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Soil organic carbon, Soil Erosion

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Contents

Abstract

In this report, we evaluate the Common Agricultural Policy (CAP) from the soil perspective and provide baseline data for the two impact indicators (soil erosion, soil organic carbon) related to monitoring soil in the context of the Common Agricultural Policy (CAP).

The Soil Organic Carbon (SOC) stocks across the EU28 for the 2018 were estimated by modelling the changes over a 9-year period from the 2009 baseline (data available in ESDAC) with a statistical model trained with LUCAS soil survey observations. In relation to spatial estimates of SOC stocks, it was observed a marked influence of environmental and site-specific edaphic conditions such as soil clay content. The combined effect of such natural property affecting soil organic carbon directly limits or enhances the potential of carbon sequestration by soil management practices. The mean SOC stock in the EU agricultural areas is about 57.5 t ha^{-1} (croplands mean stock: 46.6 t ha^{-1}; grasslands mean stock: 84.6 t ha^{-1}).

A first-ever assessment at European scale combines the risks of water, wind, tillage and harvesting to reveal the cumulative impact on arable land. It is a basis for developing a comprehensive monitoring system for soil health. This first assessment could be the basis for a composite soil erosion indicator including all erosional processes. Summing up the total soil displacement of all erosional process, we estimate a 575 million tonnes of soil loss. According to our multi-model approach, water erosion is the most dominant erosional process contributing to 51% of the total soil loss in EU and UK. Compared to pre-2000, the soil erosion by water has been reduced by 20% in EU arable lands (reference year: 2016). The soil conservation efforts in the EU focused in a) increasing vegetation cover in arable lands through the year and b) reducing the tillage intensity.

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The authors are thankful to contributors of LUCAS topsoil dataset and the EU Soil Observatory. The authors would like to thank Dr. Pasquale Borrelli (Roma Tre University) for his contribution in wind and tillage erosion. Many thanks also to Leonidas Liakos for his technical support.

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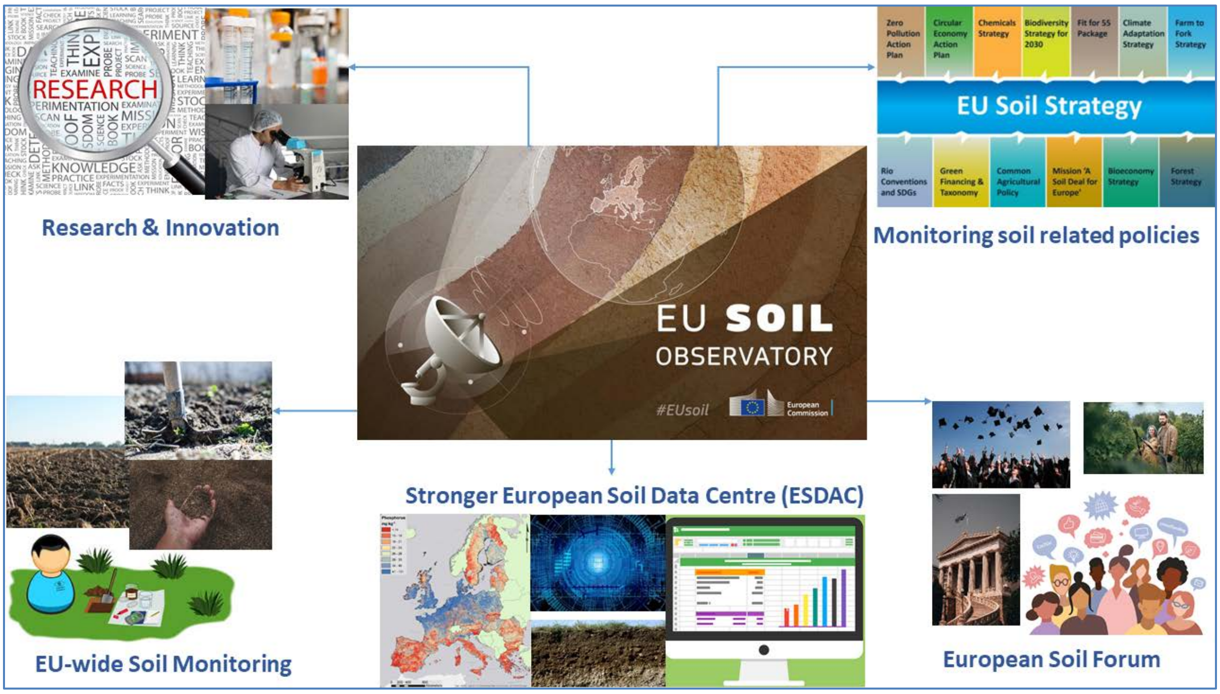
1 Introduction

Soil is essential for life and represents the key element to grow crops that feed people and animals. Agricultural practices influence soil viability, while agriculture is heavily dependent on soil quality. The Common Agricultural Policy (CAP) is a key EU land management policy and a central driver for the management of agricultural land. In the current CAP, under cross-compliance rules, the beneficiaries of the CAP have their payments linked with crop diversity, non-permanent Ecological Focus Areas and good agricultural and environmental conditions (GAECs) such as minimum soil cover, minimum land management to limit erosion and maintenance of soil organic matter (Carey, 2019; Borrelli et al., 2016).

Among the key priorities for the CAP 2023–2027, the support for the sustainable growth of food production and the greener farm practices through eco-schemes are particularly relevant to soils. Under these schemes, specific payments will be provided to farmers that adopt climate-sensitive and nature-sensitive practices in line with the European Green Deal objectives. Examples of these actions include organic farming, crop rotation, and preservation of carbon rich soils. In the CAP 2023–2027, the enhanced conditionality includes more GAECs relevant to soil protection such as: protection of wetlands/peatlands, minimum soil disturbance and crop rotation.

The recently established EU Soil Observatory will support the implementation of the soil related EU policies, such as the EU Soil Strategy 2030, monitoring of agricultural soils in the context of the Common Agricultural Policy (CAP) or the Clean Soil Outlook of the Zero Pollution Action Plan (Figure 1).

Figure 1. *The objectives of the EU Soil Observatory.*



The European Commission has set up the common monitoring and evaluation framework (CMEF) to assess the performance of the 2014-20 common agricultural policy (CAP) and improve its efficiency (Matthews, 2020). A transitional regulation was introduced extending most of the 2014-20 CAP rules until the end of 2022. To ensure proper monitoring and evaluation, the political objectives must be related to the planned measures. The CAP objectives include among others the stainable management of natural resources and climate action, with a focus on greenhouse gas emissions, biodiversity, soil and water. In the current CMEF, a number of indicator types were defined to support the assessment of the CAP's performance (Context Indicators). This includes Indicator C40 "Soil organic matter in arable land" which estimates the total organic carbon content in arable soils and Indicator C41 "Soil erosion by water" which access the rate and agricultural area affected by water erosion (CMEF, 2022).

On the 6 December 2021, Regulation (EU) 2021/2115 of the European Parliament and of the Council establishing rules on support for CAP Strategic Plans was adopted. This regulation establishes the performance monitoring and evaluation framework (PMEF), which applies for the CAP from 2023 until 2027. The PMEF supports the shift in policy focus from compliance with rules to performance and results. This new performance-based delivery model uses a set of common performance indicators. This new framework includes a set of common performance indicators which will be used to assess the overall policy performance against CAP objectives. In the new PMEF, the indicators relevant to soil are C.40 "Soil organic carbon in agricultural land" (ex C.41) and C.41 "Soil erosion by water" (ex C.42).

2 Soil Organic Carbon

Healthy soils will make the EU more resilient and reduce its vulnerability to climate change. The new EU Soil Strategy aims to increase the soil carbon in agricultural land, combat desertification, restore degraded land and soil, and ensure that by 2050, all soil ecosystems are in a healthy condition. Increasing the depleted SOC stocks can represent an important step towards the development of more sustainable agricultural systems. Therefore, the quantification of current SOC stocks and possible future trends in the EU is paramount in the preparation and evaluation of agricultural policies that aim at enhancing the resilience of EU agricultural systems.

2.1 Policy context

The EU has put as a priority the Fit for 55 package has the aim of ensuring that EU policies are in line with the climate goals agreed by the Council and the European Parliament. This is translated in the EU's target of reducing net greenhouse gas emissions by at least 55% by 2030 (compared to 1990 levels). The European Climate Law sets the goal for Europe's economy and society to become climate-neutral by 2050 (Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999.

The EU's Common Agricultural Policy (CAP) objectives include a contribution to climate change mitigation and adaptation, by reducing greenhouse gas emissions and enhancing carbon sequestration, as well as promoting sustainable energy.

The earth's soils contain two to three times more carbon than the atmosphere. The potential of soils to store carbon is enormous and can be targeted with specific land management practices. Soil organic carbon, the major component of soil organic matter, is extremely important in all soil processes. Organic matter in the soil is essentially derived from residual plant tissues, while microbial, fungal and animal contributions constitute a small part of its total amount. Microbes, fungi and animals decompose organic matter more or less efficiently depending on temperature, moisture and ambient soil conditions.

In this context, the EU Commission strengthens the contribution of the land use, land-use change and forestry (LULUCF) sector to the EU's increased overall climate ambition and recognizes the need to reverse the current declining trend of carbon removals. The agricultural sector may provide a consistent contribution through carbon sequestration in soils although, currently, the land use, land-use change (LULUCF) sector is not part of the EU climate and energy package. The current legislation proposes to set an EU-level target for net removals of greenhouse gases of at least 310 million tonnes of CO_2 equivalent in the LULUCF sector by 2030, which is distributed among the member states as binding targets.

The EU Soil Strategy 2030 'Reaping the benefits of healthy soils for people, food, nature and climate' (COM(2021) 699 final) recognises that targeted and continued sustainable soil management practices can significantly help in achieving climate neutrality by eliminating the anthropogenic emissions from organic soils and by increasing the carbon stocked in mineral soils.

On top of those policy developments, the EU has an active engagement and to supports international partners on climate action, in particular through the UN Framework Convention of Climate Change (UNFCCC) and its Paris Agreement.

There is evidence that carbon farming can contribute significantly to the EU's efforts to tackle climate change but also brings other co-benefits such as increased biodiversity and the preservation of ecosystems (Bumbiere et al., 2022; Paul et al., 2023).

Finally, the European Court of Auditor's 2021 Report 16 on Common Agricultural Policy and climate recommends to the Commission to take action so that the CAP reduces emissions from agriculture; takes steps to reduce emissions from cultivated drained organic soils; and reports regularly on the contribution of the CAP to climate mitigation.

2.2 Soil Organic Carbon in arable lands

The CAP context indicators monitor the Socio-Economic and environmental impact of the Common Agricultural Policy (CAP) 2014-2020 by using a set of 45 indicators (socio-economic, sectoral, Environmental). CAP indicators serve for the assessment of CAP performance. Soil erosion and soil organic carbon are the two soil-relevant indicators to monitor the impact of the CAP in soils.

The CAP Context indicators 41 “Soil organic matter in arable land” estimates the total soil organic carbon content in arable soils. It consists of two sub-indicators:

- The total estimate of organic carbon content in arable lands
- The mean organic carbon content

The Objective of the CAP 2023-2027 "To contribute to climate change mitigation and adaptation, including by reducing greenhouse gas emissions and enhancing carbon sequestration, as well as to promote sustainable energy" includes 4 indicators relevant to carbon. In the new performance monitoring and evaluation framework (PMEF), we address the "C.40 - Enhancing carbon sequestration" (ex- C.41 in the old CMEF) which is relevant to "Soil organic carbon in agricultural land".

The indicator is expressed with 3 specific indicators:

- estimate of the total organic carbon content in soils on agricultural land of EU Member States (with a breakdown by arable land, grassland and permanent crops)
- the mean organic carbon content in agricultural land
- estimate of SOC changes over time.

2.2.1 Material and methods

The current total SOC content in arable lands was estimated by modelling the changes occurred across EU+UK during the period 2009-2018. Changes in SOC hereafter defined as Δ SOC (g C kg^{-1} y^{-1}) were assessed by fitting a quantile Generalised Additive Model (qGAM) (Fasiolo et al., 2021) on Δ SOC calculated from SOC concertation data obtained from the revisited points of LUCAS topsoil (0-20cm) surveys of 2009 and 2018. The trained model was then used to predict Δ SOC at spatial level using available gridded predictors at 500 m resolution obtained from ESDAC. The final map of current SOC stocks at European level was produced by summing the previously (ESDAC) estimated SOC stock for the 2009 with the spatially predicted changes (Δ SOC stocks, this study) occurred during the 2009-2018.

2.2.1.1 Modelling approach and data source

The qGAM was used to predict the median Δ SOC across Europe. GAM models are semi-parametric regression models and have the capability to flexibly capture the non-linear relationship between response and explanatory variables. The qGAM was selected for this modelling exercise due to it does is less sensitive to outliers than others regression-like models (Fasiolo et al., 2021, Weldon et al., 2022).

The response variable Δ SOC, expressed as the arithmetic differences between SOC levels of 2018 and 2009 was calculated from the revisited points of Land Use/Land Cover Area Frame Survey (LUCAS) soil surveys collected from specific agricultural lands i.e. cropland and grassland. The LUCAS survey is a project to monitor land use and land cover changes across the EU. Soil surveys were performed in 2009, 2015 and 2018 across 28 current and former EU Member States. LUCAS soil survey is the largest comprehensive and harmonized source of topsoil information at European scale. For each soil survey an excess of 22000 locations were sampled and the soil samples were analysed for their physical and chemical properties following ISO standard procedures. The sample analysis were performed by a single laboratory, contributing to data comparability by avoiding uncertainties due to analysis based on different methods or different calibrations in multiple laboratories. Further details regarding LUCAS soil survey and soil related chemical analysis can be found in (Orgiazzi et al., 2018)

The predictive variables used in the model were:

Land cover information for each revisited LUCAS point in 2009, 2015 and 2018 for cropland (C) and grassland (G) included in the model as parametric variable. This data provided useful information to assess the effect of land cover and land cover change i.e. continued grassland (GGG) or cropland (CCC), from grassland to cropland (GGC or GCC) and vice versa (CGG or CCG) on Δ SOC.

Combined influence of SOC content (g C kg-1) and soil clay content (%) at 0-20 cm depth in the 2009/12 were obtained from the 2009/12 LUCAS soil survey.

Combined influence of annual long-term mean precipitation (P, mm) with precipitation seasonality (coefficient of variation, P_CV) and the combined influence of annual long-term temperature (MAT,°C) with temperature seasonality (standard deviation, MAT_SD) were extracted from the WorldClim climatic datasets (http://worldclim.org). The WorldClim datasets have average monthly climate data for minimum, mean and maximum temperatures and for precipitation for 1970–2000 at a resolution of 1000 m.

The annular precipitation, precipitation seasonality and SOC levels of 2009 were log transformed while the soil clay content was square root transformed to achieve better dispersion of the observed variables (Wood, 2006). The model formula was as follows:

$$q_i(\Delta\,\mathrm{SOC}) \sim Land\ Use + f_1\left(log(SOC_{2009}), \sqrt{Clay}\right) + f_2(MAT, MAT\_SD) + f_3\left(log(P), log(P\_CV)\right)$$

The model performance was assessed by cross validation by splitting the measured dataset in different thresholds of training and testing data.

2.2.1.2 Upscaling model predictions

The validated model was used to upscale Δ SOC predictions across EU, using the same covariates spatially explicit at a resolution of 500 m. The initial SOC levels (2009) soil Clay content and were obtained from the physical properties available in ESDAC (Ballabio et al., 2016). Long-term mean annual temperature (MAT, °C), temperature inter annual variation, annual precipitation (P, mm) and precipitation inter annual variation were obtained from the high-resolution WorldClim datasets. The derived land cover/use data were obtained from Corine Land Cover (CLC: https://land.copernicus.eu/pan-european/corine-land-cover) using the closest years to the LUCAS sampling surveys, and resampled to a resolution of 500 m. The study refers to 161 Million ha covering croplands (CLC classes: 2.1, 2.2, 2.4.1, 2.4.2) and grasslands/pastures (CLC class: 2.3)

The predicted values were then converted in SOC stocks at 0-20 cm depth. The soil bulk density used to convert SOC concertation to stocks was predicted using an empirically derived pedotransfer function, developed by (Hollis et al., 2012).

The final map of the predicted Δ SOC stocks was then used to estimate the current total SOC content in arable lands by summing the previously (Panagos et al., 2020) estimated SOC stock for 2009 with the spatially predicted changes (Δ SOC stocks, this study) occurred during the 2009-2018 period as follows:

$$SOC_{2018} = SOC_{2009} + (\pm\Delta\,\mathrm{SOC})$$

2.2.2 Current SOC stocks and SOC rate in European cropland and grassland

The current estimated SOC stock for cropland and grassland at 0-20 cm depth for Europe was 9.3 Gt C (Table 1). Grasslands across Europe, despite accounting only for 29% of the total cultivated area (Cropland 71%), hold 43% of the total SOC stocks (3.9 Gt C). The highest SOC stocks, above 100 t C ha^{-1}, were observed in Finland, Ireland, western United Kingdom and central Europe, specifically Austria and the centre of France (Figure 2). France, with its 26 Mha of cultivated land, holds the highest SOC stock with 1.5 Gt C) followed by United Kingdom (1.3 Gt C and 14.5 Mha) and Germany (1 Gt C and 16.7 Mha). However, Finland, Ireland and United Kingdom had the highest average SOC stock that ranged between 91 to 107 t C ha^{-1} versus 57 t C ha^{-1} for France. The lowest SOC stocks were estimated in the Mediterranean area and almost all estimated values were below 40 t C ha^{-1} (Figure 2). Indeed, for Spain, Italy and Greece where the predominant land use is cropland (average share of 82% of the total cultivated area) the mean SOC stock was estimated to be below 45 t C ha^{-1}. For central and eastern Europe, the spatial variability of pedo-climatic conditions along with mixed land use resulted in a complex SOC stock distribution (Figure 2). For Lithuania and Slovakia, SOC stocks estimates were generally above 50 t C ha^{-1} (Figure 2) holding a total SOC stocks of 134.3 and 100.6 Mt C, respectively (Table 1). In contrast, for neighbouring countries/regions such as North-east of Germany and Poland, where the soil is characterized by a low clay content, estimated SOC stocks ranged between < 30 and 40 t C ha^{-1}. For the latter, grassland occupies only 17% of the total cultivated area (Table 1). Soil clay content pays an important role in determining the amount of C that can be store in the soil profile (Wiesmeier et al., 2019). Clay minerals have large surface area where organic compounds directly binds to the clays surface. Clay mineral associated organic matter due to its high stability have a residence time in the soils that spans from decades to century (Bai & Cotrufo, 2022).

Figure 2. *Mean soil organic carbon (SOC) rates of 2018 aggregated data at NUTs2 level.*

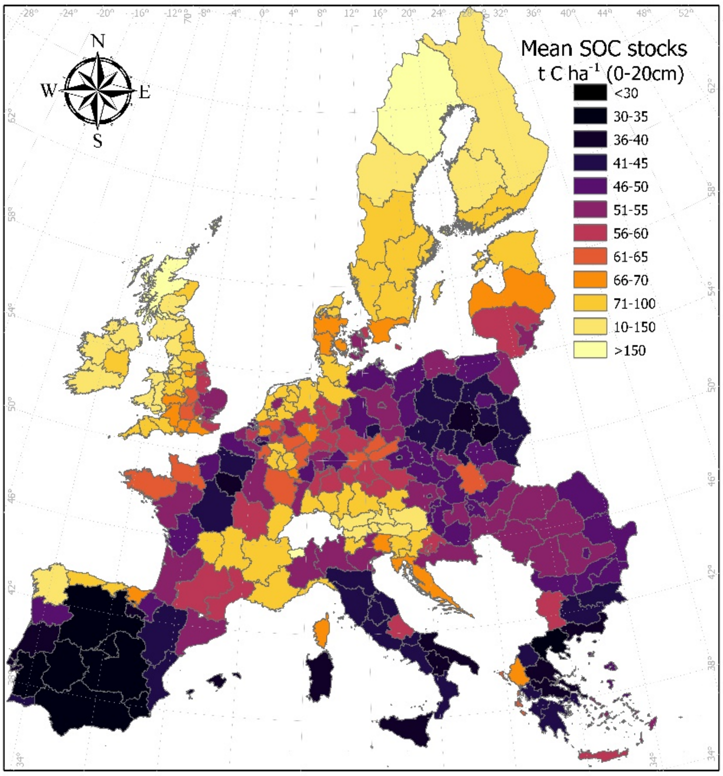


***Table 1**. Cultivated (cropland and grassland) area and estimated SOC stocks across Europe along with the shares of cultivated area and SOC stocks between cropland and grassland for the 2018.*

Country	*Total area Mha*	*Total SOC Mt C ha^{-1}*	*Mean SOC ha^{-1}*	*Share area Cropland %*	*Share area Grassland %*	*Share SOC Stock Cropland %*	*Share SOC Stock Grassland %*
AT	2.5	231.9	92.2	53	47	31	69
BE	1.0	61.3	60.3	66	34	53	47
BG	4.7	230.1	48.5	84	16	79	21
CY	0.3	11.3	38.6	92	8	90	10
CZ	3.7	189.8	51.4	78	22	69	31
DE	16.7	1003.8	60.2	73	27	62	38
DK	2.6	166.7	63.0	97	3	96	4
EE	1.0	73.0	75.9	67	33	61	39
EL	3.8	157.5	41.7	75	25	63	37
ES	20.8	757.2	36.4	80	20	68	32
FI	1.2	122.6	99.2	100	0	99	1
FR	26.0	1480.5	56.9	63	37	50	50
HR	0.9	58.4	63.1	47	53	36	64
HU	5.7	286.0	49.9	84	16	82	18

IE	4.0	427.7	105.7	8	92	5	95
IT	11.3	506.7	45.0	90	10	81	19
LT	2.4	132.8	55.5	85	15	81	19
LU	0.1	4.8	70.6	49	51	44	56
LV	1.7	113.6	68.4	65	35	57	43
MT	0.0	0.0	36.1	100	0	100	0
NL	1.7	129.2	74.3	41	59	32	68
PL	16.0	705.0	44.1	83	17	74	26
PT	1.7	67.2	38.9	41	59	48	52
RO	11.9	579.6	48.7	76	24	69	31
SE	3.2	287.9	90.8	87	13	77	23
SI	0.2	19.0	80.5	51	49	39	61
SK	1.9	100.2	53.6	85	15	77	23
UK	14.5	1331.7	92.1	45	55	30	70
EU+UK	161.6	9235.9	57.2	71	29	57	43

Source: JRC D.3 soil Team (De Rosa et al., in submission 2023)

Marked differences in terms of mean SOC stock were observed between cropland and grassland across Europe (Figure 3 and Figure 4). The mean SOC rate for cropland across Europe was much lower than grassland (46.6 t C ha^{-1} for cropland versus 80.9 t C ha^{-1} for grassland). This further confirms the SOC sequestration potential of grassland. However, a similar spatial trend was observed between cropland and grasslands. For both, the highest SOC rates were observed in north Europe while the lowest rates were observed for Countries in the Mediterranean basin (Figure 3 and Figure 4).The observed spatial trend at this scale is linked to climatic conditions, namely temperature and precipitations. Generally, colder, moister areas favour accumulation of SOC, moderate SOC storage occurs in warmer, moist regions and lower SOC storage is found in drier, hotter regions. These patterns, interpreted as natural spatial constraints for SOC accumulation should be taken in considerations when developing policies that aim at promoting soil C sequestration.

Figure 3. *Mean soil organic carbon (SOC) rates for Cropland of 2018 aggregated data at NUTs2 level.*

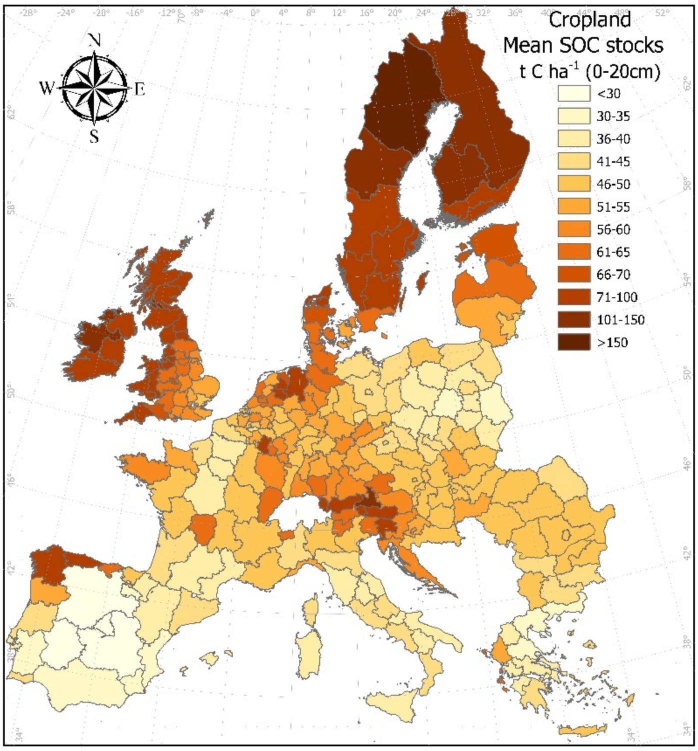
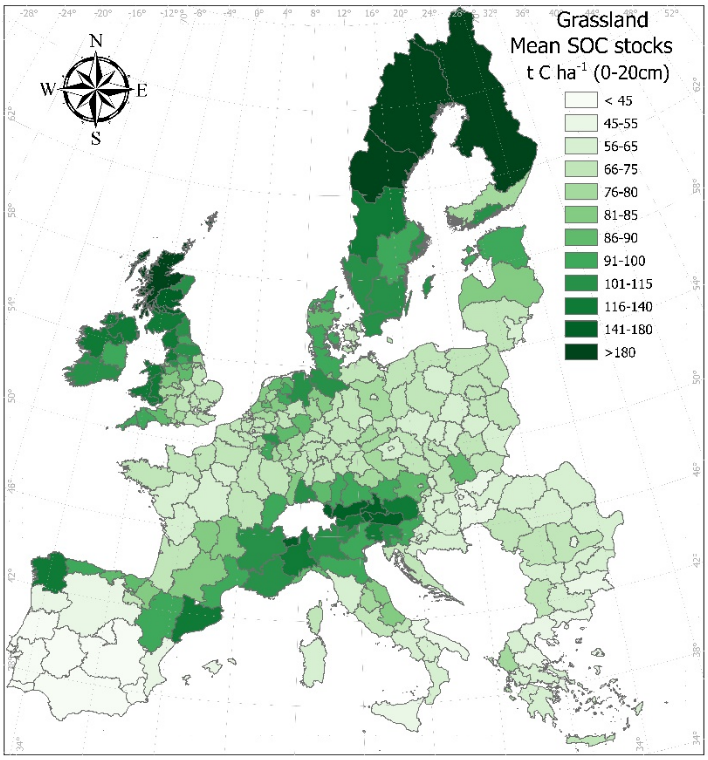


Figure 4*. Mean soil organic carbon (SOC) rates for Grassland of 2018 aggregated data at NUTs2 level.*



2.3 Concluding remarks for Soil organic carbon

The SOC stocks across Europe for the 2018 were estimated by modelling the changes over a 9-year period from the 2009 baseline (ESDAC) with a statistical model trained with LUCAS soil survey observations. In the final model spatial estimates of SOC stocks show a marked influence of environmental and site-specific edaphic conditions such as soil clay content. The combined effect of such natural variables therefore directly limits or enhances the potential of carbon sequestration soil management practices.

In the European policy context, considering these natural occurring constraints would aid at defining spatially variable policy actions that would seamlessly maximise the environmental and economic return of allocated investments.

The spatially variable delineation of potential SOC sequestration targets in agricultural soils provide the opportunity to better estimate economic and environmental trade-offs associated with CAP objectives as well as facilitate the assessment of future carbon sequestration initiatives.

3 Soil Erosion

Soil erosion is a serious threat leading to the loss of soil and soil functions as well as land productivity and crop yield decline. In addition, it may lead to off-site effects such as sedimentation, carbon loss, biodiversity decline, siltation of dams, flooding and damage of important infrastructures.

3.1 Policy context

The CAP context indicators monitor the Socio-Economic and environmental impact of the Common Agricultural Policy (CAP) 2014-2020 by using a set of 45 indicators (socio-economic, sectoral, Environmental). CAP indicators serve the assessment of CAP performance. Soil erosion and soil organic carbon are the two soil-relevant indicators to monitor the impact of the CAP in soils.

The soil erosion CAP context indicator No42 consists of 2 sub-indicators: 1) Estimated rate of soil loss by water erosion as t ha^{-1} yr^{-1}; 2) "percentage of agricultural land at risk of moderate and severe soil erosion. The estimated area is also expressed as share of the total agricultural area (%). The indicators assess the soil loss by water erosion processes (rain splash, sheet wash and rills) and give indications of the areas affected by a certain rate of soil erosion (moderate to severe, i.e. >11 t ha^{-1} yr^{-1} in the OECD definition).

Data link: https://agridata.ec.europa.eu/extensions/IndicatorsEnvironmental/SoilErosionByWater.html

The latest update on this indicators refers to 2016 (Panagos et al., 2020) and includes trends compared to 2010 and 2000. Access to the document:

https://esdac.jrc.ec.europa.eu/node/67762

The main outputs of the updated 2016 soil erosion assessment are:

- The estimated soil erosion rates in 2016 (2.45 t ha^{-1} yr^{-1}) show a limited decrease of 0.4% in all lands and 0.8% in arable lands compared to 2010 (Panagos et al., 2020). In the past decade (2000-2010) the corresponding decrease was stronger as soil erosion decreased by 9% in all lands and 19% in arable ones.
- Regarding the conservation practices to reduce soil erosion: a) the grass margins increase in the period 2010-2016 was quite limited (8%); b) The conservation tillage shows a very limited increase (0.8%) from 21.6% to 22.4%; c) The cover crops are applied to 8.9% of the EU arable lands compared to 6.5% in 2010; d) on the contrary, the plant residues show a decrease from 10.6% in 2010 to 9.1% in 2016 (Borrelli et al., 2020).
- The small overall increase in conservation practices for the period 2010-2016 (implying a decrease in erosion rates) has been offset by a decrease of management practices (leading to an increase of erosion rates) in more sensitive (erosive) areas such as the Mediterranean basin. Summarising, the majority of countries (and regions) perform well as they increase conservation practices; however, the most erosive regions have shown an opposite trend.
- Taking into account that soil formation rates found in the literature are about to 1.4 - 2 t ha^{-1} yr^{-1} , more than ¼ of the EU lands have erosion rates higher than the 2 t ha^{-1} yr^{-1} threshold. In addition, 6.6% of the EU agricultural lands suffer from severe erosion (> 11 t ha^{-1} yr^{-1}).

The update of soil erosion for 2020 is delayed as the Farm Field Survey (FSS) for 2020 has not been included the management practices necessary to model soil erosion. Important datasets (e.g. tillage practices, cover crops, plant residues) are results from the Farm Structure Survey (FSS) performed by the Statistical Office of the EU (Eurostat). Eurostat collected data from the Farm Structure Survey on Agricultural Production Methods, a survey carried out in 2010 and repeated in 2016 and collected data at farm level on agro-environmental measures. The EU Member States collected information from individual agricultural holdings and, following rules of confidentiality, these data were transmitted to Eurostat and aggregated at the NUTS2 regional level. In this study, the statistical data of tillage practices, cover crops and plant residues are used at the regional level (NUTS2). The 2023 FSS includes the management practices which are important inputs to estimate the trends in soil erosion.

The data are available at: https://ec.europa.eu/eurostat/web/agriculture/data/database

The FSS data for 2023 are planned to be released in 2024/25; therefore, the update of the indicator is planned for 2024.

In the next sections, the latest state of the art datasets for different soil erosion processes are presented.

3.2 Soil erosion by water

Processes of water erosion may include splash erosion, sheetwash, rill erosion, piping erosion (or tunnel erosion) and (ephemeral or permanent) gully erosion.

Soil erosion by water is one of the major threats to soils in the European Union, with a negative impact on ecosystem services, crop production, drinking water and carbon stocks. The application of a modified (hybrid) version of the Revised Universal Soil Loss Equation (RUSLE) model (RUSLE2015) is used to estimate soil loss in Europe for the reference years 2000, 2010 and 2016. The modelled approach gets as inputs the Rainfall erosivity, Soil erodibility, Cover-Management, Topography, Support practices which are estimated with the most recently available pan-European datasets. A major benefit of proposed approach compared to past models is that it can incorporate the effects of policy scenarios based on land-use changes and support practices. The impact of the Good Agricultural and Environmental Condition (GAEC) requirements of the Common Agricultural Policy (CAP) and the EU's guidelines for soil protection can be grouped under land management (reduced/no till, plant residues, cover crops), greening (crop rotation, Ecological Focus Areas) and support practices (contour farming, maintenance of stone walls and grass margins).

The modified (hybrid) version of the RUSLE model (RUSLE2015, based on Renard et al., 1997) calculates mean annual soil loss rates by sheet and rill erosion according to the following equation:

$$E = R \times K \times C \times LS \times P \qquad (1)$$

where

E: annual average soil loss (t ha^{-1} yr^{-1}), R: rainfall erosivity factor (MJ mm ha^{-1} h^{-1} yr^{-1}), K: soil erodibility factor (t ha h ha^{-1} MJ^{-1} mm^{-1}), C: cover-management factor (dimensionless), slope length and slope steepness factor (dimensionless), and P: support practices factor (dimensionless.

The Soil erodibility (K-factor) is estimated for the 20,000 field sampling points included in the Land Use/Cover Area frame (LUCAS) survey.

The rainfall erosivity (R-factor) is a long-term average of annual erosivity records which has been calculated based on high temporal rainfall records (30 minutes) for a mean of 17-years covering the period 2000-2010.

The Cover-Management (C-factor) was modelled in non-arable lands using a combination of land-use class and vegetation density while in arable lands C-factor is based on crop composition and land management practices (reduced/no tillage, cover crops and plant residues).

The LS-factor is calculated using the recent Digital Elevation Model (DEM) at 25 m and applying the equations proposed by Desmet and Govers (1996).

The support practices (P-factor) takes into account a) contour farming implemented in EU agro-environmental policies, and the protection against soil loss provided by (b) stone walls and (c) grass margins.

Mean erosion in arable lands I about 2.67 ± 0.15 t ha^{-1} y^{-1}. Arable lands show a small decrease of erosion rates in 2016 compared to 2010 rates. The main driver for change in soil erosion are the management practices which are mainly applied in arable lands (reduced tillage, plant residues, grass margins and cover crops).

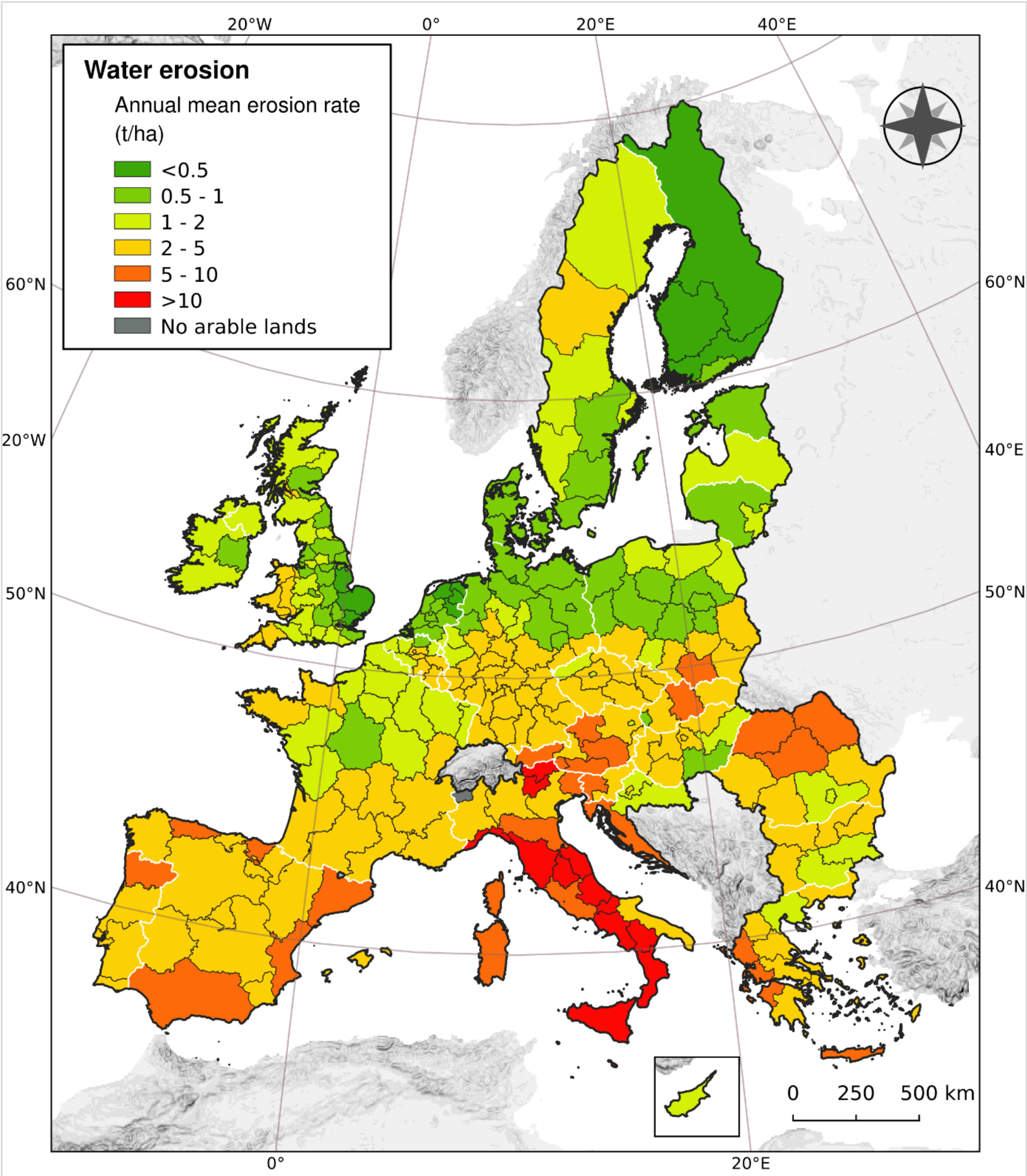
In 2016, the conservation tillage is applied in 22.4% of EU arable lands (+0.8% compared to 2010) and the no-till has a share of 4.2% (+0.2%). Conservation tillage has been increased in France, Austria, Estonia and Portugal (overall country increase > 7%), while decreases are recorded in Bulgaria, Greece, Poland (overall country decreases <-4%) and parts of Italy. Cover crops have increased quite substantially in 6-years (2010-2016) as they are applied in 8.9% of EU arable lands compared to the 6.5% in 2010 (Borrelli and Panagos, 2020). On the contrary, the soil cover by plant residue management show a decrease of 1.5% compared to 2010 and have been applied in 9.1% of EU arable lands. The changes (%) for the period 2010-2016 both in tillage practices and cover crops are mapped at regional level recently (Borrelli and Panagos, 2020).

The geographical distribution of the mean erosion rates suggests an increase in 8 countries and a decrease in 20 countries. Among the later ones, there are apparent positive signs of conservation practices increase in

Estonia, Austria, Denmark, Germany, Estonia, France Malta and Portugal. In those countries the application of conservation practices reduced erosion by at least 3.5% in arable lands.

The total soil displacement due to water erosion in EU and UK is about 295 million tonnes. According to the water erosion estimates, 32.6% of the arable area has shown water erosion rates higher than 2 t ha^{-1} y^{-1} (Figure 5). Data at NUTS2 level can be downloaded from the European Soil Data Centre (ESDAC): https://esdac.jrc.ec.europa.eu/themes/indicators-soil-erosion

***Figure 5**. Soil loss by water erosion (Reference year: 2016). Aggregated data at NUTs2 level.*



3.3 Wind erosion

Soil erosion by wind (wind erosion) is an environmental problem (Lal, 1994) often resulting in severe forms of soil degradation (Warren, 2003; Zhang et al., 2014). Wind erosion occurs in dry conditions when the soil is exposed to wind (Webb et al., 2006). It is a wind-forced movement of soil (Shao, 2008) where the finest particles, particularly organic matter, clay and loam, are removed and transported over long distances before being redeposited elsewhere. In recent times, however, intensive farming has increased the frequency and magnitude of this geomorphic process with consequences especially for sensitive lands, important for food production (Dostal et al., 2006). Land management practices such as intensive crop cultivation, increased mechanisation, enlargement of field sizes, removal of hedges, high residues/biomass exploitation of vegetation and consecutive bare fallow years in cultivated lands exacerbated both environmental and economic effects of wind erosion (Colazo & Buschiazzo, 2015). To gain a better understanding of the wind erosion situation in Europe, the JRC carried out the first European Union assessment of land susceptibility to wind erosion (Borrelli et al., 2014; Borrelli et al., 2016).

The Revised Wind Erosion Equation (RWEQ; Fryrear et al., 2000) is an equation extensively tested to perform field based predictions of soil loss due to wind erosion. A number of studies have found good agreement between the yields predicted by RWEQ and the field measures (Buschiazzo & Zobeck, 2008; Youssef et al., 2012). The significant relationship between the observed and predicted transport capacity and soil loss (Zobeck et al., 2001), as well as the limited need for input data compared with mechanistic wind erosion models like the Wind Erosion Prediction System (Hagen, 2004), makes RWEQ a suitable tool for a largescale prediction of the wind erosion potential (Zobeck et al., 2000; Youssef et al., 2012). In this study, a geographic information system (GIS) version of the RWEQ (named GIS-RWEQ) is presented to quantitatively assess soil loss by wind over large study areas and to evaluate the reliability of its results (Figure 6) .

The soil displacement (SL) estimates obtained by the application of GIS-RWEQ (Borrelli et al., 2017) are used for large scale applications. GIS-RWEQ is a simplified version of RWEQ with a driving force (i.e. the wind factor, WF), resistance terms (i.e. the soil erodible fraction, EF; soil crust factor, SCF; and soil roughness, K), and other factors representing the farming characteristics and practices, i.e. the field size and orientation (Field) and crops on the ground (COG). More specifically:

$$SL = \frac{2x}{s^2} Q_{max} e^{-\left(\frac{x}{s}\right)^2} \quad (2)$$

where S is the critical field length (meters) and Q_{max} (kg m^{-1}) expresses the maximum transport capacity:

$$Q_{max} = 109.8 \, (WF \cdot EF \cdot SCF \cdot K \cdot COG) \quad (5)$$

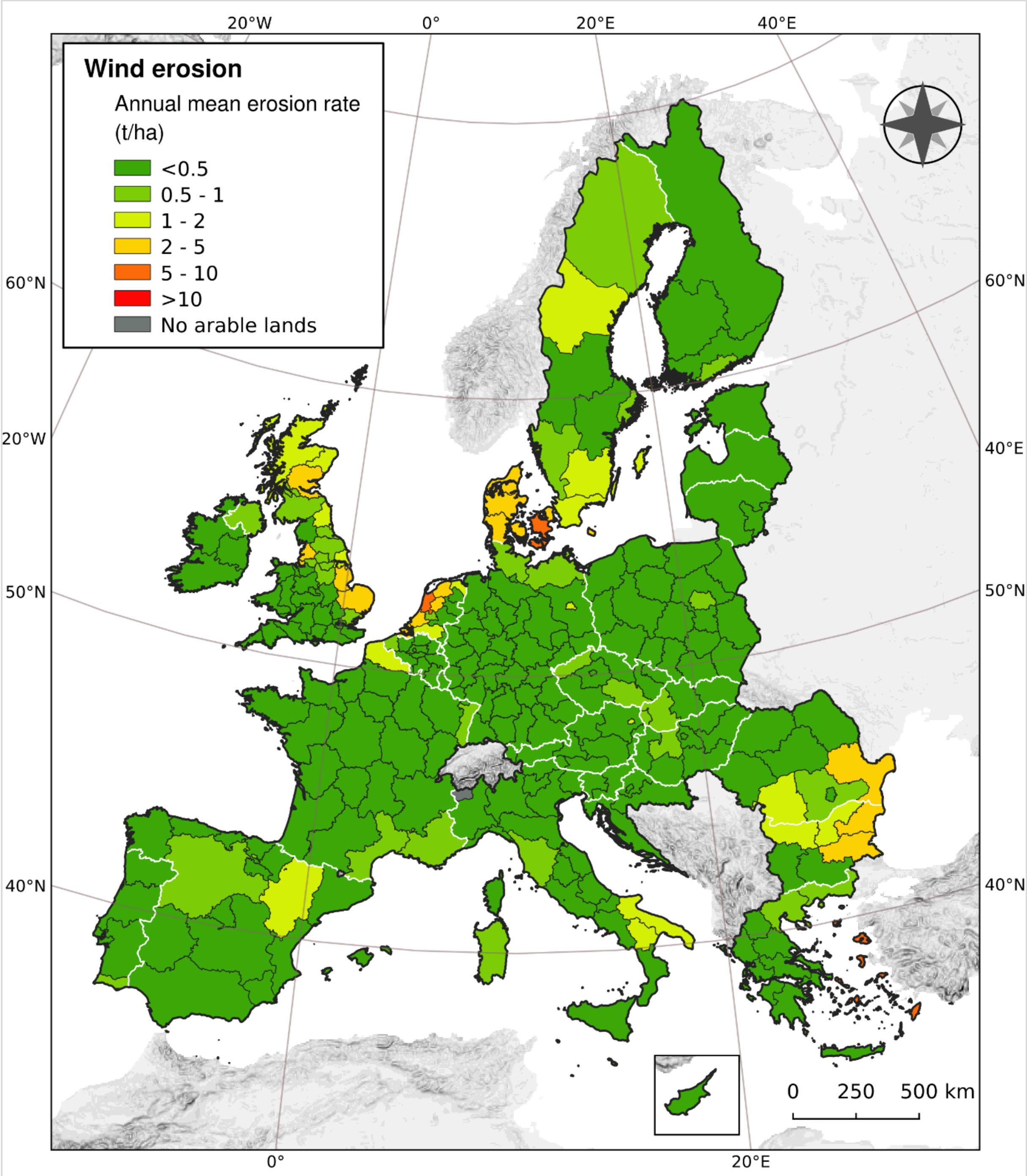
$$S = 150.71 \, (WF \cdot EF \cdot SCF \cdot K \cdot COG)^{-0.3711} \quad (6)$$

The native spatial resolution of the GIS-RWEQ map is 1 km and we resampled at a 100m grid cell. The original and resampled data can be downloaded from the European Soil Data Centre (ESDAC): https://esdac.jrc.ec.europa.eu/content/multiple-concurrent-soil-erosion-processes

The average annual soil loss rates predicted for the period 2001–2010 totalled 0.52 t ha^{-1} y^{-1} (uncertainty range: -0.1 t ha^{-1} yr^{-1}, +0.1 t ha^{-1} yr^{-1}), with the second quantile and fourth quantile equal to 0.3 and 1.9 t ha^{-1} y^{-1}, respectively. The total soil displacement due to wind erosion in EU and UK is about 57 million tonnes. According to the wind erosion estimates, 6.8% of the area has shown wind erosion rates higher than 2 t ha^{-1} y^{-1}.

Approximately a third (36.3%) of the investigated arable land showed no sign of wind erosion while a major part of the EU has rates lower than 0.5 t ha^{-1} y^{-1} . A cross-country analysis showed the highest annual soil loss rate in Denmark (3 t ha^{-1} y^{-1} .), the Netherlands (2.6 t ha^{-1} y^{-1} .), Bulgaria (1.8 t ha^{-1} y^{-1} .) and to a lesser extent also in the Romania and Greece.

***Figure 6**. Soil loss by wind erosion. Aggregated data at NUTs2 level.*



3.4 Crop harvesting erosion

Considerable amounts of soil can be removed from the field due to soil sticking to the harvested roots. Soil Loss due to Crop Harvesting (SLCH) is defined as the loss (or export) of top soil from arable land during harvesting of crops such as potato, sugar beet, carrot or chicory roots (Poesen et al., 2001). During the harvest of root and tuber crops, soil is sticking to the crop and is removed from the field (or it is displaced from the plot) together with stable soil clods and rock fragments (Ruysschaert et al., 2004). In addition, SLCH depends much on the soil disturbance during the harvest operation (Arnhold et al., 2014).

Several factors control the magnitude of SLCH and the rates of soil losses. The most important factors are: i) soil (soil moisture, soil texture, soil organic matter and soil structure), ii) the crop type, iii) the agronomic practices (e.g. plant density, crop yield), and iv) the harvest techniques (technology, effectiveness and velocity of harvester) (Ruysschaert et al., 2004, Ruysschaert et al., 2005).

In a first instance, the SLCH combined crop statistics of the European Union and United Kingdom (aggregate at regional EU level NUTS2) with soil-displacement rates due to crop harvesting reported in literature (Ruysschaert et al., 2004; 2005; 2006; Poesen et al., 2001). The crops considered were sugar beets and potatoes, which according to the European Commission Statistical Office, in the period 2000–2016, covered 1.1% (1.92 M ha) and 1.3% (2.27 M ha) of the EU-utilized agricultural area (reference year 2018), respectively. The average regional SLCH was estimated as follows:

$$SLCH = NUTS2_{ha} \times \text{Textural Index} \times SLCH_{rate} \quad (3)$$

where

$NUTS2_{ha}$ represents the hectares cultivated with sugar beets and potatoes in each EU NUTS2 region.

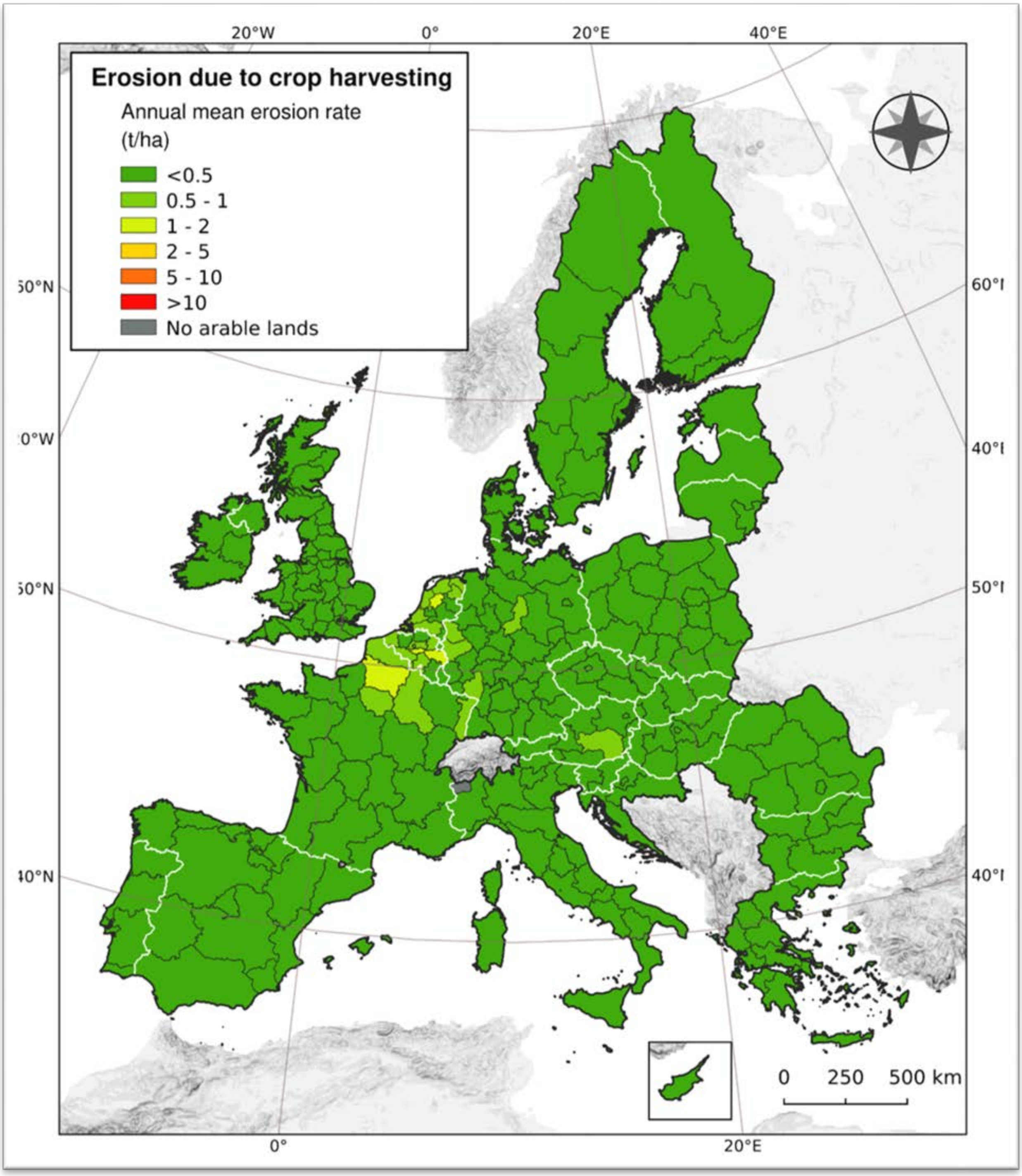
$SLCH_{rate}$ represents an estimate of the potential average soil-displacement rate per country based on available data from the literature. For sugar beets, this ranges from 4.7 Mg ha^{-1} per harvest in the United Kingdom to 10 Mg ha^{-1} per harvest in Denmark and France. For potatoes, SLCH is assumed to be 3 Mg ha^{-1} per harvest in all considered countries.

The textural index is a correction factor that adjusts the SLCH to describe the impact of the soil physical properties on $SLCH_{rate}$. This is higher in clay soils and lower in sandy soils as described in detail of the EU assessment of SLCH (Panagos et al., 2019).

In a second step, the approach of SLCH has been applied in a spatially explicit pixel-based fashion, overcoming the original limitation related to the regional aggregation to the EU NUTS2 level (Figure 7). To do so, we used the pan-European crop-type map (reference year 2018) developed in JRC (D' Andrimont et al., 2021) which provides gridded information about potato and sugar beet locations. Therefore, we make available a pixel-based soil loss by harvesting crops dataset. . The original and resampled data can be downloaded from the European Soil Data Centre (ESDAC): https://esdac.jrc.ec.europa.eu/content/multiple-concurrent-soil-erosion-processes

Annually, the mean total SLCH in EU-27 is ca. 15 million tons; 65% of this loss is due to sugar beets and the rest 35% due to potatoes. The mean EU SLCH rate is about 0.14 t ha^{-1} yr^{-1} (uncertainty range: -0.4 t ha^{-1} yr^{-1}, +0.4 t ha^{-1} yr^{-1}). This implies that 3.2% of the EU Arable land has rates higher than 2 t ha^{-1} yr^{-1} due to SLCH. The European mean SLCH rate for sugar beets is 5 t ha^{-1} per harvest summing up to 9.5 million tons of soil loss for a harvested area of 1.9 million ha. The EU SLCH rate for potatoes is 2.25 t ha^{-1} per harvest showing small variations between the EU Member States attributable to soil texture differences.

Figure 7. *Soil loss by crop harvesting (SLCH). Aggregated data at NUTs2 level.*



3.5 Tillage erosion

Tillage erosion occurs in cultivated fields through the net downhill movement of soil due to tillage operations (Lindstrom et al., 1992). According to some research findings, tillage is a soil degradation process *per se*, rather than a process that simply makes the soil more sensitive to other forms of erosion (Govers et al., 1994). The variation in soil displacement rates due to tillage erosion may be rather large, depending primarily on topographic characteristics, tillage depth and tillage direction, and to a lesser extent to tillage velocity and implement characteristics.

Tillage erosion is derived from estimated of a pan-European assessment of soil displacement due to tillage erosion in agricultural lands (Van Oost et al., 2009). The basis for this assessment is a modified version of the Tillage Erosion Model (Lobb et al., 1999).

The model is based on a minimal parameterization, where the downhill movement of soil due to tillage operations (E_t) (Eq. 2) is a function of the erosivity of tillage operations (T_e) and the erodibility (L_e) of the cultivated landscape:

$$E_t \approx \mathrm{f}(T_e, L_e) \quad (2)$$

A simplified version of the model applied by Van Oost et al (2009) for large-scale applications is organized as follow:

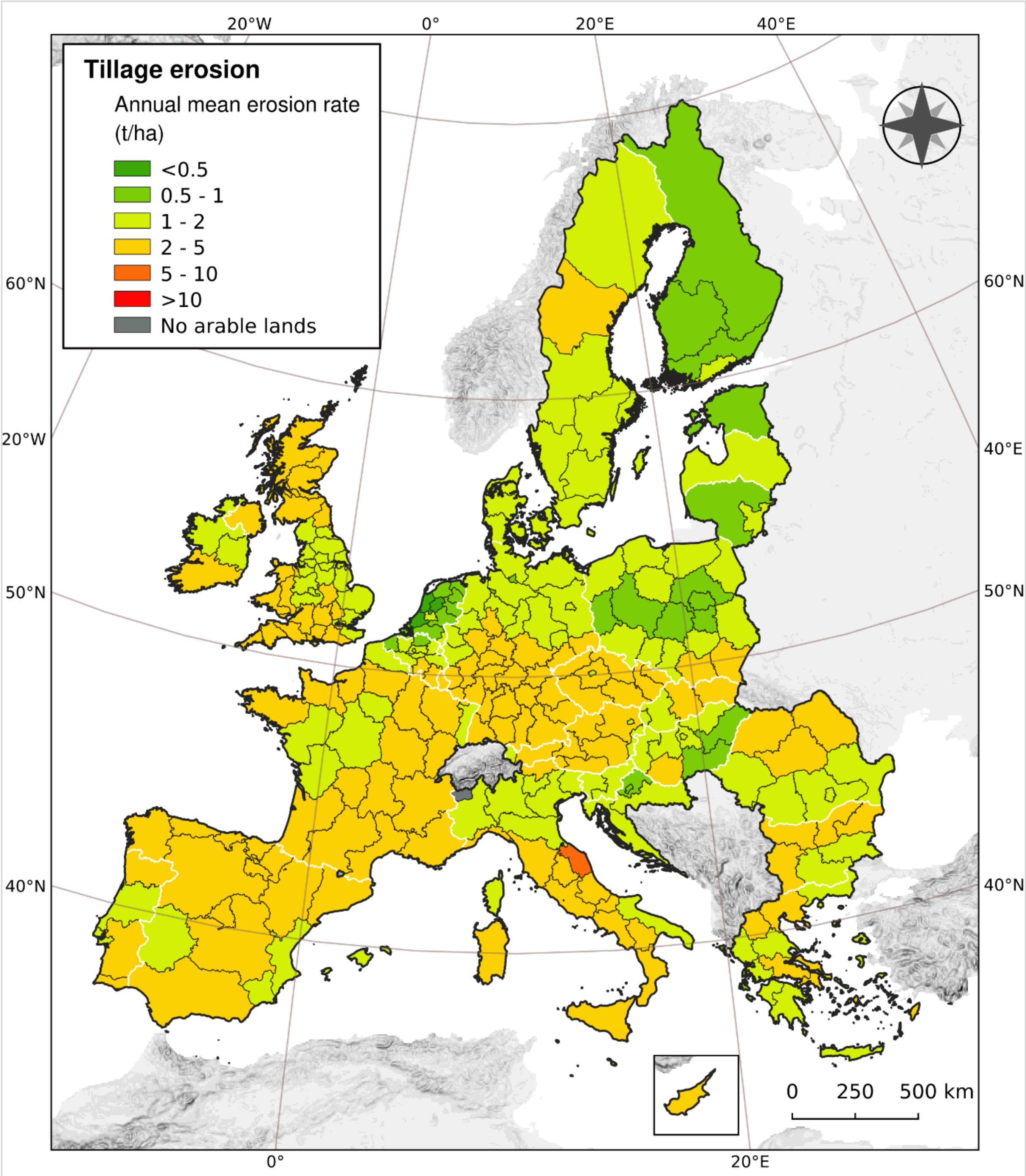
$$E_t = K_{til}\left(\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2}\right) \quad (3)$$

where (E_t) is the tillage soil displacement rate (in kg m^{-2} per unit time), h is the elevation (in metres), x and y are distances (in metres) and K_{til} is the tillage (soil) transport coefficient (in kg m^{-1} per unit time).

A diffusion-type model where T_e was defined using the proportionality factor K_{til} (set constant to 500 kg m^{-1} y^{-1} for the whole of Europe, as also done by Van Oost et al.(2009) and L_e was spatially defined using the topography total curvature (rate of change in slope gradient) obtained by the 25m cell size European digital surface model (EU-DEM).

The mean EU tillage erosion rate is about 1.88 t ha^{-1} yr^{-1} (uncertainty range: -0.2 t ha^{-1} yr^{-1}, +0.7 t ha^{-1} yr^{-1}). This is about 200 million tonnes of soil displacement due to tillage erosion and 26% of EU arable lands having tillage erosion rates higher than 2 ha^{-1} yr^{-1} (Figure 8). Addressing tillage erosion may involve more direct interaction with farmers, whereas wind erosion may require involvement of policymakers at a more regional scale. The data can be downloaded from the European Soil Data Centre (ESDAC): https://esdac.jrc.ec.europa.eu/content/multiple-concurrent-soil-erosion-processes

***Figure 8.** Soil loss by tillage erosion (SLCH). Aggregated data at NUTs2 level.*

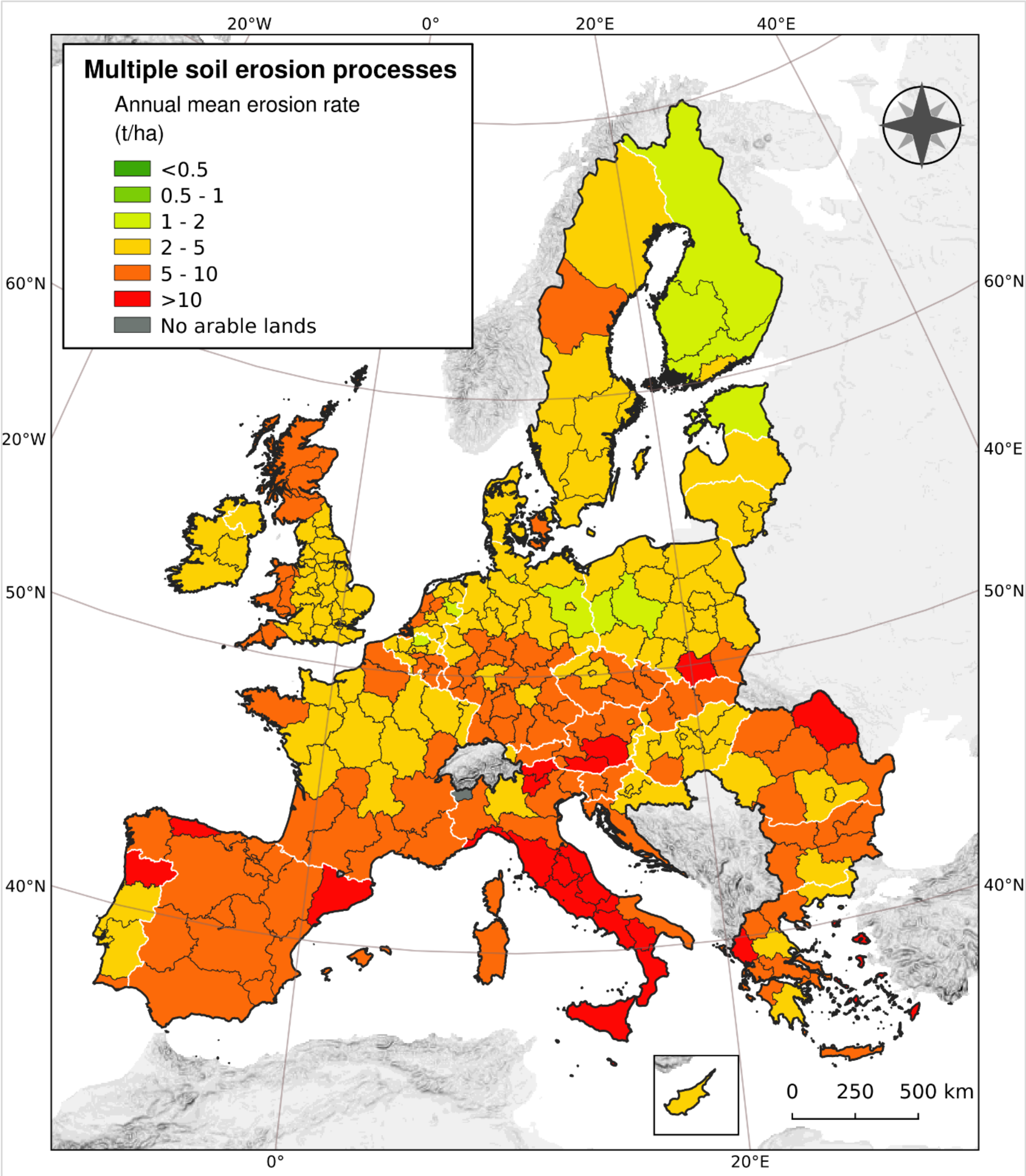


3.6 Multiple concurrent processes

For first time, the JRC in collaboration with members of the Working Group of Soil Erosion in the EU Soil Observatory (EUSO) applied a multi-model approach which provides estimates of gross soil loss due to water, wind, tillage and root crop harvesting (Borrelli et al., 2022).

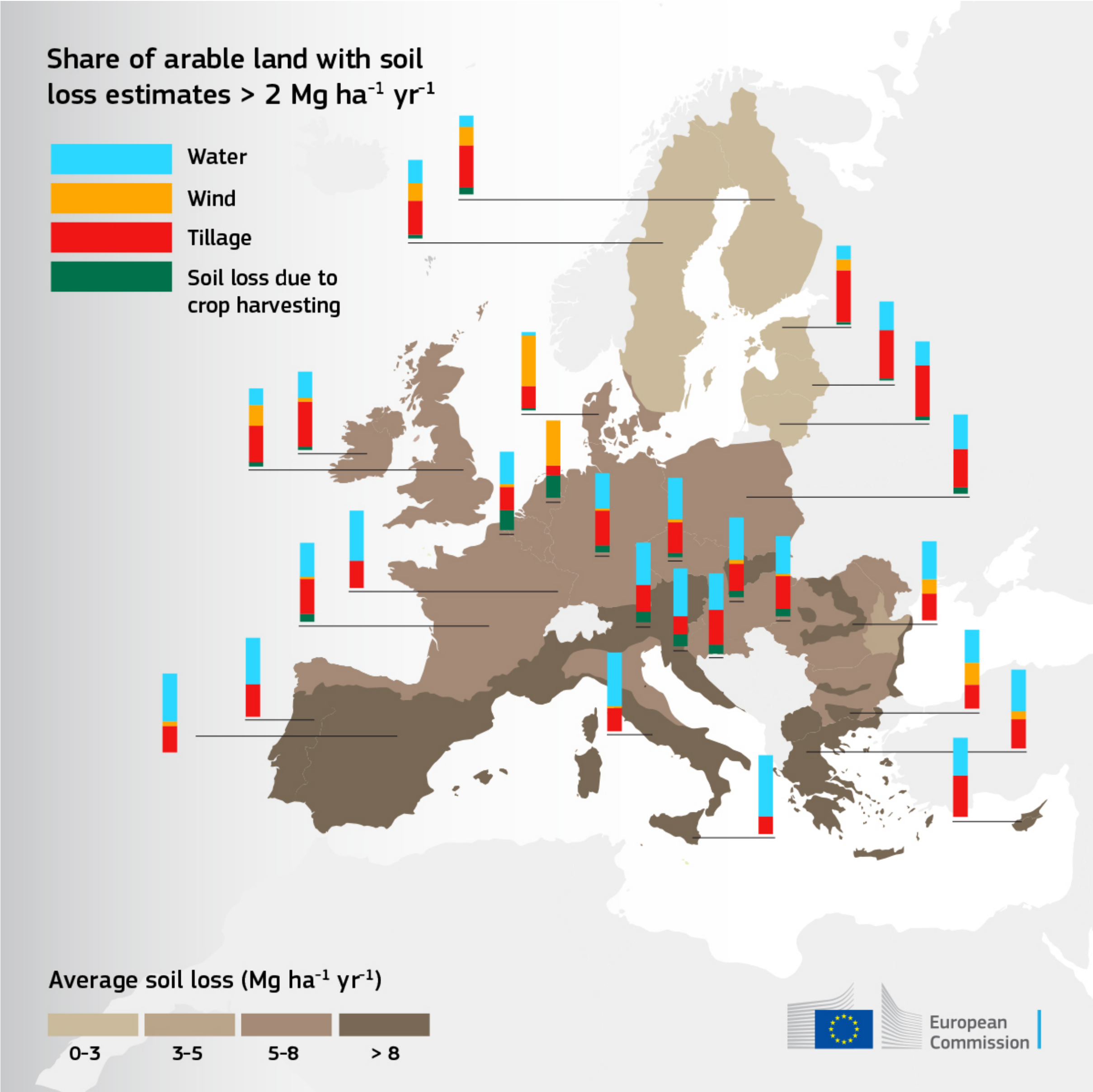
An estimated total of 575 (uncertainty range -56, +108) million tonnes of soil is annually displaced by these four erosion processes over 110 million ha of arable and in the EU and UK. This corresponds to an average area-specific soil displacement of 5.2 t ha^{-1} yr^{-1} which is almost double compared to the soil loss by water erosion. Therefore, the total soil displacement by summing up all processes (Figure 9) includes many regions in with rates higher than 5.2 t ha^{-1} yr^{-1}.

Figure 9. *Soil loss by summing up all the erosional processes: Water, Wind, Tillage and harvesting root crops.*



Considering the commonly accepted long term tolerable soil displacement rate of 2 Mg ha^{-1} yr^{-1} (Verheijen et al.2009), the results show unsustainable soil erosion rates occurring over half of the EU arable land (53.7% of arable lands or ~55 M ha). With regard to the individual processes, soil displacement by water erosion is dominant for 51% of the total displacement. Tillage erosion is the second largest driver of soil displacement with an estimated 36%, followed by wind erosion and crop harvesting with 10% and 2.7%, respectively (Figure 10).

Figure 10. *The total annual soil erosion rate per climate zone and the share of each erosional process per country (vertical bars).*



Identifying trends with past erosion assessments, we highlight actions for reducing erosion, such as increasing vegetation cover on arable land throughout the year and reducing tillage intensity. These actions are beneficial to the functional agrobiodiversity of the farming system.

For this concern, soil-conservation standards, related to the Common Agricultural Policy (CAP), integrated in the cross-compliance mechanism are considered as relevant. Good Agricultural and Environmental Conditions (GAEC), defined at national or regional level, include a set of standards especially on minimum soil cover and soil minimum land management to limit erosion.

The modelling approach by JRC scientists and the co-authors of the analysis shows that – compared to a pre-CAP baseline scenario and assuming no implementation of soil-conservation measures – GAEC soil-conservation standards reported in a 2016 EU Farm Structure Survey could reduce soil displacement by a computed 20% for water erosion, 27% for tillage erosion and 9% for wind erosion. This evidence has been shown in the comparing the soil loss by water erosion for three different data points (2000, 2010 and 2016). The soil conservation measures in EU agricultural soils during the last 15 years had as a result to reduce soil loss by water erosion (Panagos et al., 2016).

3.7 Future projections and analysis of policy options

Changes in future soil erosion rates are driven by climatic conditions, land use patterns, socio-economic development, farmers' choices, and importantly modified by agro-environmental policies. In this chapter, we simulated the impact of expected climatic and land use change projections on future rates of soil erosion by water (sheet and rill processes) in 2050 within the arable areas of the European Union and the UK, compared to a current representative baseline (2016).

Climate change and land use change are recognized as the main drivers of soil erosion dynamics, justifying that this research field needs to be addressed more in forthcoming studies (Poesen, 2018). The aim of this chapter is therefore to present the possible effects of climate change and land use change on soil erosion rates in the agricultural soils of the EU and UK by 2050.

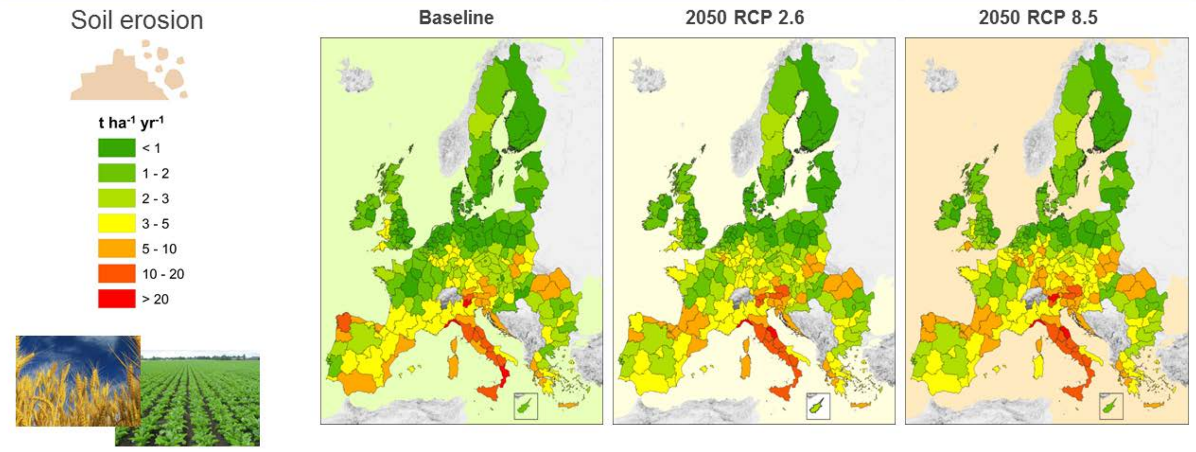
The impact of climate change on rainfall erosivity is modelled using 19 Global Climate Models (GCMs) across three Representative Concentration Pathway (RCP) scenarios in 2050 (Panagos et al., 2022). The land use dynamics are modelled with the Common Agricultural Policy Regional Impact Analysis (CAPRI) model which simulates the use dynamics of the cropping sector in 2050 at regional level (Himics et al., 2014).

In 2050, the mean study area soil losses in the RCP2.6 climate change scenario are projected to be 3.07 t ha^{-1} yr^{-1}, while the RCP8.5 scenario projected a mean soil loss of 3.36 t ha^{-1} yr^{-1} in EU plus the UK arable lands (Fig......). Considering both the climate change projections and land cover changes, the mean soil losses due to water erosion are projected to increase by 15%–26% depending of the climate scenario (Panagos et al. 2021).

The areas with severe water erosion (> 10 t ha^{-1} yr^{-1}) and unstainable soil erosion rates (> 2 t ha^{-1} yr^{-1}) will increase considerably and the total loss is projected to reach 370 million tons (Figure 11). Climate projections for 2050 suggest that potential future net increases in rainfall erosivity (Panagos et al., 2022) would probably offset the effect of current soil conservation efforts leading to soil losses noted pre-2000. It is evident that soil conservation policies need to propose a stronger package of soil conservation practices (e.g., cover crops, reduced tillage, contouring, hedgerows, stone walls, grass margins) compared to the current baseline to mitigate the soil erosion increases by 2050.

Figure 11. *Future projections in soil erosion (EU Arable lands)*

	Baseline	2050 RCP 2.6	2050 RCP 8.5
Total soil loss [Mt]	295	339 (+15%)	372 (+26%)
Mean soil loss [t ha^{-1} yr^{-1}]	2.67	3.07 (+14.9%)	3.36 (+25.8%)
% of land with higher >2 t ha^{-1}	32.2	38	42.3
% of land in severe erosion	12.6	15	16.8
% of land with increased erosion (Future vs. Baseline)	-	70	80



JRC has performed a series of scenario analysis on how to mitigate the impact of climate change in soil erosion. To estimate the mitigation potential of future policy measures, we assume different uptake and application rates for two management practices (green soil coverage, reduced tillage) in a series of policy scenarios. The Agricultural Management Practices (AMPs) focused on mix of the two management practices with different application shares.

Therefore, introducing a flat rate of 50 % soil coverage per country (scenario #1) has a very limited effect. Scenario #2 a minimum soil coverage depending on the erosion rate (10% where soil loss is 1-2 t ha^{-1} yr^{-1} , 25% coverage where soil loss is 2-5 t ha^{-1} yr^{-1} and 50% where sol loss is > t ha^{-1} yr^{-1}) may reduce by half the impact of climate change. A more environmentally ambitious scenario with higher soil coverage shares targeting the erosion hotspots (scenario #3) with stricter application of cover crops (till 75% in hotspots) is even more effective than scenario #2. The targeting scenarios #2 and #3 have a progressive application of cover crops depending on the erosion rates per country.

The application of reduced tillage is progressively increasing in areas with higher erosion rates (from 5% share in the low erosion class to 20 % share in the hotspots). The combined scenario (#5) of reduced tillage and cover crops may counteract the negative effects of climate change on soil erosion. In the combined scenario #5, the management practices (reduced tillage, cover crops) are applied to almost 50 % of the hotspots (> 5 t ha^{-1} yr^{-1}) and could neutralize the effect of climate change as they can reduce the mean soil erosion rates by 22.5% compared to the case of no action.

3.8 Concluding remarks for soil erosion

Soil erosion estimates are of high importance for a number of EU policies such as the CAP, the Soil Strategy 2030, and other related initiatives (e.g. SDGs). Potentially, the soil erosion indicators may also be included in assessing ecosystem services, biodiversity loss (Biodiversity Strategy 2030), sediments pollution (Zero Pollution Action Plan) and Farm to Fork.

Out of the 110 Million ha of arable land in EU and UK, 43 Million ha are vulnerable to at least one erosional process (water, wind, harvest erosion, tillage erosion). For first time, we address all the erosional processes and the likehood to of multiple erosion co-occurrence. Soil erosion by water is the dominant process in the EU causing half of the soil losses (295 Million tonnes; mean: 2.67 t ha^{-1} yr^{-1}). Tillage erosion is dominant in North and Western EU arable lands having a significant contribution to soil losses (208 Million tonnes; mean: 1.88 t ha^{-1} yr^{-1}). Wind erosion is present in Denmark, UK and coastal areas of the Mediterranean (losses of 57 million tonnes; mean: 0.52 t ha^{-1} yr^{-1}). Soil loss by harvesting crops is dominant in areas with root crops (Netherlands, Belgium) and has a minor contribution to the total losses (15 Million tonnes; mean: 0.14 t ha^{-1} yr^{-1}).

According to our modelling approach the application of GAEC soil conservation standards had a positive impact in reducing soil loss by water erosion by about 20% in EU arable lands during the last 16 years. In addition, the reduced tillage application had a positive impact in reducing tillage erosion by 27% in the same period. The soil conservation measures have also contributed to a reduction of 9% in wind erosion. The temporary Ecological Focus Areas and the crop diversification impact on soil erosion could not be accessed as data at EU scale and high resolution are not available.

However, the climate projections suggest that the future increases of rainfall erosivity in Europe will offset the effect of current soil conservation practices. According to latest projections of using all series of RCPs (RCP2.6, RCP4.5 and RCP8.5), the soil loss by water erosion may increase by 15-26% by 2050. Therefore, a stronger soil conservation package has to be introduced to agro-environmental policies.

The thorough comparison of multiple soil erosion processes will help overcoming the dominant idea in policymaking that soil erosion by water is a synonym for soil erosion. Soil erosion by water certainly constitutes a major threat to soils. Multiple processes, however, contribute to soil degradation due to erosion, and, as our results suggest, tillage erosion is potentially just as big a threat as water-driven erosion for the European Union. Depending on the location one investigates, other processes of soil erosion may be more important. Scientists and decision makers should give adequate attention to this and develop appropriate solutions accounting for the processes co-occurrence.

References

Arnhold, S., Lindner, S., Lee, B., Martin, E., Kettering, J., Nguyen, T.T., Koellner, T., Ok, Y.S. and Huwe, B., 2014. Conventional and organic farming: Soil erosion and conservation potential for row crop cultivation. Geoderma, 219, pp.89-105.

Bai, Y., & Cotrufo, M. F. (2022). Grassland soil carbon sequestration: Current understanding, challenges, and solutions. Science, 377(6606), 603–608. https://doi.org/10.1126/science.abo2380

Borrelli, P. and Panagos, P., 2020. An indicator to reflect the mitigating effect of Common Agricultural Policy on soil erosion. Land Use Policy, 92, p.104467.

Borrelli, P., Paustian, K., Panagos, P., Jones, A., Schütt, B., Lugato, E., 2016. Effect of good agricultural and environmental conditions on erosion and soil organic carbon balance: a national case study. Land Use Policy 50, pp. 408–421

Borrelli P, Panagos P, Ballabio C, Lugato E, Weynants M, Montanarella L. 2016. Towards a Pan-European assessment of land susceptibility to wind erosion. Land Degradation and Development 27: 1093–1105. DOI:10.1002/ldr.2318.

Borrelli P, Ballabio C, Panagos P, Montanarella L. 2014b. Wind erosion susceptibility of European soils. Geoderma 232: 471–478. DOI:10.1016/j.geoderma.2014.06.008

Borrelli, P., Panagos, P., Alewell, C., Ballabio, C., de Oliveira Fagundes, H., Haregeweyn, N., Lugato, E., Maerker, M., Poesen, J., Vanmaercke, M. and Robinson, D.A., 2022. Policy implications of multiple concurrent soil erosion processes in European farmland. Nature Sustainability. DOI: 0.1038/s41893-022-00988-4

Bumbiere, K., Sanchez, F.A.D., Pubule, J. and Blumberga, D., 2022. Development and Assessment of Carbon Farming Solutions. Environmental and Climate Technologies, 26(1), pp.898-916.

Buschiazzo DE, Zobeck TM. 2008. Validation of WEQ, RWEQ and WEPS wind erosion for different arable land management systems in the Argentinean Pampas. Earth Surface Processes and Landforms 33: 1839–1850. DOI:10.1002/esp.1738.

Carey, M., 2019. The Common Agricultural Policy's New Delivery Model Post-2020: National Administration Perspective. EuroChoices, 18(1), pp.11-17.

CMEF, 2022. Access in https://agriculture.ec.europa.eu/common-agricultural-policy/cap-overview/cmef_en

Colazo JC, Buschiazzo D. 2015. The impact of agriculture on soil texture due to wind erosion. Land Degradation and Development 26: 62–70. DOI:10.1002/ldr.2297

d'Andrimont, R., Verhegghen, A., Lemoine, G., Kempeneers, P., Meroni, M. and Van der Velde, M., 2021. From parcel to continental scale–A first European crop type map based on Sentinel-1 and LUCAS Copernicus in-situ observations. Remote sensing of environment, 266, p.112708.

Dostal T, Janecek M, Kliment Z, Krasa J, Langhammer J, VaskaJ VK. 2006. Czech Republic. In Soil erosion in Europe, Boardman J, Poesen J (eds). Wiley: Chichester; 107–116

Fasiolo, M., Wood, S. N., Zaffran, M., Nedellec, R., & Goude, Y. (2021). Fast Calibrated Additive Quantile Regression. Journal of the American Statistical Association, 116(535), 1402–1412. https://doi.org/10.1080/01621459.2020.1725521

Fryrear DW, Bilbro JD, Saleh A, Schomberg H, Stout JE, Zobeck TM. 2000. RWEQ: improved wind erosion technology. Journal of Soil and Water Conservation 55: 183–189

Himics, M., Artavia, M., Helaine, S., Boysen, O., 2014. Calibrating the CAPRI and ESIM Models to the Mid-term Commodity Market Outlook of the European Commission. JRC Science and Policy Reports. European Commission, Office for Official. Publications of the European Communities.

Govers, G., Vandaele, K., Desmet, P., Poesen, J. & Bunte, K. 1994. The role of tillage in soil redistribution on hillslopes. Eur. J. Soil Sci. 45, 469–478.

Matthews, A., 2020. The new CAP must be linked more closely to the UN Sustainable Development Goals. Agricultural and Food Economics, 8(1), pp.1-4.

Lindstrom, M. J., Nelson, W. W. & Schumacher, T. E. 1992. Quantifying tillage erosion rates due to moldboard plowing. Soil Tillage Res. 24, 243–255.

Lobb, D.A., Kachanoski, R.G. and Miller, M.H., 1999. Tillage translocation and tillage erosion in the complex upland landscapes of southwestern Ontario, Canada. Soil and Tillage Research, 51(3-4), pp.189-209.

Lugato, E., Bampa, F., Panagos, P., Montanarella, L., & Jones, A. (2014). Potential carbon sequestration of European arable soils estimated by modelling a comprehensive set of management practices. Global Change Biology, 20(11), 3557–3567. https://doi.org/https://doi.org/10.1111/gcb.12551

Panagos, P., Borrelli, P., Poesen, J., Ballabio, C., Lugato, E., Meusburger, K., Montanarella, L., Alewell, C., 2015. The new assessment of soil loss by water erosion in Europe. Environmental science & policy 54, pp. 438–447

Panagos, P., Ballabio, C., Borrelli, P., Meusburger, K., Klik, A., et al., 2015. Rainfall erosivity in Europe. Science of Total Environment 511, 801–814.

Panagos, P., Imeson, A., Meusburger, K., Borrelli, P., Poesen, J. and Alewell, C., 2016. Soil conservation in Europe: wish or reality?. Land Degradation & Development, 27(6): 1547-1551.

Panagos, P., Ballabio, C., Poesen, J., Lugato, E., Scarpa, S., Montanarella, L. and Borrelli, P., 2020. A soil erosion indicator for supporting agricultural, environmental and climate policies in the European Union. Remote Sensing, 12(9), 1365.

Panagos, P., Ballabio, C., Scarpa, S., Borrelli, P., Lugato, E. and Montanarella, L., Soil related indicators to support agri-environmental policies, EUR 30090 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-15644-4, doi:10.2760/011194, JRC119220.

Panagos, P., Ballabio, C., Himics, M., Scarpa, S., Matthews, F., Bogonos, M., Poesen, J. and Borrelli, P., 2021. Projections of soil loss by water erosion in Europe by 2050. Environmental Science & Policy, 124, pp.380-392.

Panagos, P., Borrelli, P. and Poesen, J., 2019. Soil loss due to crop harvesting in the European Union: A first estimation of an underrated geomorphic process. Science of the Total Environment, 664, pp.487-498.

Panagos, P., Borrelli, P., Matthews, F., Liakos, L., Bezak, N., Diodato, N. and Ballabio, C., 2022. Global rainfall erosivity projections for 2050 and 2070. Journal of Hydrology, 610, at.no.127865.

Paul, C., Bartkowski, B., Dönmez, C., Don, A., Mayer, S., Steffens, M., Weigl, S., Wiesmeier, M., Wolf, A. and Helming, K., 2023. Carbon farming: Are soil carbon certificates a suitable tool for climate change mitigation?. Journal of Environmental Management, 330, art.no.117142.

Poesen, J.W., Verstraeten, G., Soenens, R. and Seynaeve, L., 2001. Soil losses due to harvesting of chicory roots and sugar beet: an underrated geomorphic process?. Catena, 43(1), pp.35-47.

Poesen, J., 2018. Soil erosion in the Anthropocene: research needs. Earth Surf. Process. Landf. 43, 64–84

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

Ruysschaert, G., Poesen, J., Verstraeten, G. and Govers, G., 2004. Soil loss due to crop harvesting: significance and determining factors. Progress in Physical Geography, 28(4), pp.467-501.

Ruysschaert, G., Poesen, J., Verstraeten, G. and Govers, G., 2005. Interannual variation of soil losses due to sugar beet harvesting in West Europe. Agriculture, ecosystems & environment, 107(4), pp.317-329.

Ruysschaert, G., Poesen, J., Verstraeten, G. and Govers, G., 2006. Soil losses due to mechanized potato harvesting. Soil and Tillage Research, 86(1), pp.52-72.

Warren A. 2003. Wind erosion on agricultural land in Europe: research results for land managers. Office for Official Publications of the European Communities: Luxembourg

Weldon, J., Merder, J., Ferretti, M. et al. Nitrogen deposition causes eutrophication in bryophyte communities in central and northern European forests. Annals of Forest Science 79, 24 (2022). https://doi.org/10.1186/s13595-022-01148-6

Wiesmeier, M., Urbanski, L., Hobley, E., Lang, B., von Lützow, M., Marin-Spiotta, E., van Wesemael, B., Rabot, E., Ließ, M., Garcia-Franco, N., Wollschläger, U., Vogel, H.-J., & Kögel-Knabner, I. (2019). Soil organic carbon storage as a key function of soils - A review of drivers and indicators at various scales. Geoderma, 333, 149–162. https://doi.org/https://doi.org/10.1016/j.geoderma.2018.07.026

Youssef F, Visser S, Karssenberg D, Bruggeman A, Erpul G. 2012. Calibration of RWEQ in a patchy landscape; a first step towards a regional scale wind erosion model. Aeolian Research 3: 467–476. DOI:10.1016/j.aeolia.2011.03.009

Van Oost, K., Cerdan, O. and Quine, T.A., 2009. Accelerated sediment fluxes by water and tillage erosion on European agricultural land. Earth Surface Processes and Landforms, 34(12), pp.1625-1634.

Verheijen, F.G., Jones, R.J., Rickson, R.J. and Smith, C.J., 2009. Tolerable versus actual soil erosion rates in Europe. Earth-Science Reviews, 94(1-4), pp.23-38.

Zhang K., Qu J, Han Q, Xie S, Kai K, Niu Q, An Z. 2014. Wind tunnel simulation of windblown sand along China's Qinghai-Tibet railway. Land Degradation and Development 25: 244–250. DOI: 10. 1002/ldr.2137

Zobeck TM, Pelt SV, Stout JE, Popham TW, Flanagan DC. 2001. Validation of the Revised Wind Erosion Equation (RWEQ) for single events and discrete periods. In Soil erosion research for the 21st century. Proceedings of the International Symposium, Honolulu, Hawaii, USA, 471–474.

Zobeck TM, Parker NC, Haskell S, Guoding K. 2000. Scaling up from fieldto region for wind erosion prediction using a field-scale wind erosion model and GIS. Agriculture, Ecosystems & Environment 82: 247–259. DOI:10.1016/S0167-8809(00)00229-2.

List of abbreviations and definitions

CAP	Common Agricultural Policy
CAPRI	Common Agricultural Policy Regional Impact
CMEF	Common Monitoring and Evaluation Framework
ESDAC	European Soil Data Centre
GAEC	Good Agricultural and Environmental Conditions
GAM	Generalised Additive Model
PMEF	Performance Monitoring and Evaluation Framework
RCP	Representative Concentration Pathway
RUSLE	Revised Universal Loss Equation
RWEQ	Revised Wind Erosion Equation
SLCH	Soil Loss by Crop Harvesting
SOC	Soil Organic Carbon
qGAM	Quantile Generalised Additive model

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