. S1).
Topography (LS)	Calculated in this study from LiDAR-based two-meter resolution digital elevation model (DEM) (National Land Survey of Finland, 2020) using the method of Desmet and Govers (1996).
Cover-management (C)	Calibration: Crops and management from the experimental field data (Finnish Environment Institute, 2019; The Field Drainage Research Association) (Tab. 2).
	Actual erosion risk: Crops and management from the field parcel data for 2019 (Finnish Food Authority). The data contains the crop and vegetation cover for over two million georeferenced field parcels. The erosion reduction measures of reduced autumn tillage and winter-time vegetation cover are also indicated.
Support practices (P)	Sub-surface drainage status of fields based on drainage plans up to year 2017 (Finnish Field Drainage Association).

2.3 RUSLE calibration and testing

150 The RUSLE was calibrated at seven monitored field sites with year-round soil loss measurements (Tab. 2, Fig. S2). Aurajoki, Liperi, Kotkanoja, Nummela and Toholampi sites are experimental fields with multiple plots and practices, while Gårdskulla and Hovi sites are single field areas in normal agricultural use. The fields have varying soil and topographical conditions, and all, except Aurajoki site, were subsurface drained during the measurement campaigns (Tab. 2).

The fields were under different crops and management practices during the measurements, including spring cereals (wheat,
155 oat, barley) with conventional autumn ploughing, shallow autumn stubble tillage, autumn cultivator tillage, no autumn till (winter-time stubble) and direct sowing (winter-time stubble); winter cereals (wheat, rye); perennial grass; and perennial pasture. From the data, each crop and management practice with a minimum of four years of measurements was included in the calibration. This provided 20 crop and management cases that were divided to six treatment groups for the calibration: cereals with autumn ploughing, cereals with reduced autumn tillage, cereals with winter-time stubble, winter cereals, perennial
160 grass and perennial pasture (Tab. 4).

The model was calibrated against the average annual soil loss of the measurement periods. The sum of soil loss via surface and sub-surface drainage was considered, as a large share of the eroded material can be transported from the soil surface via

subsurface drains in structured soils (Warsta et al., 2013; Uusitalo et al., 2001; Øygarden et al., 1997; Turtola and Paajanen, 1995).

165   The C factor was chosen as the calibration parameter as the sensitivity analyses show that the C factor is the largest source of uncertainty (Estrada-Carmona et al., 2017) and it can vary by location depending on cultivation practices (Hudson, 1993). Therefore, in the calibration the difference between the RUSLE erosion estimates and the measured soil losses was minimized by adjusting the C value of each treatment group with least squares method.

The sub-surface drainage was considered in the P factor. The research on the effect of sub-surface drainage on erosion is

170   limited, but studies in the North-Western US found a reduction effect of 28-51% (Formanek et al., 1987; Istok et al., 1985). A study in Finland in turn found that substituting of old drainage pipes with new ones reduced erosion up to 15% on a clay soil (Turtola and Paajanen, 1995). In this study, however, a reduction effect of 40% (P=0.6) was used, following Lilja et al. (2017a).

Table 2: Fields with soil loss (kg ha⁻¹ yr⁻¹) measurements used for calibrating RUSLE.

Field	Description	More detailed field description / data source
Aurajoki (F1)	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, erosion 570 (perennial grass) - 2100 kg ha⁻¹ yr⁻¹ (cereals with autumn ploughing)	Puustinen et al. (2005) / Finnish Environment Intitute (2019)
Gårdskulla (F2)	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, erosion 751 kg ha⁻¹ yr⁻¹ (perennial pasture)	Turunen et al. (2017) / The Field Drainage Research Association
Hovi (F3)	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, erosion 640 kg ha⁻¹ yr⁻¹ (cereals with autumn ploughing)	Bengtsson et al. (1992) / Finnish Environment Intitute (2019)
Kotkanoja (F4)	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, erosion 541 (perennial grass) - 987 kg ha⁻¹ yr⁻¹ (cereals with autumn shallow stubble tillage)	Uusitalo et al. (2018) / Finnish Environment Intitute (2019)
Liperi (F5)	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, erosion 55 (perennial grass) - 125 kg ha⁻¹ yr⁻¹ (cereals with autumn ploughing)	Kukkonen et al. (2004) / Puustinen et al. (2010)
Nummela (F6)	Southern Finland (60.8660°N, 23.4300°E), slope 0.8%, Stagnosol (clay), single field 9 ha, sub-surface drained, data period 2007-2016, erosion 1245 kg ha⁻¹ yr⁻¹ (cereals with autumn cultivator tillage)	Äijö et al. (2018) / The Field Drainage Research Association

| Toholampi (F7) | 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, erosion 195 (no autumn till) - 380 kg ha^{-1} yr^{-1} (cereals with autumn ploughing) | Turtola ja Kemppainen (1998) / Finnish Environment Institute (2019) |

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The validation of erosion models, such as the RUSLE, is typically difficult and rarely done mainly due to limitations in data availability (Batista et al., 2019). To get an indication of the performance of the RUSLE on larger spatial scales, the current model was tested at river basin and small catchment scales against total suspended solid measurements (TSS) from streams and rivers. The test was done by analysing the statistical relationship of estimated potential erosion risk (t yr^{-1}) of agricultural

180   lands by RUSLE and measured average TSS (t yr^{-1}). However, this test is considered only indicative of RUSLE's performance due to three reasons. First, the potential erosion risk describes only erosion from agricultural lands, whereas TSS measurements account for erosion from all land uses. Second, potential erosion risk emphasizes the source of erosion rather than later phases of the erosion-transport-sedimentation process that affect actual TSS quantities in rivers. Third, the agricultural practices have varied in the catchments and basins over the TSS measurement periods that could not be accounted for, and therefore, the

185   potential erosion risk was used. Despite these limitations, the test provides useful information for understanding the performance of the RUSLE beyond the calibration conditions and in a larger scale, but it is noteworthy that it does not equal model validation.

The test catchments and basins were selected so that the share of agricultural land was higher than 10% of total and large lakes and major dams with reservoirs were absent, since these surface water features reduce the transport of sediments and

190   would reduce the commensurability between the measurements and the model outputs. Data was available for five small catchments with sizes varying from 5.3 to 15.2 km^2 and share of agricultural land varying from 17 to 63% (Tab. S2 and Fig. S2) (Finnish Environment Institute, 2019). For river basins, data was available for 32 river basins from which 14 filled the criteria defined above. The 14 selected basins varied in size from 566 to 3095 km^2 and the share of agricultural land varied from 11 to 43% (Tab. S2 and Fig. S2) (Finnish Environment Institute, 2019). The measurements spanned from one to three

195   decades and the agricultural practices in the catchments varied and evolved in time.

2.4 Potential erosion risk

The potential erosion risk (kg ha^{-1} yr^{-1}) describes the maximum potential erosion of agricultural land, which was defined here as bare fallow land without sub-surface drainage. Bare fallow is as land that is not under crop rotation and has no planted vegetation cover. The potential erosion risk was calculated from the erosion susceptibility data by multiplying it with a C factor

200   value of 0.5 suggested for bare fallow land by the literature (Panagos et al., 2015b). The resulting two-meter resolution potential erosion risk data allows a spatially consistent analysis of erosion risk without the effects of crops and management.

In this study, the data was analysed at 2 m resolution at two case study areas, and at sub-basin scale for the whole Finland. In addition, the potential erosion risk was analysed in the proximity (< 50 m) of main water bodies that were defined according to the stream network, river area, and lake area data (Finnish Environment Institute, 2010).

2.5 Actual erosion risk

The actual erosion risk (kg ha^{-1} yr^{-1}) was calculated using the erosion susceptibility data and by considering the agricultural practices of 2019 in the C factor and the sub-surface drainage in the P factor. The calculation of the actual erosion risk was done by using average value of the erosion susceptibility for each field parcel and by multiplying this with field parcel specific C and P values. The resulting data is a vector data with actual erosion risk estimate for each field parcel.

The agricultural practices of 2019 were taken from the field parcel data of Finnish Food Authority, which contains field parcel specific information on cultivated crops and erosion reduction measures, including reduced autumn tillage, winter-time vegetation cover and buffer zones. The data are collected annually from farmers through government controlled self-reporting process, and it is also the basis for payment of agricultural and environmental subsidies. According to this data, Finland had 2,34 million hectares of agricultural land with 1,09 million field parcels with 212 different crop and vegetation cover types.

The crops in the field parcel data were parametrised in the C_{crop}, and the calibration provided values for 89% of the agricultural area (cereals and grasses). The literature (Panagos et al., 2015b) provided further C_{crop} values for many crops, but not for all. Remaining crops were divided to groups according to their similarities and a C_{crop} value of most similar crop in the RUSLE calibration or literature were assigned for those. For example, all large root vegeTab.s were placed in the same group and they were given the C_{crop} value of potato and sugar beet in the literature (Panagos et al., 2015b). There were still few annual crops that could not be given C_{crop} values according to calibration and literature, and for these, calibrated C_{crop} value of cereals was used. The parameterisation is summarized in Tab. 3.

The erosion reduction measure of reduced autumn tillage was parametrised in the $C_{tillage}$. The $C_{tillage}$ of normal, conventional autumn ploughing was assumed to have a value of 1, similarly to Panagos et al. (Panagos et al., 2015b), and the $C_{tillage}$ for reduced autumn tillage was defined as the ratio of calibrated C value of cereals with reduced autumn tillage (cultivator, shallow stubble tillage) and C value of autumn ploughing.

The winter-time vegetation cover was parametrised in the C_{cover} and it was defined as the ratio of calibrated C value of cereals with winter-time stubble (no autumn till, direct sowing) and C value of normal autumn ploughing. Thus, in the calculation of actual erosion risk the winter-time vegetation corresponds to winter-time stubble. However, in the field parcel data the winter-time vegetation cover can consist of different types, including grasses, stubble, vegetation covered fallow, over-wintering vegetation and perennial plants, but these were not distinguished in the data.

The subsurface drainage data was from the Finnish Field Drainage Association and it contained information on drainage status of field parcels. It is based on regional reporting that has been arranged into a database. The data is the best available on field parcel level with adequately comprehensive coverage, but it may lack information on drainage status of some individual fields. The P factor value of 0.6 was used for the sub-surface drainage, similarly to Lilja et al. (2017a) and RUSLE calibration.

235   The retention effect of buffer zones is typically considered in the P factor, but due to limitations in the data this could not

to be considered in the calculation of actual erosion risk. The retention effect refers to retention of eroded soil and solids that

are transported by overland flow from the uphill field area over the buffer zone. The field parcel data identifies buffer zones

as individual field parcels, but it does not identify the field parcel from which the buffer zone is intended to capture the eroded

and transported soil and solid material. In addition, entire fields have been classified as buffer zones in the field parcel data

240   due to regulatory issues. Therefore, an analytical and systematic approach for quantifying retention effect was not possible.

The vegetation cover of buffer zone areas themselves was, however, considered in the C_{crop}, and calibrated C_{crop} value of grass

was used.

After the calculation of actual erosion risk data, it was analysed on municipal level, which is a suitable administrative level

from policy perspective. The vector data was first rasterized to 10 m resolution before calculating zonal statistics for municipal

245   areas.

Table 3: Summary of the parametrisation of C and P factors for calculation of actual erosion risk.

Field parcel variable	Factor	Description
Crops and vegetation cover	C_{crop}	Calibration provided 89% of C_{crop} values for crops while literature (Panagos et al., 2015b) provided values for several crops. Some crops were given C_{crop} according to their similarity with crops for which C_{crop} was available (e.g., large root vegetables). For a few crops C_{crop} values could not be given according to calibration or literature, and calibrated C_{crop} value of cereals was used.
Reduced tillage	$C_{tillage}$	$C_{tillage}$ was defined as ratio of calibrated C of cereals with reduced tillage (shallow stubble tillage, cultivator) and calibrated C of cereals with autumn ploughing.
Winter-time vegetation cover	C_{cover}	C_{cover} was defined as ratio of calibrated C of cereals with winter-time stubble (no autumn till, direct sowing) and calibrated C of cereals with autumn ploughing.
Sub-surface drainage	P	P value of 0.6 was used similarly to Lilja et al. (2017a)
Buffer zones	C_{crop}	Calibrated C_{crop} of grass was used for buffer zone areas. The retention effect could not be considered.

2.6 Erosion Management Index

250   A quantitative Erosion Management Index (EMI) was developed to estimate the level of erosion management over specific areas. The index is dimensionless, and it varies from 0 to 1. Higher values indicate that the area is closer to minimum potential erosion and thus the erosion management efforts are more effective. The EMI can be calculated as (Eq. 4)

$$EMI_i = (E_{max,i} - E_i)/(E_{max,i} - E_{min,i}),$$ (4)

where EMI_i is the index value for an area i, $E_{max,i}$ is the maximum and $E_{min,i}$ is the minimum potential erosion (kg/ha/yr), and

255   E_i is the crop and management specific erosion (kg/ha/yr). The E_{max}, E_{min} and E_i can be defined case specifically. The strength of the index is that it can be used for spatially and temporally consistent evaluation of erosion management.

In this study, the E_{max} was defined as the calculated potential erosion risk, corresponding to field conditions with bare fallow land and with no sub-surface drainage. E_{min} was defined as erosion under field conditions with perennial grass cover and with sub-surface drainage. The E_i was defined as the calculated actual erosion risk, which meant that the erosion

260   management measures considered in the *EMI* were crop and vegetation cover type, winter-time vegetation cover, reduced tillage, and sub-surface drainage. The buffer zones were considered only partially, as in the actual erosion risk.

The calculated EMI was then analysed on municipal level together with the agricultural area data from field parcel data (Finnish Food Authority) and with the calculated actual erosion risk data. The used methods included Pearson's linear correlation (Pearson, 1920), Kendal's rank correlation (Kendall, 1975) and Welch's t-test (Welch, 1951).

265   ## 3 Results

3.1 RUSLE performance

The overall RUSLE performance was reasonable, although with some limitations. The calibrated RUSLE estimated erosion relatively accurately at five experimental fields – Aurajoki, Gårdskulla, Hovi, Liperi and Toholampi – and underestimated it at two clayey experimental fields – Kotkanoja and Nummela – as shown in Tab. 4. The mean error at the five accurately

270   estimated fields was -2% and varied from -43 to +22%, and at the two underestimated fields the errors were -90 and -49%. The R^2 for all seven fields was 0.75 (p-value < 0.000) (Fig. S3A), and for the five relatively accurately estimated fields 0.98 (p-value < 0.000). The average ratio of all estimated to measured erosion rates of the seven fields was 0.83.

Table 4: Measured and estimated erosion rates at seven experimental fields (Tab. 2 and Fig. S2).

Crop and tillage management	Field	Treatment	Measured [kg ha⁻¹ yr⁻¹]	Estimated [kg ha⁻¹ yr⁻¹]	Error [%]
Spring cereals with autumn ploughing	Aurajoki	Normal ploughing	2100	2213	5 %
	Liperi	Normal ploughing	125	146	16 %
	Toholampi	Normal ploughing	380	329	-13 %
	Kotkanoja	Normal ploughing	968	489	-49 %
	Hovi	Normal ploughing	640	638	0 %

Cereals with reduced autumn tillage	Aurajoki	Shallow stubble tillage	1420	1699	20 %
	Aurajoki	Cultivator	1760	1699	-3 %
	Kotkanoja	Shallow stubble tillage	987	379	-62 %
	Nummela	Cultivator	1246	125	-90 %
Winter cereals	Aurajoki	Winter wheat	1555	1566	1 %
	Liperi	Winter rye	90	103	14 %
Cereals with winter-time stubble	Aurajoki	No autumn till	790	754	-5 %
	Liperi	No autumn till	80	50	-38 %
	Toholampi	No autumn till	195	112	-43 %
	Aurajoki	Direct Sowing	620	754	22 %
	Kotkanoja	Direct sowing	541	168	-69 %
Perennial grass	Aurajoki	Grass ley	570	571	0 %
	Liperi	Grass ley	55	38	-32 %
	Kotkanoja	Grass ley	631	262	-58 %
Perennial pasture	Gårdskulla	Pasture	720	720	0 %

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The calibrated C values are shown in Tab. 5, and they provide estimates for the effect of crops and management on erosion. According to the C factor values for cereals, winter-time stubble reduces erosion by 66%, reduced autumn tillage by 23%, winter cereals by 29% compared to autumn ploughing. The perennial grass and pasture have 69% and 54% lower erosion than the cereals with normal ploughing, respectively. The C_{cover} for winter-time vegetation and $C_{tillage}$ for reduced autumn tillage

280 that were calculated from calibrated C factor values, are 0.341 and 0.768, respectively (Tab. 5).

Table 5: The calibrated C factor values, and calculated C_{cover} value for winter-time vegetation cover and $C_{tillage}$ values for autumn ploughing and reduced autumn tillage.

Crop and management	Calibrated	Calculated			Panagos et al. (2015b)
	C	C_{crop}	C_{cover}	$C_{tillage}$	
Cereals with normal autumn ploughing	0.211	0.211	-	1	C_{crop}: 0.2, $C_{tillage}$: 1
Cereals with reduced autumn tillage (cultivator, shallow stubble tillage)	0.162	0.211	-	0.768	-
Winter cereals	0.149	-	-	-	-
Cereals with winter-time stubble (no autumn tillage, direct sowing)	0.072	0.211	0.341	-	$C_{tillage}$: 0.25 (no till)
Perennial grass	0.065	-	-	-	C: 0.0273
Perennial pasture	0.097	-	-	-	C: 0.0971

285 The testing of RUSLE against TSS measurements at the five small catchments and fourteen river basins (Tab. S2) indicated good performance at large spatial scales. At the small catchments the R^2 for estimated potential erosion risk and TSS measurements was 0.49 (p-value = 0.1896), but the tau of Kendall's rank correlation was 1.00 (p-value=0.0167). This indicates that while the estimated potential erosion risk deviated from the measurements, RUSLE was able to rank the magnitude of erosion correctly between the catchments. At the river basins the R^2 was 0.90 (p-value < 0.000) and the Kendall's tau 0.78 (p-

290 value < 0.000) (Fig. S3B).

3.2 Potential erosion risk

Samples of the estimated two-meter resolution potential erosion risk data from two neighbouring basins – Karjaanjoki and Paimionjoki – in the Southern coast of Finland are shown in Fig. 2, to exemplify how the potential erosion risk varies in the landscape and between basins. At the Karjaanjoki basin, the average potential erosion risk was estimated to be 4530 kg ha^{-1}

295 yr^{-1}, the average field slope varies between 1.5-5.0° by sub-basin, and high erosion areas are scattered in the landscape. At the Paimionjoki basin, in turn, the average potential erosion risk was estimated to be lower, 2020 kg ha^{-1} yr^{-1}, with lower average slope of 0.4-2.1°, and the areas of highest erosion are concentrated near the river and stream channels.
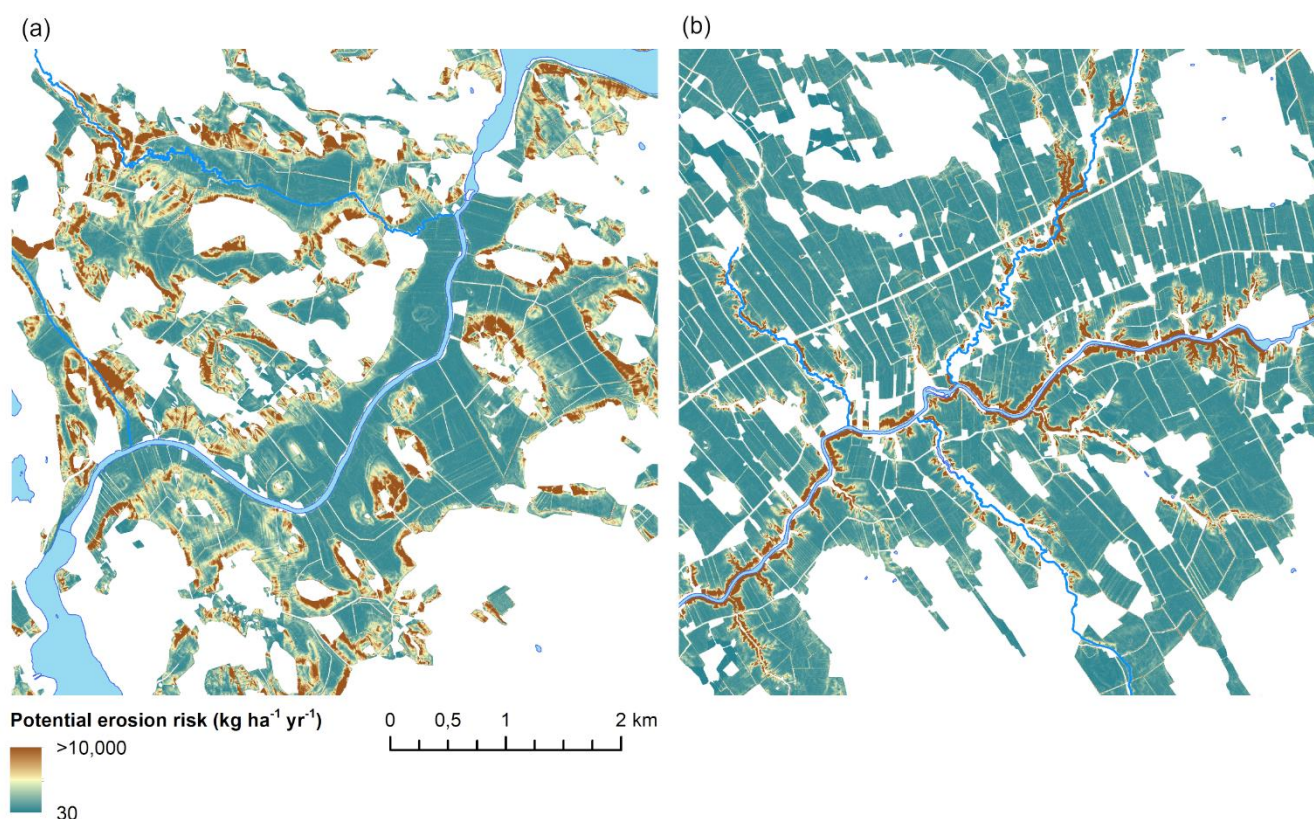
Figure 2: Samples of estimated two-meter resolution potential erosion risk data (kg ha^{-1} yr^{-1}) for agricultural lands in two river
300 **basins in the Southern Finland: a) Karjaanjoki and b) Paimionjoki. White areas are non-agricultural land.**

On the country scale, the average potential erosion risk of agricultural lands was estimated to be 2,010 kg ha^{-1} yr^{-1}, and it varied between 110 and 14,030 kg ha^{-1} yr^{-1} by sub-basin, as shown in Fig. 3. Two high erosion risk regions were identified, one in the central Southern Finland and the other at the coastal area in the South-Western Finland. A large region with relatively low potential erosion risk in turn was found in the coastal area of the central Western Finland.

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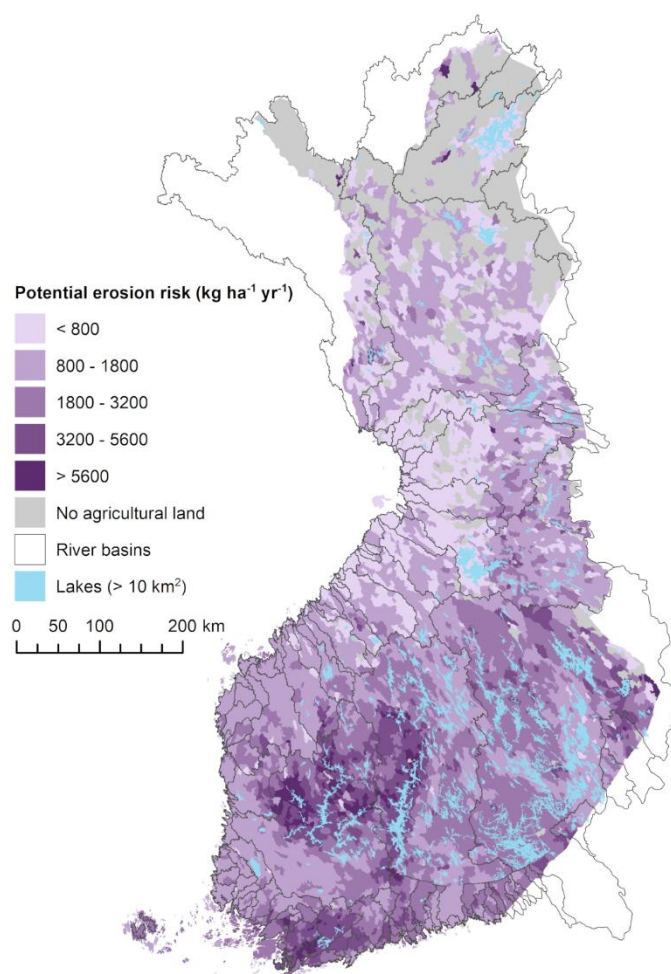
Figure 3: Estimated potential erosion risk (kg ha⁻¹ yr⁻¹) of agricultural lands by sub-basins. Potential erosion risk corresponds to bare fallow land without planted vegetation cover and any erosion mitigation measures (e.g. buffer zones, sub-surface drainage).

The topography of the fields was the most influential factor in the estimation of potential erosion risk. The linear correlation between slope length and steepness factor (LS) and the potential erosion risk at sub-basin level was 0.67 (p-value < 0.000)

310   whereas it was it was 0.51 (p-value < 0.000) for soil erodibility (K) and 0.39 (p-value < 0.000) for rainfall erosivity (R).

The LS factor was also a major contributing factor in the two regions of high erosion risk identified in Fig. 3. The LS factor had heightened values in those same regions as shown in Fig. 4. Similarly, the lower LS factor values in the western coast were contributing to the lower erosion risk in those areas. According to the K factor, large areas of erosive soils were found in the Southwest, and highly erosive soils were found in the western coast, and particularly in the river valleys (Fig. 5b). The

315   areas with highest rainfall erosivity were found in the western coast of Southern Finland (Fig. 5a).
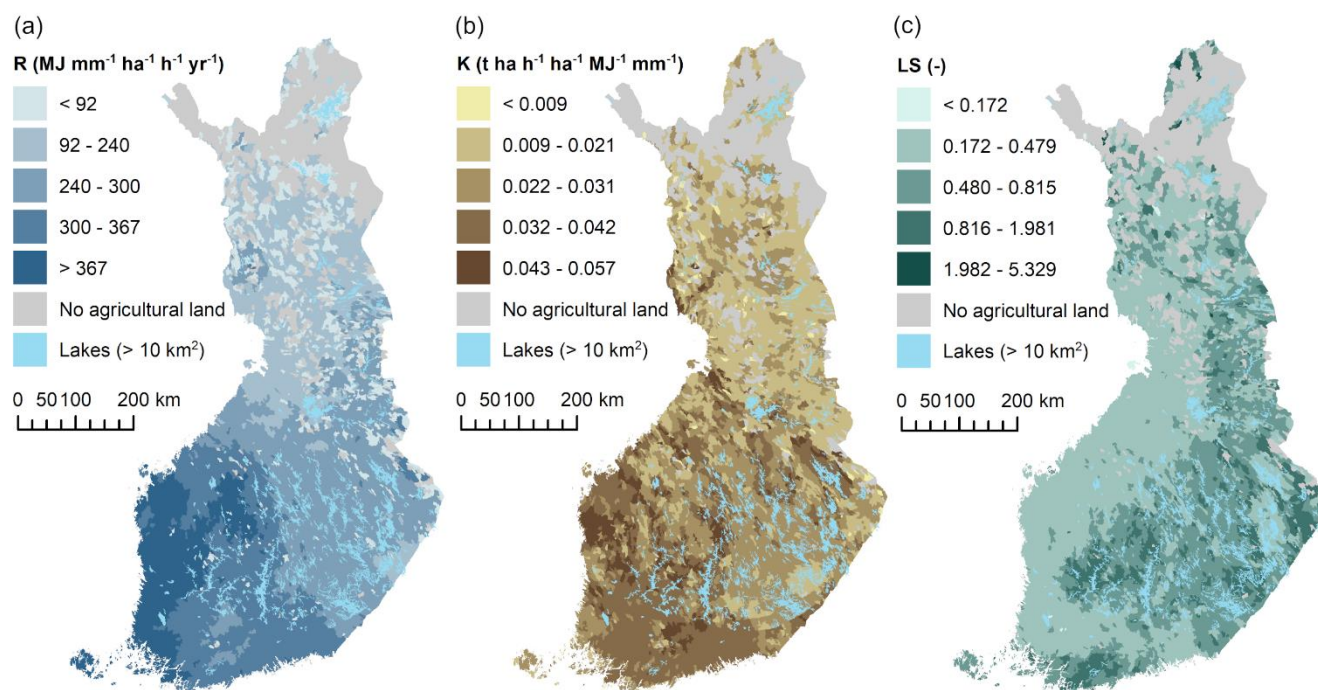
Figure 4: The RUSLE factors for agricultural lands by sub-basin: a) Rainfall erosivity (R) (Panagos et al., 2015a), b) soil erodibility (K) (Lilja et al., 2017b, 2017a) and c) estimated slope length and steepness (LS) factors.

320   The potential erosion risk within 50 m distance from main water bodies was estimated to be on average 3,140 kg ha^{-1} yr^{-1}, which is 1.6 times the average of all agricultural lands. In 10% of the sub-basins this ratio was higher than 2.3, as shown in Fig. 5. The agricultural areas within 50 m distance from main water bodies account for 6% of arable land, but their total erosion risk (t/yr) was 9% of all agricultural lands, which demonstrates their importance as sources of erosion.

       Two regions with considerably higher potential erosion risk near the water bodies were identified, and both are situated by

325   the coast of the Baltic sea (Fig. 5). The largest one is in the Southwest Finland and the smaller in South Finland (Fig. 5). Also, the western coast seems to have several sub-basins with higher potential erosion risk near the water bodies. Southeast Finland in turn has a large region where the erosion is more uniform in all agricultural areas and where lakes form a large proportion of the area. In the Northern Finland, with low proportion of agricultural land, the situation is mixed.

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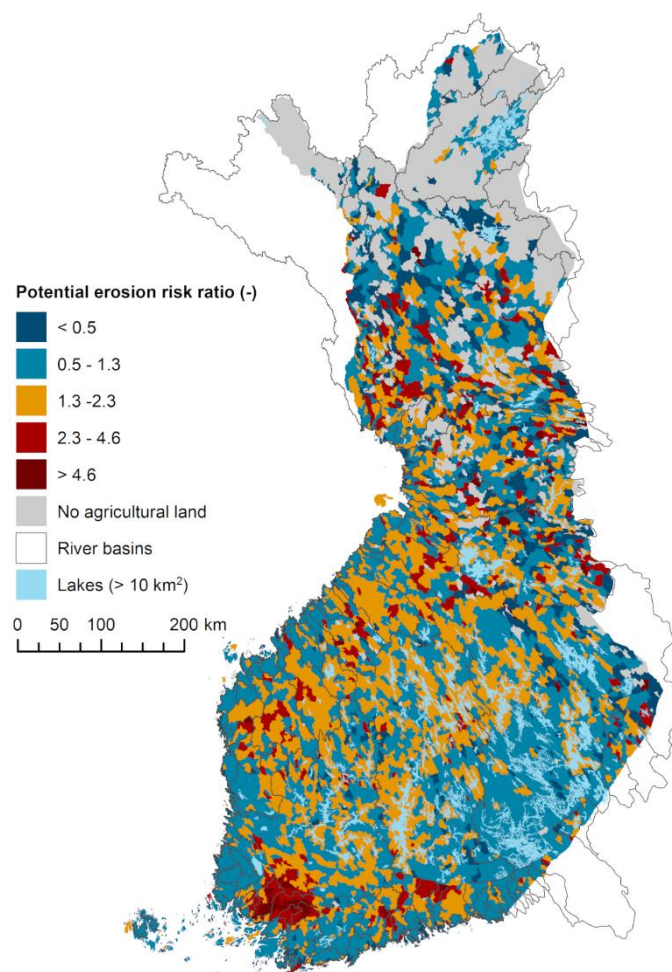
Figure 5: Potential Erosion risk near the main water bodies (<50 m) compared to potential erosion risk of all agricultural lands by sub-catchments. The map values are the ratio of these two, and the values above (below) one refers to higher (lower) erosion risk within 50 m distance from the main water bodies. The main river basins and lakes (>10 km^2) are also shown in the map.

3.3 Actual erosion risk

335 RUSLE estimate for the actual erosion risk with management practices of 2019 was on average 426 kg ha^{-1} yr^{-1} and it varied by municipality from 102 to 1288 kg ha^{-1} yr^{-1} as shown in Fig. 6A (Fig. S4, Tab. S4). The spatial distribution of the actual erosion risk resembled the erosion risk in Fig. 3. The two areas with the highest erosion were similarly detected in central and coastal area in Southern Finland, and a large area with low erosion was also identified in the coastal area in central Western Finland.

340 The estimate for the actual total erosion risk of agricultural land was 985,942 t yr^{-1}, and it varied by municipality from 13 to 33,088 t yr^{-1} (Tab. S4). Majority of the total erosion occurs in Southwest Finland, as shown in Fig. 6B. Agriculture is most intensive in Southern and Western Finland, where over 50% of the land area of some municipalities can be agricultural land.

Individual municipalities with high actual total erosion are also situated in the inland parts of Central Finland. Altogether, 37% of actual total erosion occurred in 10% of the municipalities (n=31) with highest total erosion risk.

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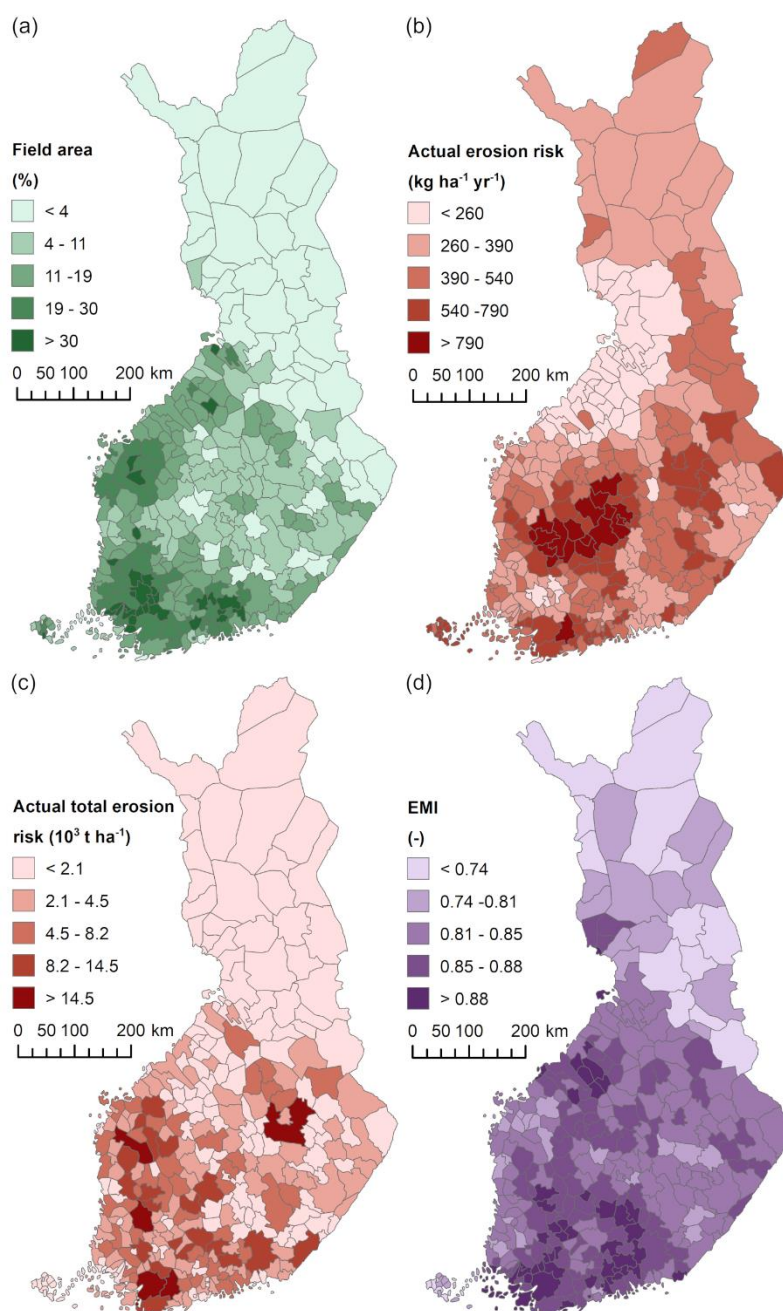
Figure 6: a) Agricultural land area to total land area (%), and estimated b) actual erosion risk (kg ha^{-1} yr^{-1}), c) actual total erosion risk (t yr^{-1}) and d) Erosion Management Index (EMI) at municipal level in 2019. Higher EMI values indicate more effective erosion management.

3.4 Erosion Management Index

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The average EMI of municipalities was 0.84, and the variability between the municipalities was high, ranging from 0.60 to 0.99, as shown in Fig. 6D and Fig. 7 (Tab. S4). The visual examination of EMI values, contrasted with ranked municipalities in Fig. 7 does not reveal strong patterns that would indicate better erosion management in areas with high field area (%), high actual erosion risk (kg ha^{-1} yr^{-1}) or high actual total erosion risk (t yr^{-1}). However, in areas with very low field area (<10%) and

355 actual total erosion risk (<160,000 t yr^{-1}), the EMI values were lower. Most interestingly, the EMI values tend to be lower in municipalities with high actual erosion risk (Fig. 7B), indicating that the erosion management measures have not been targeted according to the erosion risk. Many municipalities with high field area, high actual erosion risk and high actual total erosion risk have also below average EMI values.

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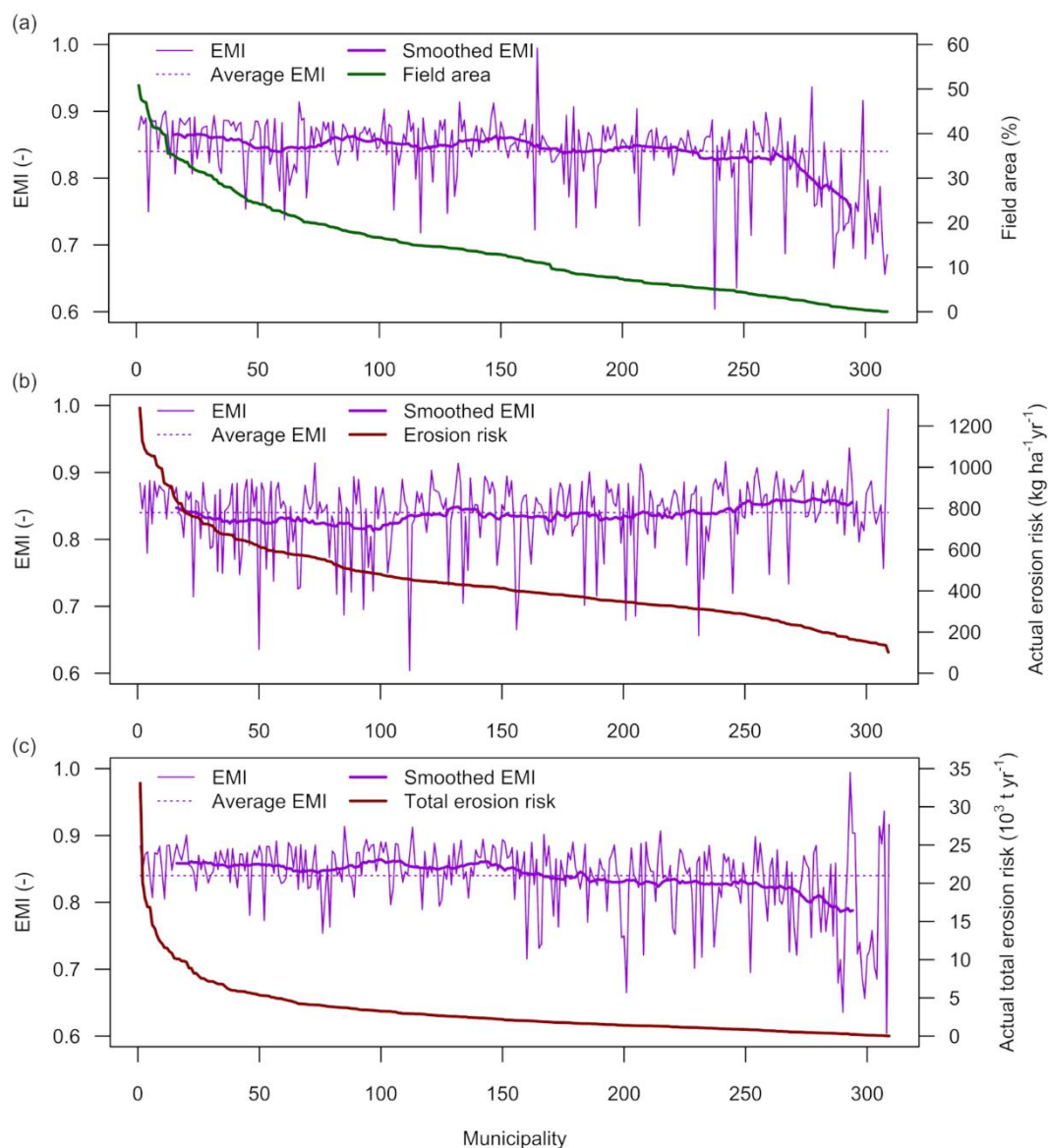
Figure 7: Erosion Management Index (EMI) of municipalities contrasted with ranked a) field area (share of total area, %) b) actual erosion risk (kg ha⁻¹ yr⁻¹) and c) actual total erosion risk (t yr⁻¹). Higher EMI values indicate more effective erosion management. EMI data is smoothed with moving average window (window size=31).

365   The statistical analyses support the visual interpretation of EMI, but they also reveal some statistically significant patterns. Pearson's and Kendal's correlation analyses show statistically significant but weak relationships between EMI (-) and field area (%), and between EMI and actual total erosion risk (t yr⁻¹), but there was no statistically significant relationship between

EMI and actual erosion risk (kg ha^{-1} yr^{-1}), as shown in Tab. 6. This can indicate that erosion management efforts have been targeted slightly more to intensive agricultural areas, but not specifically to areas with high erosion risk.

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Tab. 6. Correlation of the erosion management index (EMI) with field area (%), actual erosion risk (kg ha^{-1} yr^{-1}) and actual total erosion risk (t yr^{-1}) on municipal level (n=309).

	Pearsons' r (p-value)	Kendal's tau (p-value)
Field area (%)	0.36 (< 0.000)	0.3 (< 0.000)
Actual erosion risk (kg ha^{-1} yr^{-1})	-0.05 (0.341)	0.06 (0.09)
Actual total erosion risk (t yr^{-1})	0.24 (< 0.000)	0.2 (< 0.000)

Also, Welch's t-test suggests that the 10% of the municipalities with highest field area (%) and actual total erosion risk (t yr^{-1}) have slightly higher (+2.5% and +4.5%, respectively) EMI values than the rest of the municipalities, but in the case of actual erosion risk (kg ha^{-1} yr^{-1}) the EMI values did not differ between the ranked top 10% and rest of the municipalities, as shown in Tab. 7. This also supports the interpretation that erosion management efforts have been targeted slightly more to intensive agricultural areas, but not to areas with highest erosion risk.

380 **Tab. 7. Comparison of average erosion management index (EMI) of top 10% of municipalities having highest field area, highest actual erosion risk, and highest actual total erosion risk with the average EMI of the rest of the municipalities using Welch's t-test.**

Ranking of municipalities	Average EMI of 90th percentile of the municipalities (n=31)	Average EMI of the municipalities below 90th percentile (n=278)	t-value	p-value
Field area (%)	0.865	0.836	4.287	<0.000
Actual erosion risk (kg ha^{-1} yr^{-1})	0.845	0.838	1.140	0.261
Actual total erosion risk (t yr^{-1})	0.858	0.837	4.050	<0.000

4 Discussion

4.1 Earlier erosion estimates

Large scale model-based erosion research is limited in Finland, but at least three earlier studies exist. A European scale study,
385 based on RUSLE2015, estimated the average erosion of agricultural lands in Finland to be on average 460 kg ha-1 yr-1, and one of the lowest in Europe (Panagos et al., 2015c). National scale studies, based on RUSLE2015 and VIHMA models and crop and management data for 2010, estimated the average erosion to be on average 418 and 485 kg ha^{-1} yr^{-1}, respectively (Lilja et al., 2017b; Puustinen et al., 2010). In our study, the average erosion was estimated to be 425 kg ha^{-1} yr^{-1}, and thus the modelling approaches agree on the average magnitude of erosion in agricultural lands of Finland.

390   The performance of RUSLE in this study was also similar to previous evaluation of RUSLE that was based on calibration with partially same experimental fields (Lilja et al., 2017a). There the model passed the ± 50% error criteria in 72% of the 19 cover and management cases, while in this study, the model passed the same criteria in 76% of the 20 cases. The evaluation of (Lilja et al., 2017a) focused only on erosion via surface runoff and sub-surface drainage was excluded, and therefore, the C factor values were also lower than in our study. The C factor values in the European scale study (Panagos et al., 2015b) were

395   similar, although slightly lower, than in this study, as shown in Tab. 5.

4.2 Uncertainties

The strength of the RUSLE is in its capability to estimate spatial distribution of erosion magnitude within landscapes, and it is shown in this study and in earlier research (Renard et al., 1997; Wischmeier and Smith, 1978) that the emergent long-term bulk erosion magnitude can be a result of the a few dominant controlling factors. However, it is also recognized that the model

400   includes uncertainties rising from a range of generalizations and simplifications in its description of the erosion process, and even validated models are subject to uncertainties when model predictions are conducted (e.g., Højberg and Refsgaard, 2005; Refsgaard et al., 2006). The quantification of the total uncertainties remains as a challenge regarding the large spatial estimates, as well as for model applications at large (Batista et al., 2019; Beven, 2016).

     According to sensitivity analyses, the LS and C factors are the largest sources of uncertainty in RUSLE (Estrada-Carmona

405   et al., 2017). The resolution of DEM for computing the LS factor is known to affect the estimation of slope in gently sloping areas and the estimation of up-slope contributing area in steep areas, and high-resolution DEM's reduce the resulting uncertainty (Gertner et al., 2002). The choice of computation method of LS factor is also found to affect the magnitude of the erosion estimates (Hrabalíková and Janeček, 2017) and the emphasis between rill and inter-rill erosion (Erskine et al., 2006). In this study, the LS factor was computed using a high-resolution DEM (National Land Survey of Finland, 2020) and with a

410   well-established method (Desmet and Govers, 1996), and is therefore expected to provide an adequate description of the LS-factor and a reasonable estimate of the location of high erosion areas within the fields for erosion management purposes.

     The C factor values for crops and management vary by location depending on local conditions and practices (Panagos et al., 2015b) and they may contain uncertainties. However, 89% of the crop area was parameterised according calibration at Finnish experimental fields and, therefore, the parameterisation is largely expected to be representative of Finnish conditions

415   and practices. The parametrisation of winter-time vegetation was, however, based on winter-time stubble (no autumn till), whereas the crop and management data (Finnish Food Authority) considers various cover types as winter-time vegetation cover, but does not specify them.

     The used K factor was based on national 1:200,000 scale soil data (Lilja et al., 2017c; Lilja and Nevalainen, 2006) and it does not capture all local heterogeneities affecting the erosion process. The estimation of K factor values of different soils is

420   also limited in Finland, and the underestimation of erosion observed at Kotkanoja and Nummela fields suggest further research is needed, particularly in the case of heavy clay soils. Likely the soil structure dynamics of clay soils (e.g., Bissonnais, 2016; Turunen et al. 2017) is one source of uncertainties in the estimates regarding the cohesive soils.

The sub-surface drainage was parameterised in the P factor with the support of literature, but the empirical research on the effect of sub-surface drainage on erosion is scarce. The effect of sub-surface drainage is likely to vary depending on the soil

425 and catchment properties as well as the type, condition, and design parameters of the drainage system.

Furthermore, the exclusion of the retention effect of buffer zones in the P factor may have led to overestimation of erosion risk, although the overestimation in this study is expected to be small. A study in Finland, on the effect of 10-m-wide buffer zones at the lower end of a subsurface drained field on clay soil, found that the buffer zones reduced erosion loading via overland flow by 11-58% depending on crop and management types (Uusi-Kämppä and Jauhiainen, 2010). However,

430 according to the experimental field data (clayey soils of Gårdskulla, Kotkanoja, Nummela and sandy soil of Toholampi) used in this study 50-92% of erosion matter is transported via sub-surface drain flow, which corresponds findings in earlier research (Turunen et al., 2017; Warsta et al., 2013; Uusitalo et al., 2001; Turtola and Paajanen, 1995; Øygarden et al., 1997). Thus, at sub-surface drained fields the retention effect is likely smaller than in non-subsurface drained fields, but the effect may vary considerably between fields. Buffer zones can, however, have a significant role in preventing erosion from their own area, as

435 they are often located in sloping lands near water bodies.

Despite these limitations, the calibration of RUSLE at field parcel scale and testing at catchment and basin scales indicate that the results and the developed data are of reasonable quality, and they markedly improve the understanding of distribution of erosion and the possibilities of erosion management in Finland. One of the most promising features of the model application was that the calibration of the RUSLE differentiated well between crops and management types, which provides a good basis

440 development and assessment of different crop and management scenarios. However, certain level of care is needed in the interpretation of data, particularly at the field parcel scale, as the RUSLE underestimated erosion at two of the seven fields.

4.3 Policy and management implications

The results showed considerable spatial variability in erosion risk over multiple spatial scales and this heterogeneity includes large potential to be accounted for in the Finnish agricultural policy and environmental programmes. The results also suggest

445 that the erosion reduction measures have not been targeted efficiently to high erosion risk areas, which is also largely due to lack data on erosion risk. These limitations call for improvements in policy and management, and this study formulates how improvements can be made through an erosion management approach, where

1) the erosion management is guided by spatially explicit erosion risk data,

2) the spatial distribution and magnitude of erosion risk is considered in addition to location and total area of the fields,

450 3) the high erosion risk areas and their sizes and locations are identified with systematic data analysis over multiple spatial scales and erosion management measures are targeted accordingly, and

4) the erosion management measures are chosen and implemented according to the local erosion conditions.

In addition to these, the study provides a generalisation of the effect of different management practices on erosion, that is based on RUSLE calibration with measurement data from seven Finnish experimental fields. In cereal cultivation, the most effective

455 erosion reduction measure was found to be winter-time stubble (-66%), whereas winter cereals (-29%) and reduced autumn

tillage (-23%) were found to be less effective. Perennial grass type vegetation cover, in turn, was found to reduce erosion even more (-69%) than cereals with winter-time stubble. Therefore, in the targeting of environmental measures, winter-time stubble could be preferred over winter cereals as a winter-time vegetation cover. Perennial grass type vegetation cover could be emphasized at field parcels with high erosion risk and potentially highest off-site impacts, such as those with steep slopes near

460   water bodies.

4.4 Future research directions

The uncertainties in the RUSLE erosion estimates can be reduced with further empirical data and consequently by improving the parameterization and model testing approaches. In the Finnish case, the improvement of spatial accuracy of soil data and its parameterisation in the K factor would yield more accurate erosion estimates. Improvements in the parameterisation of

465   erosion mitigation measures in the C and P factor would improve the estimation of the effect of erosion reduction measures.

The RUSLE does not consider sediment transport and approaches, such as the sediment connectivity (Najafi et al., 2021; Heckmann et al., 2018; Bracken et al., 2015) would complement the RUSLE erosion risk estimates and improve the targeting of erosion reduction measures. Sediments are likely to be transported differently from each field parcel to water bodies and to the outlet of the basin, and this may have influence on how the erosion management efforts should be targeted.

470   The developed data enables improved location specific erosion management strategies, and this potential should be further investigated. The current study revealed that the targeting of erosion management measures can be improved, but the erosion reduction potential of such improvements is yet to be quantitatively evaluated.

In addition, the developed RUSLE data provides a basis for estimation of losses of soil bound phosphorous and carbon, and research in these directions would further improve understanding of agricultural loading to water bodies and carbon

475   balances in agricultural soils.

5 Conclusions

A major impediment for efficient agricultural erosion management in Finland has been the lack of comprehensive spatial data on erosion risk, which has affected the formulation of policy and targeting of the erosion reduction measures. This limitation was addressed in this study by developing a two-meter resolution erosion risk data for Finland using RUSLE, and by analysing

480   the spatial distribution of erosion risk and its management in agricultural lands.

The developed data considerably improves the understanding on erosion risk in Finland, and it was found that erosion risk varies substantially in the landscape over multiple spatial scales. The average erosion of agricultural lands was estimated to be 430 kg ha^{-1} yr^{-1} with agricultural practices of 2019, and it varied from 100 to 1290 kg ha^{-1} yr^{-1} by municipality. On more local scales, the erosion risk had even greater variability. The findings also suggest that erosion management has not been well-

485   targeted according to the erosion risk.

The produced data opens a possibility for the policies and programmes aiming for erosion reduction to (1) take advantage of the estimate on spatial distribution of erosion risk, (2) have greater emphasis on erosion risk, (3) consider erosion risk over multiple spatial scales, and (4) support more location specific erosion reduction measures to achieve more effective outcomes. Additionally, the produced data opens possibilities for new research, including the assessment of the loss of soil bound

490 phosphorous and carbon through soil erosion. These directions are applicable also in other regions, in addition to Finland.

The benefits of including modelling approaches in the formulation of policy and planning of are well demonstrated by this study, but the modelling related uncertainties also need to be considered and communicated. Therefore, the inclusion of models is best implemented as part of broader framework, which includes empirical data, comparative models, expertise from different areas, and uncertainty management. The uncertainty in erosion modelling can be reduced by new empirical measurement

495 campaigns, more accurate soil maps, and by further model development.

Data availability. The erosion risk data for agricultural lands will be publicly available through data repositories of Natural Resources Institute Finland (www.luke.fi).

500 *Author contributions.* TAR, SP, and ET conceptualised the study. TAR collected and prepared all data, performed all calculations and analyses, and wrote the initial draft manuscript. MT provided expertise on modelling the erosion processes. JU-K, and ET provided expertise on field measurements data, agricultural practices, erosion processes and erosion mitigation measures. All authors contributed to the writing of the manuscript.

505 *Competing interests.* The authors declare no conflict of interest.

Acknowledgements. The work was funded by Ministry of Agriculture and Forestry of Finland and Natural Resources Institute Finland. The authors also want to acknowledge the work of Harri Lilja on 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

510 parcel data; and Helena Äijö and Jyrki Nurminen from Finnish Field Drainage Association/The Field Drainage Research Association for preparing and providing the measurement data for Gårdskulla and Nummela fields and the data on national sub-surface drainage coverage.

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