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Projections of soil loss by water erosion in Europe by 2050

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ABSTRACT

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. This study simulates 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 agricultural areas of the European Union and the UK, compared to a current representative baseline (2016). We used the Revised Universal Soil Loss Equation (RUSLE) adjusted at continental scale with projections of future rainfall erosivity and land use change. Future rainfall erosivity is predicted using an average composite of 19 Global Climate Models (GCMs) from the Coupled Model Inter-comparison Projects (CMIP5) WorldClim dataset across three Representative Concentration Pathways (RCP2.6, RCP4.5 and RCP8.5). Concerning future land use change and crop dynamics, we used the projections provided by the Common Agricultural Policy Regional Impact Analysis (CAPRI) model.

Depending on the RCP scenario, we estimate a +13 %-22.5 % increase in the mean soil erosion rate in the EU and UK, rising from an estimated 3.07 t ha^{-1} yr^{-1} (2016) to between 3.46 t ha^{-1} yr^{-1} (RCP2.6 scenario) and 3.76 t ha^{-1} yr^{-1} (RCP8.5 scenario). Here, we disentangle the impact of land use change and climate change in relation to future soil losses. Projected land use change in the EU and UK indicates an overall increase of pasture coverage in place of croplands. This land use change is estimated to reduce soil erosion rates (-3%). In contrast, the increases in future rainfall erosivity (+15.7 %–25.5 %) will force important increases of soil erosion requiring further targeted intervention measures.

Given that agro-environmental policies will be the most effective mechanisms to offset this future increase in soil erosion rates, this study proposes soil conservation instruments foreseen in the EU Common Agricultural Policy (CAP) to run policy scenarios. A targeted application of cover crops in soil erosion hotspots combined with limited soil disturbance measures can partially or completely mitigate the effect of climate change on soil losses. Effective mitigation of future soil losses requires policy measures for soil conservation on at least 50 % of agricultural land with erosion rates above 5 t ha^{-1} yr^{-1}.

1. Introduction

The latest Intergovernmental Panel on Climate Change (IPCC) special report on climate change and land underlines that the increase of the global mean surface temperature, relative to pre-industrial levels, may substantially affect processes involved in desertification (water scarcity), land degradation (soil erosion, vegetation loss, wildfire, permafrost thaw) and food security (crop yield and food supply instabilities) (IPCC et al., 2019). Climate change is projected to increase severe storm intensity (Brooks, 2013), increasing runoff and decreasing infiltration in arable crops (Basche and DeLonge, 2017) which may cause even greater soil losses than in the beginning of the 21st century(Borrelli et al., 2017).

The importance of climate and land use change in relation to future estimates of soil erosion was already addressed in the early 21st century (Nearing et al., 2004; Yang et al., 2003). The development of climate models has contributed to an exponential increase of literature (from

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less than 50 papers in 2004 to more than 250 papers in 2013; source: Web of Science) investigating the impacts of climate change on soil erosion (Li and Fang, 2016).

In Europe, regional and local studies have projected the impact of future climate change on soil erosion (e.g. Eekhout and De Vente, 2020; Grillakis et al., 2020; Klik and Eitzinger, 2010; Luetzenburg et al., 2020; Mullan et al., 2012, 2019; Routschek et al., 2014). In most of these studies, the authors concluded that rainfall erosivity may increase, resulting in higher soil losses from agricultural fields even if the future mean annual precipitation depth may decrease. Although climate change is a major driver of soil erosion change, some studies have also addressed land use changes and crop rotation as the most prominent factors that will increase future soil erosion (e.g. Paroissien et al., 2015). In addition, a recent review highlights that land use change from natural vegetation to agricultural land, alongside the intensification of agricultural soil management practices have strong links to increased rates of soil erosion (Vanwalleghem et al., 2017).

Climate change and land use change are recognized as the main drivers of future soil erosion dynamics, justifying that this research field needs to be addressed more in forthcoming studies (Poesen, 2018). The aim of this study is therefore to model 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

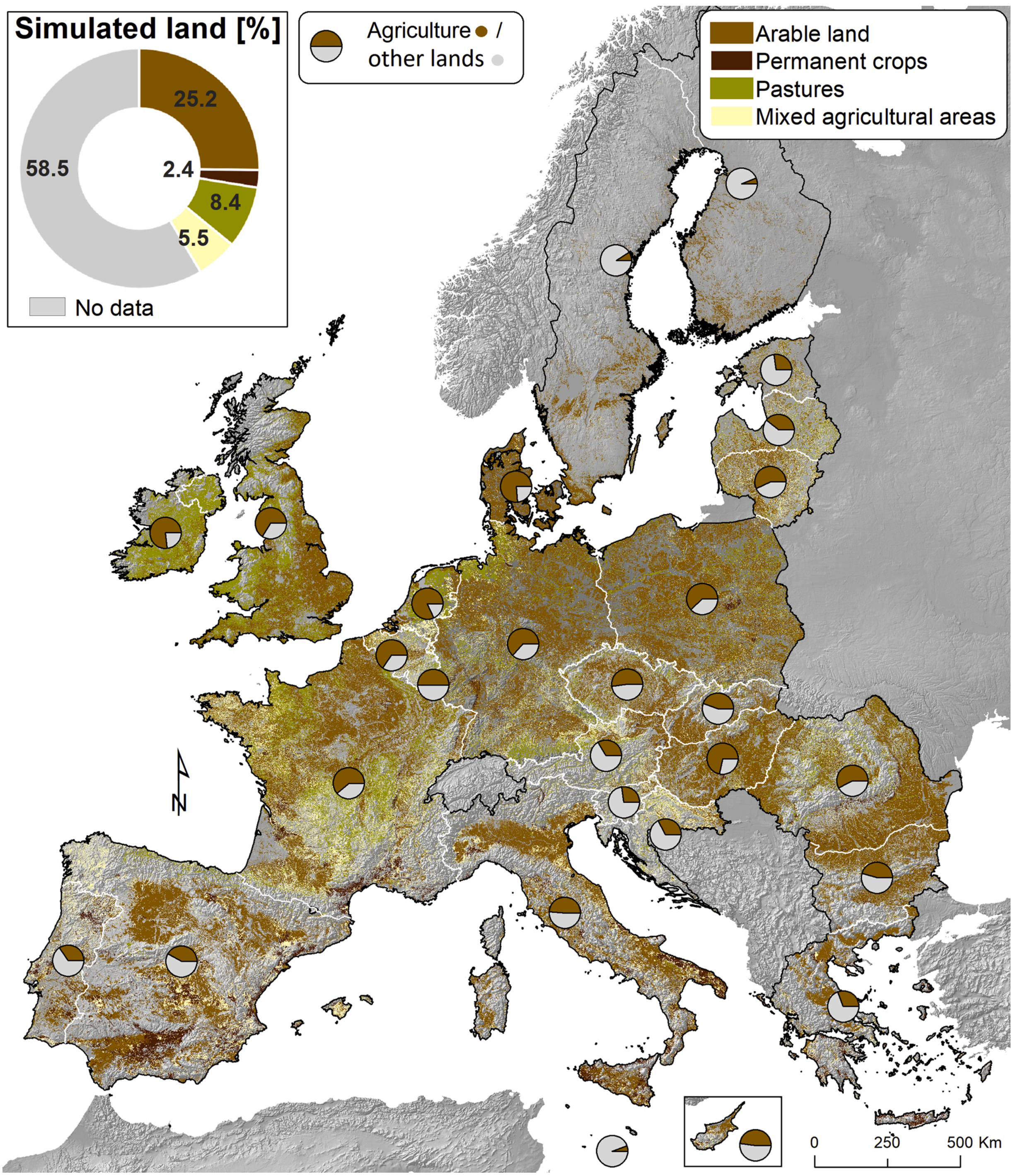


Fig. 1. Study area and spatial distribution of agricultural areas in the EU and the UK (the pie charts represent the % of agricultural area in each country).

three Representative Concentration Pathway (RCP) scenarios in 2050. 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. In addition, this study assesses the effectiveness of EU agro-environmental policies for mitigating soil erosion by promoting farming practices with permanent (or semi-permanent) green cover and limiting soil disturbance from agricultural activities.

2. Data and methods

2.1. Study area

The study area includes all agricultural lands of the European Union (EU) plus the United Kingdom (UK). These cover about 41.5 % of the total land area (Fig. 1), showing substantial variations between countries. The agricultural lands are spatially defined by all the CORINE Land Cover (CLC) groups of arable lands (CLC code: 2.1), permanent crops (2.2), pastures (2.3) and the major part of heteronomous agricultural areas (i.e., crops associated with permanent crops – code 2.4.1, complex cultivation pattern – code 2.4.2). The definitions and classification of land cover groups follows the guidelines of the European Environmental Agency (Kosztra et al., 2017). The CORINE Land Cover dataset (100 m cell size) used is a hybrid land cover layer which is based on the CORINE Land Cover 2006 version with the application of a Land Cover Changes 2006–2012 layer. This land cover layer was used as the main input to update the cover-management factor (C in the RUSLE model) for the European Union as described by Borrelli and Panagos (2020) and to estimate the 2016 soil erosion dataset (Panagos et al., 2020).

As mentioned above, the fraction of the total area occupied by agricultural land is not equally distributed amongst European countries. For example, this value exceeds more than ¾ in Ireland, the Netherlands, and Denmark while this share is less than ¼ in Malta, Finland and Sweden (pie charts in Fig. 1).

2.2. Model integration

At continental scale, the use of an empirical model to predict soil losses by water erosion (sheet and rill processes) such as the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997) is preferable compared to process-based models because of data availability, less complexity and available baselines (Fenta et al., 2020). Both complex and empirical soil erosion models take mainly as inputs the pedological conditions (soil properties), climate (rainfall intensity), topography (slope steepness and length), vegetation coverage (land cover, crop) and the anthropogenic influence (management practices). The European version of RUSLE (named RUSLE2015) has been adjusted to continental scale based on the best available and harmonised input layers (*detailed model description in Chapter 1 of* supplementary *material*).

The pedological and topographic conditions are assumed as static properties through time; therefore the soil properties derived factor and the topographic factor (Fig. 2) remain those used for the baseline (2016) soil erosion assessment in Europe (Panagos et al., 2015c). The other three factor inputs (i.e. climate, land cover, management) are mainly driven by anthropogenic activities and they change both in time and space. Climate change introduces fluctuations in rainfall intensity; economic development influences the land use change; agro-environmental policies may have an impact on agricultural soil management. The time horizon of this outlook (2050) gives the capacity to model the impact of climate change, land use change and the policy options. The projections of climate change, land use change and policy impact have large uncertainties which are discussed below.

Rainfall erosivity change, land use dynamics and policy-driven management practices form the three dynamic modules of the RUSLE model and apply the following three models: a) Gaussian Process Regression (GPR) for rainfall erosivity change b) Common Agricultural Policy Regional Impact analysis (CAPRI) and Land Use and Management (LANDUM) for land use dynamics and c) LANDUM for management practices change (Fig. 2).

2.2.1. Agricultural land use dynamics 2050

The main agricultural land use dynamics influencing soil erosion

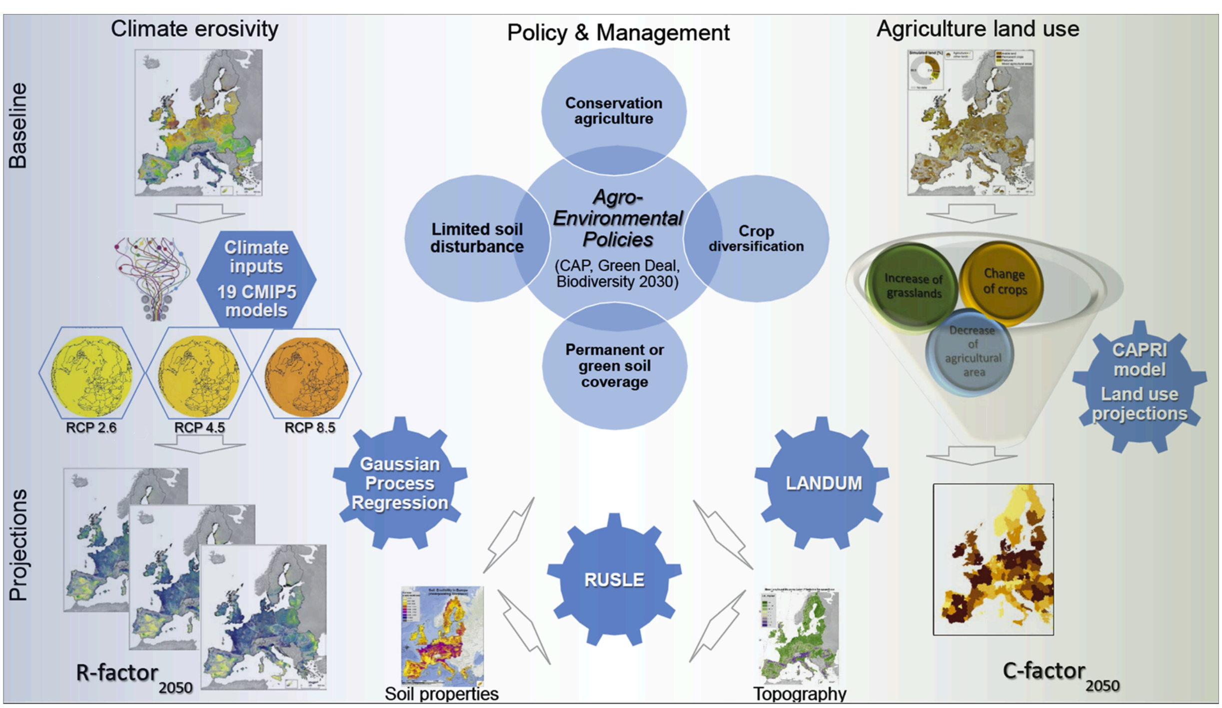


Fig. 2. Model integration for estimating the erosion projections 2050. Left side: modelling future projections of rainfall erosivity. Right side: Modelling land use dynamics. Middle: Modelling policy impact in management practices. Acronyms are explained in the text.

projections in 2050 are: a) changes in crop types, b) the conversion of arable land to pastures and c) the shrinkage of EU agricultural area. Below, we outline some figures for each of the three dynamic factors.

Agricultural land use (41.5 % coverage) remains the primary usage in the EU and the UK, despite competition from other uses. According to the current baseline, agricultural land use (arable, permanent crops, and pastures) is estimated to cover ca. 180 million ha which is distributed as following: 109 million ha of arable crops (61 % of total), 11.5 million ha of permanent crops (6%) and the rest 59 million ha (33 %) are pastures together with mixed areas.

The CAPRI model is used here to quantify future agricultural land use dynamics. CAPRI is a comparative static, partial equilibrium model of the agricultural sector and global food commodity markets (Britz, 2008). CAPRI covers the impact of global agri-food trade on commodity prices, with indirect effects on feed and food demand, and on agricultural supply. CAPRI includes a detailed database with production statistics for 37 cropping activities in more than 220 EU regions (NUTS2 level). In Chapter 2 of the supplementary material (Table S1), we provide the land-use shares of the crops both for the baseline (current) and for the projected year 2050.

In this study, CAPRI provides land use projections (crop and land cover dynamics) for European agriculture in 2050. This can be done as CAPRI includes a trend projection module for deriving consistent future trends on agricultural production. These projections are derived with the trend projection module of CAPRI, which combines historical data with various external economic projections (Himics et al., 2014, 2018). The nested land allocation structure of CAPRI simulates land moving in and out of agriculture, as well as transformation between arable and grassland use (Renwick et al., 2013). (*Detailed description of CAPRI model in Chapter 2 of Additional material)*.

The CAPRI model is coupled with the Land Use and Management (LANDUM) model which is a hybrid empirical model to estimate the cover-management factor (C-factor) in the RUSLE model (Borrelli and Panagos, 2020; Panagos et al., 2015b). LANDUM first assigns a C-factor value to each crop type (Fig. 2) and then estimates the C-factor at regional level based on crop composition and the influence of management practices (Lilja et al., 2017; Vijith et al., 2018). In practice, for each region, the C-factor in the agricultural land is calculated by multiplying the share of each crop (%) with its C-factor value (supplementary material Table S2) and then summing the results for the 37 available crops (Eq. 1).

$$\mathbf{C-factor_{Crops}} = \sum_{n=1}^{37} C_{crop-n} * [\%]Region_{Crop-n} \qquad (1)$$

As crop composition, we define the shares per crop in each region. The crop composition is important for calculating the cover management factor (C) in a region as the presence of less erosive crops (e.g., wheat, rice) reduce water erosion rates compared to highly erosive crops (e.g., maize, tobacco, sugar beets). The arable area includes cereals (soft wheat, durum wheat, rye, barley, oats, grain maize, and rice), oilseeds (rape, sunflowers, soya, other oils), other arable crops (pulses, potatoes, sugar beets, flaxes, tobacco, industrial crops), vegetables (tomatoes, nurseries, flowers, new energy crops), fodder crops (fodder maize, fodder root crops) and set aside land. The permanent crops category includes apples, citrus fruits, other fruits, table grapes, vineyards, table olives and oil olive trees (detailed description of LANDUM model in Chapter 3 of supplementary material).

The cover-management factor is the most dynamic component of the RUSLE soil erosion model used in the study. CAPRI simulates per region (NUTS2 level) the three types of agricultural land use dynamics which fit into the RUSLE erosion model (Fig. 2): a) dynamic change of arable crops (crop composition of an area) b) transformation between arable land and grassland use and c) decrease of agricultural land. The LANDUM model used the 2050 CAPRI-derived agricultural condition, producing the C-factor 2050. The 2016–2050 C-factor fluctuations at regional level are the result of the crop composition in 2050 and the land cover dynamics (transformation arable to/from grassland, decrease/increase of agricultural area per region).

2.2.2. *Climate change and rainfall erosivity dynamics*

The IPCC climate change projections for Representative Concentration Pathways (RCP) (IPCC, 2014; Pachauri et al., 2014) indicate that the mean surface air temperature is expected to increase in 2046−65 by a mean of 1 °C (range: 0.4–1.6 °C) in RCP2.6, 1.4 °C (range: 0.9−2 °C) in RCP4.5 and 2.0 °C (range: 1.4–2.6 °C) in RCP8.5 compared to the period 1986−2005. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (Stocker et al., 2014) and other scientific studies (Thorndahl et al., 2017) also concluded that the frequency and intensity of heavy rainfall events are likely to increase during this period.

The rainfall erosivity projections use three Representative Concentration Pathways (RCPs) from the most aggressive mitigation pathway (RCP 2.6) to the less aggressive one (RCP8.5). For each of the RCPs (2.6, 4.5 and 8.5) the climatic data of the available model scenarios are inputs to estimate the future erosivity. To avoid possible biases due to the choice of one particular model projection over another, we decided to include all 19 Global Climate Models (supplementary material Table S4) which are currently available at the highest requested spatial resolution (30 seconds). Therefore, the downscaled Coupled Model Intercomparison Projects (CMIP5) (Fick and Hijmans, 2017; WorldClim, 2019) made accessible the climate data (19 models across three RCPs) such as monthly precipitation, air temperature (min, max) and other bioclimatic variables (e.g. precipitation of the driest/wettest quarter or month) for the year 2050 necessary for the estimation of rainfall erosivity. The climate data and the bioclimatic variables for the 2050 represent the average of the period 2041−2060: https://www.worldclim.org/data/v1.4/cmip5_30 s.html#2050.

The rainfall erosivity baseline is the Rainfall Erosivity Database at European Scale (REDES) (Panagos et al., 2015a) which was developed across Europe using high temporal resolution (e.g. sub-hourly) precipitation data. The rainfall erosivity projections 2050 combine the REDES baseline with the WorldClim rainfall data (Fick and Hijmans, 2017; WorldClim, 2019) of the 19 CMIP5 models and the 3 RCP scenarios (Fig. 2).

At the continental scale, one of the first attempts to estimate future rainfall erosivity was made for North America in 2001 (Nearing, 2001) using the HadCM3 climate change scenario. In Europe, the 2050 rainfall erosivity projections have so far been estimated (Panagos et al., 2017) using only one scenario (HadGEM2 in RCP4.5). Here, the development of future erosivity datasets uses a two-step combined model approach. Firstly, the Gaussian Process Regression (GPR) (Williams and Rasmussen, 2006) establishes a statistical relationship between the actual erosivity values of REDES and the WorldClim baseline data (year: 2010). GPR uses an optimization technique named Simulated Annealing (Kirkpatrick et al., 1983) to find the best set of covariates to limit the Root Mean Square Error. In a second step, GPR applies the future (2050) climate data layers of the 19 models and 3 scenarios to produce the corresponding rainfall erosivity projections (R-factor 2050) (Fig. 2).

2.2.3. *Policy development and change of management practices*

Public policy entities (government, regional authorities) and the EU can propose the legislative and regulatory instruments to conduct interventions and reverse negative trends in cases of environmental threats such as soil loss. Such instruments can include legislation to limit the impacts of intensive land management (Cerdà et al., 2018; Stavi and Lal, 2015); for example, protecting agricultural lands that are susceptible to a given soil erosion threshold (e.g., > 10 t ha^{-1} yr^{-1}). Policy instruments might also propose agro-environmental indicators and set threshold values based on the exceedance of soil formation rates (1−2 t ha^{-1} yr^{-1}) or a severe erosion threshold.

The main EU agro-environmental policies (Common Agricultural

Policy, Soil Thematic Strategy) recommend the policy instruments to mitigate soil erosion. A more environmentally friendly agriculture (conservation agriculture) proposes three main groups of measures to mitigate soil erosion: diversification of cropping systems, limited soil disturbance, permanent (or green semi-permanent) soil coverage (Fig. 2). In the post-2020 CAP and the upcoming new EU Green Deal there are options to include a more sustainable soil management in agricultural soils by applying policy measures for a more environmentally friendly agriculture.

To estimate the impact of policy measures, we use again the Land Use and Management (LANDUM) model which allows the quantification of the impact of soil conservation measures in reducing the C-factor (Panagos et al., 2015b). Among an extensive list of best Agriculture Management Practices (AMPs) to improve soil quality (Barão et al.,

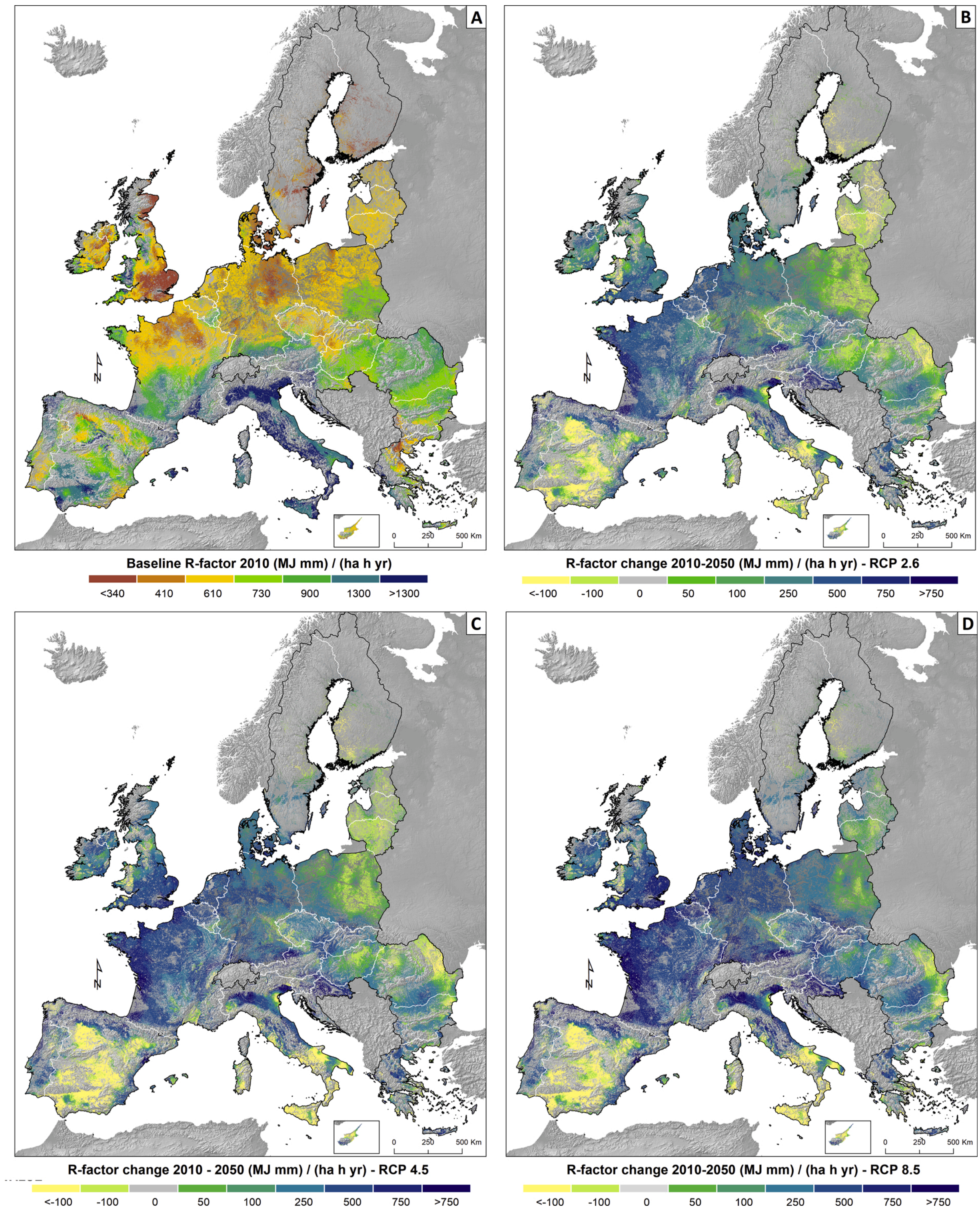


Fig. 3. Changes in annual rainfall erosivity projections in EU plus the UK agricultural lands by 2050 according to RCP scenarios. (A) The baseline annual rainfall erosivity for 2010. (B-D) Absolute changes of annual erosivity for the three RCPs scenarios (B: RCP2.6; C: RCP4.5; D: RCP8.5) compared to the baseline. Future projections for 2050 is an average for the period 2041-2060.

2019), we simulated the increased uptake of cover crops and reduced tillage. Both are already included in the Good Agricultural and Environmental Conditions (GAEC) of the EU Common Agricultural Policy (Panagos and Katsoyiannis, 2019). In the Commission proposal for the post-2020 Common Agricultural Policy (CAP), the main soil conservation policy instruments are GAECs which focuses on tillage management (GAEC 6), no bare soil (GAEC 7) and crop rotation (GAEC 8) (Heyl et al., 2020). The effects of those management practices are modelled in LANDUM taking into account experimental findings in the literature (Chapter 3 of supplementary material).

Experimental studies have shown the positive effects of crop rotation on nutrient losses and soil erosion mitigation (Golosov et al., 2017; Hunt et al., 2019; Ligonja and Shrestha, 2015). However, at the continental scale it is implausible to simulate a very large number of combined crop rotations; thus, we have not simulated the impact of crop rotation scenarios on future soil losses. Therefore, we have restricted the set of policy measures to the relevant ones for soil conservation (cover crops, reduced tillage), as proposed for the post-2020 CAP (European Commission, 2018). Cover crops reduce soil loss by at least 20 % as they improve soil structure, increase infiltration and protect the bare soil to reduce the impact of heavy storms (Kaye and Quemada, 2017; Maetens et al., 2012; Panagos et al., 2015b; Verstraeten et al., 2002). Reduced tillage preserves soil quality and can reduce soil erosion by two-thirds (Bogunovic et al., 2018; Mhazo et al., 2016; Novara et al., 2011; Wang et al., 2007).

3. Results

3.1. Future rainfall erosivity in European Union

In 2010, the mean rainfall erosivity in agricultural lands of the EU and the UK is 4% less (697.6 MJ mm ha^{-1} h^{-1} yr^{-1}) compared to the mean rainfall erosivity of the entire landmass (Panagos et al., 2015a). In the agricultural lands of the EU plus the UK, the mean rainfall erosivity 2010−2050 change varies from +22 % in RCP2.6, +23.9 % in RCP4.5 and +36.9 % in RCP8.5 scenario (Fig. 3). These averages account for all 19 downscaled models available in the Coupled Model Inter-comparison Projects (CMIP5) WorldClim database (30 seconds spatial resolution) covering Europe. The erosivity change (baseline – 2050) has a big variability between scenarios (*supplementary material Table 4; Fig. S6*). In addition, the erosivity projections 2050 do not refer to a single year they represent an average for the period 2041−2060.

The trends of future rainfall erosivity follow different patterns in the study area depending on the climate zone. In EU and UK, there are six clusters (zones) capturing the different erosivity characteristics (Ballabio et al., 2017). Cluster 1 includes Eastern Europe with high erosive events in autumn (September – November) and shows a mean rainfall erosivity increase by 2050 of 21 % (RCP2.6) to 35 % (RCP8.5) compared to the baseline. Clusters 2 and 3 occupy the largest part of the EU (North and Western Europe) with a predominance of erosive events in late spring and early summer. Cluster 2 is expected to have the highest erosivity increase (49 %–80 %) followed by cluster 3 (36 %–65 %). Cluster 4 covers the major part of the Mediterranean basin (Italy, Spain, Portugal and south France) where the erosive events in late spring and early autumn are the dominant ones. This cluster shows a relatively small increase of erosivity (7 %–12 %) compared to the other clusters. Finally, cluster 5 is limited to western France, Andalusia (ES), Calabria (IT), western Greece and western United Kingdom and shows an occurrence of erosive events in autumn and some high erosive events in winter. This is the only cluster with projected decreased erosivity (-5% to -9%). Cluster 6 is limited to the Alpine areas where agricultural lands are limited. (*Detailed mapping of the six erosivity clusters in* supplementary *material Fig. S5*).

3.2. Impact of land use change on soil loss

According to the EU Agricultural outlook, agricultural land use will cover ca. 176 million ha in 2030 and ca. 173 million ha in 2050 (European Commission, DG Agriculture and Rural, 2018). The crop land use-dynamics of the cropping sector in 2016–2050 is estimated from the agricultural land use projections of CAPRI. Accordingly, arable land will decrease by 8.4 million ha, permanent crops will remain in the same order of magnitude and there will be a small increase of about 1 million ha in pastures. This means that the share of pastures will increase by 2% by 2050 and the share of arable lands will decrease by 2.1 %. The decrease in arable lands is a combination of a 6.6 million ha decline in cereals, 2.5 million ha decline in oilseeds and an increase of 0.2 million ha in fodder crops and an increase of 0.8 million ha in vegetables. This is a summary of crop dynamics; however, the CAPRI model produced detailed land use projections for 37 cropping activities in each NUTS2 region of the EU and UK.

By coupling the crop land use-dynamics to the LANDUM model, we estimated the cover-management factor (C) for 2050 in agricultural lands of the EU plus UK (see Eq. 1). The mean estimated C-factor in agricultural lands is 0.192 in our baseline year (2016). Regarding the land use sub-categories, the mean C-factors for arable crops and permanent crops are higher (0.232 and 0.259, respectively), while the mean C-factor for pastures is 0.09. The C-factor in all agricultural areas is expected to decrease by 2.1 % (low: -1.2 %; high: -3.6 %) by 2050. The percentage change has a range (low, high) in order to capture a variation of C-factor values assigned per crop (supplementary material tables 2 and 3). For example, if we use a C-factor value of 0.05 for pastures the C-factor reduction would be higher (3.6 %) than using 0.15.

At the EU plus the UK level, the main driver of the C-factor change (-2.1 %) is the 2% increase of pastures at the expense of arable lands, while crop composition change has a minor influence. Although the C-factor change of the whole study area is relatively small, the 2016–2050 C-factor fluctuations show that at least ¼ of the regions have a >-5% change (*Figure S7 of the supplementary material*). Below, we propose some examples of C-factor variations at regional level. Among the countries with significant decreases in the C-factor, we highlight Czechia (-11 %) as the share of pasture in agricultural lands are projected to increase from 26 % to 44 %. In addition, Ireland shows an important C-factor decrease (-7%), as the share of pastures are projected to increase from 75 % to 82 %. For Portugal the C-factor is projected to decrease by 5%. A significant increase of the C-factor is expected in the Netherlands (+10 %) as the arable lands are projected to increase from 54 % to 64 % at the expense of pastures (*Fig. S7 of the supplementary material*).

The changes in crop composition within arable lands influenced the 2050 cover management factor in some regions. For example, in Denmark the 6% increase of the C-factor is due to a decrease of cropland area with cereals and an increase of energy crops. In Slovenia, the -15 % change of the C-factor is related to an increase of cereals and a decrease of more erosion-prone crops (e.g., fodder). Finally, changes in permanent crops had a small impact in some Mediterranean countries. For the whole study area, the C-factor in permanent crops shows an overall decrease by 4% on average, mainly due to a replacement of million ha of vineyards (mainly located in Spain and Italy) by olive groves and other permanent crops which are less prone to erosion.

3.3. Projections of water erosion in EU and UK agricultural soils

The baseline soil erosion dataset (2016) for the 180 million ha of agricultural lands (representing 41.5 % of the EU plus the UK) indicates a mean soil loss rate of 3.07 t ha^{-1} yr^{-1}. By multiplying this mean soil loss rate with the agricultural area of c.a. 180 million ha, we get the total mass of soil displaced with water erosion. This mass is estimated to be ca. 553 million tonnes and represents ca. 58 % of the total soil losses by water erosion in the EU and the UK.

The 2050 water erosion estimates refer to the period 2041−2060.

Compared to the 2016 baseline, the increase of soil loss by 2050 is evident (Fig. 4). Almost the whole study area (84 %) has an increasing trend in the RCP8.5 scenario with just a part of the Mediterranean projected to have less erosion than the baseline (green part in Fig. 4). In the most aggressive mitigation pathway scenario RCP2.6, the erosion is expected to increase in ¾ of the study area and decrease in the other ¼. In addition, the map of change (Fig. 4) shows the risk of having a considerable area which potentially could show a soil erosion increase of more than 1 t ha^{-1} yr^{-1} (orange - red colours in Fig. 4). The agricultural areas increasing by at least 1 t ha^{-1} yr^{-1} are 15.8 % in RCP2.6 scenario and almost ¼ (24 %) in RCP8.5.

In 2050, the mean study area soil losses in both the RCP2.6 and RCP4.5 scenarios are projected to be 3.47 and 3.46 t ha^{-1} yr^{-1} respectively, while the RCP8.5 scenario projected a mean soil loss of 3.76 t ha^{-1} yr^{-1} in EU plus the UK agricultural soils. Considering both the climate change projections and land cover changes, the mean soil losses due to water erosion are projected to increase by 13 %–22.5 % depending of the climate scenario (Fig. 5).

Whilst the RCP2.6 and RCP4.5 soil loss projections have relatively close values when we aggregate the results (Fig. 5), the spatial patterns have some differences. For example, compared to the baseline data 2016, 74 % of the area is expected to show an increasing soil erosion trend and 26 % of the agricultural lands to have a decreasing trend for the scenario RCP2.6 (Fig. 4). In the RCP4.5 scenario, soil loss by water erosion is estimated to increase in the 76 % of the agricultural lands and decrease in for the rest. Finally, under the extreme RCP8.5 scenario, only 16 % of the EU plus the UK agricultural land is expected to have decreased erosion rates compared to the 2016 baseline while the remaining 84 % will probably experience higher erosion rates (Figs. 4 and 5).

In the case of the less aggressive mitigation pathway RCP8.5, the severe soil erosion (rates higher than 10 t ha^{-1} yr^{-1}) may increase from current share of 6.6 % to the 8.6 % in 2050 (Fig. 5). The low erosion classes (0–2 t ha^{-1} yr^{-1}) occupy 65.6 % of EU plus the UK agricultural lands in the baseline. In 2050 this agricultural area subject to low erosion rates is projected to decrease by at least 9.1 % (≈ 158,000 ha) (*Detailed statistics in the* supplementary *material Chapter 4)*. In contrast, the medium and high erosion classes (>5 t ha^{-1} yr^{-1}) cover 15.1 % of EU plus the UK agricultural land in 2016 and could potentially be increased by 4.4 % (≈ 76.000 ha).

It is also interesting to disentangle the impact of climate change and land use change in relation to future soil losses. If we only consider climate change, then the mean soil losses would increase in the range of 15.7 %–25.5 % in the EU plus the UK by 2050 (Fig. 5). Therefore, the cumulative effect of land use changes contribute to mitigate average soil loss by around 3%.

In 2050, the total agricultural area in the EU and UK is expected to shrink by 7 million ha according to CAPRI projections (-3.9 %). This shrinkage of agricultural land mitigates to some extent the increase of water erosion as the soil losses may vary from 595 to 645 million tonnes depending on the scenario (Fig. 5). Compared to the baseline (2016) total soil losses, we estimate that the combined effect of land use change due to the increase of pastures and the shrinkage of agricultural lands could mitigate the total soil loss from water erosion by 7.7 %–8.5 % in 2050. This mitigation effect is the difference of soil erosion increase by considering only climate change (increase: 15.7–25.5 %) with the combined case of climate change, land use change and shrinkage of agricultural lands (increase: 8–17 %) (Fig. 5). However, the mean soil losses is projected to increase significantly (13 %–22.5 %) as the impact of increased rainfall erosivity is comparatively more substantial in a major part of the EU.

3.4. Regional soil losses in 2050

The picture of future soil erosion in the EU plus the UK shows important differences at regional scale (Fig. 6). Mean soil losses in Southern European countries will either decrease (Spain) or will not change (Italy). The change (%) of soil losses in the period 2016–2050 at regional level shows a significant shift in Central and Northern European regions from a mean soil erosion increase of 10–50 % (RCP2.6) towards a mean increase which varies in the range of 20–100 % for the RCP8.5 scenario (Fig. 6b, 6d). The effect of this shift is smoothed when we

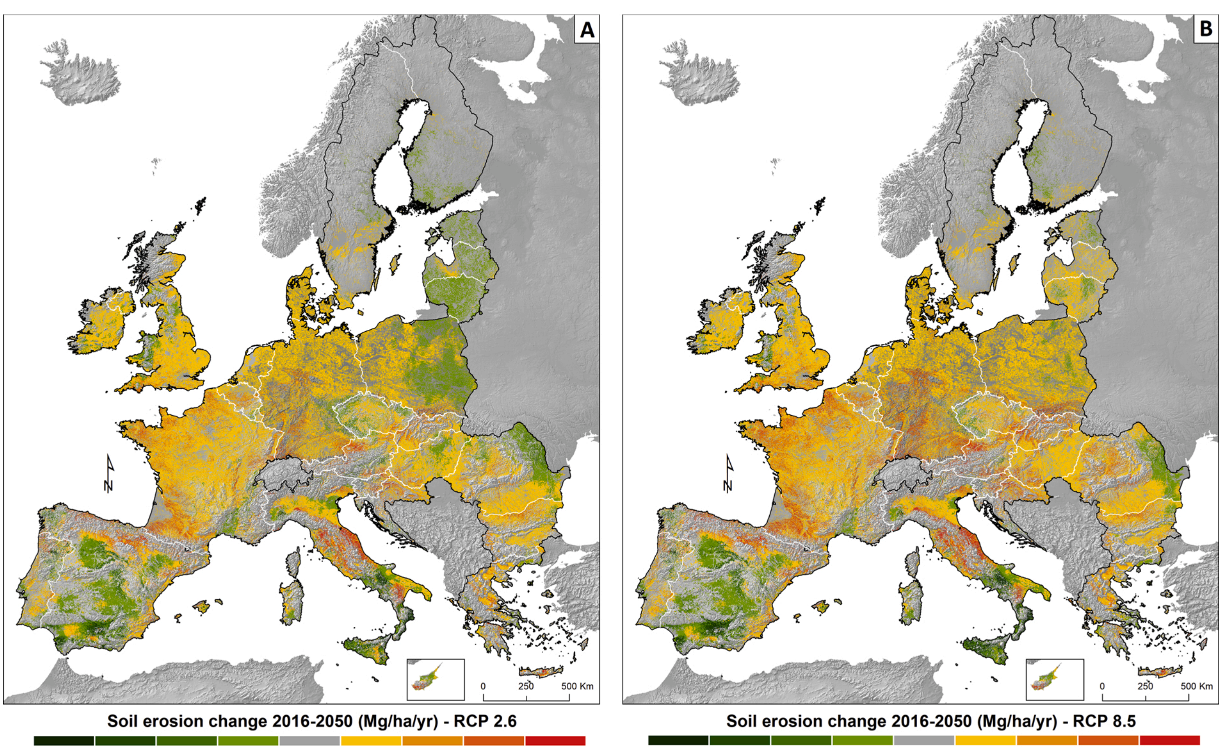
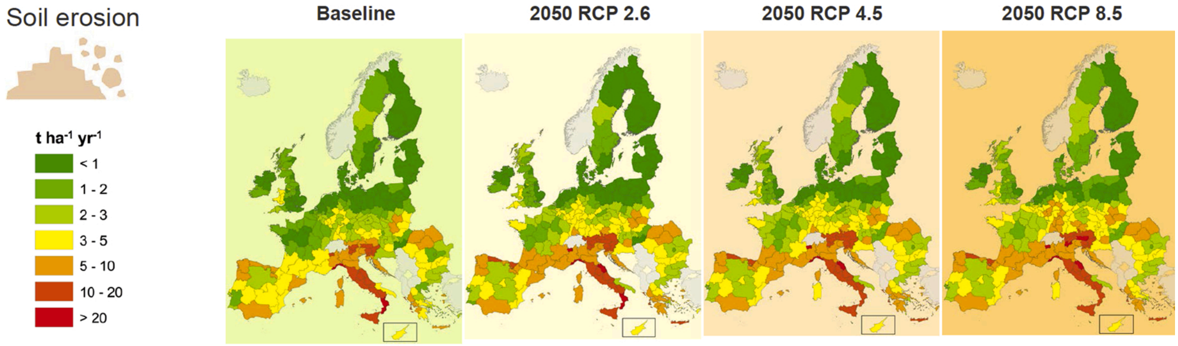


Fig. 4. Changes in soil losses by water erosion between the baseline (2016) and the two main RCPs scenarios (2.6, 8.5) for 2050.

	Baseline	2050 RCP 2.6	2050 RCP 4.5	2050 RCP 8.5
Total soil loss [Mt]	553	596 (+8%)	595 (+8%)	645 (+17%)
Mean soil loss [t ha^{-1} yr^{-1}]	3.07	3.47 (+13%)	3.46 (+13%)	3.76 (+22.5%)
% of land in severe erosion	6.6	7.8	7.7	8.6
% of land with increased erosion (Future vs. Baseline)	-	74	76	84



180.3 million ha (2016)	Utilized agricultural area: 173 million ha (-3.9%) in 2050					
Relative change due to: Land use / Climate	Land use change	Climate change	Land use change	Climate change	Land use change	Climate change
	-3.3%	+16.7%	-2.8%	+15.7%	-3%	+25.5%

Fig. 5. Summary of main indicators for soil loss by water erosion in agricultural soils of the EU by 2050: Total soil loss, Mean soil loss, % of land in severe erosion (> 10 t ha^{-1} yr^{-1}), % of land with increasing soil erosion rates (Future scenario vs. Baseline), trends, and impact of climate change and of land use change.

aggregate the data at continental scale because most of those regions have relatively low mean soil erosion rates of 1−3 t ha^{-1} yr^{-1} for the 2016 baseline (Fig. 6a).

Countries with currently low erosion rates such as France, Denmark and the Netherlands are expected to experience the largest increase, mainly due to climate change (Fig. 7). In the Netherlands, the combined effect of increased rainfall erosivity and increased C-factor values due to less pastures (more arable) compounds to almost double the mean erosion rates by 2050.

Another important feature is the large regional differences in soil loss change between Southern and Northern Europe, mainly due to climate change projections. The relatively small increase of soil loss (or even decrease in some 'green' coloured regions) in currently highly erosive areas of Italy, Slovenia, Portugal, Spain and Greece (Fig. 6) results in a lowering of the mean EU-wide soil loss increase to medium levels (13–22.5 %).

For the Southern European countries (Italy, Spain, Greece, Portugal and Bulgaria), the two extreme scenarios (RCP2.6, RCP8.5) result in very small differences (< 5%) (Fig. 7). In contrast, these two scenarios show significant differences in soil loss (almost double % change between 2016 and 2050) in Western Europe (Austria, Belgium, Denmark, Germany, Netherlands) and parts of Eastern Europe (Czechia, Hungary, Poland, Romania) (Fig. 7). In the Baltic States (Estonia, Latvia, and Lithuania) and Finland, we modelled mixed trends depending on the scenario severity. In the case of RCP2.6, erosion rates are projected to decrease in this part of the EU while a possible shift to RCP8.5 scenario will increase soil losses (Fig. 7).

4. Discussion

4.1. Policy options for mitigating soil erosion

The cumulative impact of climate change (based on the three RCP scenarios) and land use change is a projected increase in soil erosion rates of 13–22.5 % in agricultural lands of the EU plus UK by 2050. This sizable gap can be eliminated (or at least reduced) with management practices for reduced soil losses.

These management practices can be either optional or mandatory for farmers depending on the legal framework. 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. For constructing the scenarios, we followed the approach in the impact assessment of the post-2020 CAP (European Commission, 2018): we have introduced a flat rate of 50 % soil coverage per country (scenario #1), a minimum soil coverage depending on the erosion rate (scenario #2) and a more environmentally ambitious scenario with higher soil coverage shares targeting the erosion hotspots (scenario #3) (Table 1). The targeting scenarios #2 and #3 have a progressive application of cover crops depending on the erosion rates per country. Compared to the 2050 projections (Fig. 5), the reduction potential of soil losses by applying cover crops scenarios (#1, #2, #3) varies in the range 7.4 %–11.5 % (Table 1). Amongst them, the targeted #3 scenario may keep erosion rates close to the baseline for the RCP2.6 and RCP4.5 climate change scenarios, while limiting the erosion increases to 10 % in the case of RCP8.5. The results show that targeted scenarios are more efficient as they focus on soil erosion hotspots within each country.

The most efficient scenarios for reducing soil losses include those with reduced tillage (scenarios #4 and #5) as they have a reduction potential of 17 %–22.5 %. 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). Even if the reduced tillage scenario #4 results in significant decreases of soil losses, 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 (Table 1). However, the adoption of reduced tillage practices depends also on other factors such as the impact on crop yields (Van den Putte et al., 2010), the higher herbicides use compared to conventional tillage (Melander et al., 2013) and farmers' socio-economic characteristics such as age, income, region and awareness (Zikeli and Gruber, 2017) as well as their attitude (Wauters et al., 2010). Thus, cover crops are a preferable option to mitigate soil erosion.

The current CAP 2014–2020 includes rules for more greening payments such as crop diversification, maintenance of permanent

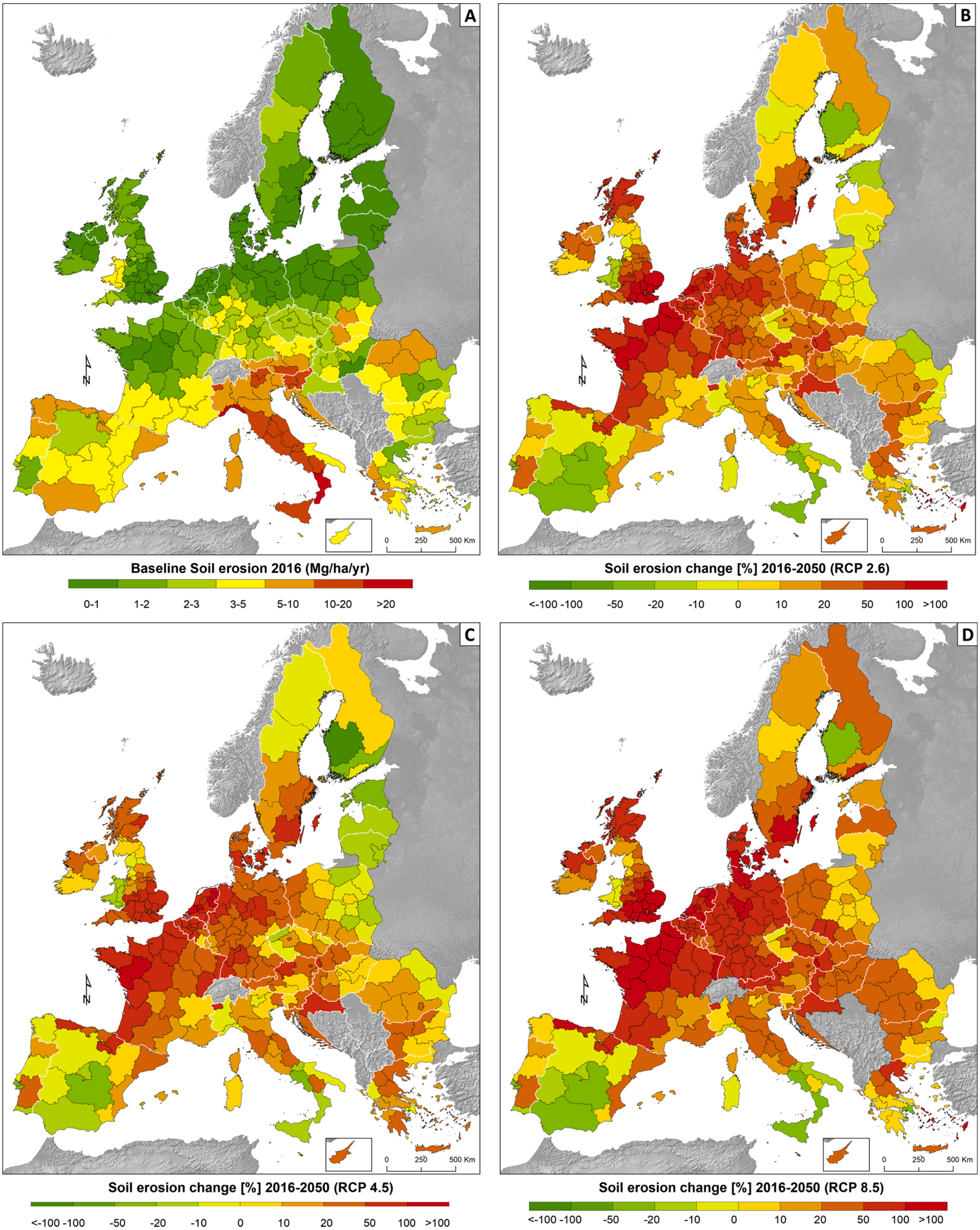


Fig. 6. Regional differences between the baseline and the future soil loss projections. (A) The baseline dataset of soil loss rate (Mg ha^{-1} yr^{-1}) in EU plus the UK agricultural soils is for 2016. (B-D) Percentage changes of mean soil loss rates by 2050 for the three RCPs scenarios compared to the baseline.

grasslands and ecological focus areas (Bouma and Wösten, 2016). However, a recent review (Pe'er et al., 2020) proposes a more sustainable agriculture for the post-2020 CAP with more effective tools for climate mitigation and biodiversity protection. A greener CAP would require the decoupling of financial incentives from production, instead of linking them with environmental targets and a greener performance (Navarro and López-Bao, 2018). In this debate, it is evident that policy makers would propose a stronger package of soil conservation practices (e.g., cover crops, reduced tillage, contouring, stone walls, grass margins) compared to the current baseline to mitigate the soil erosion increases by 2050.

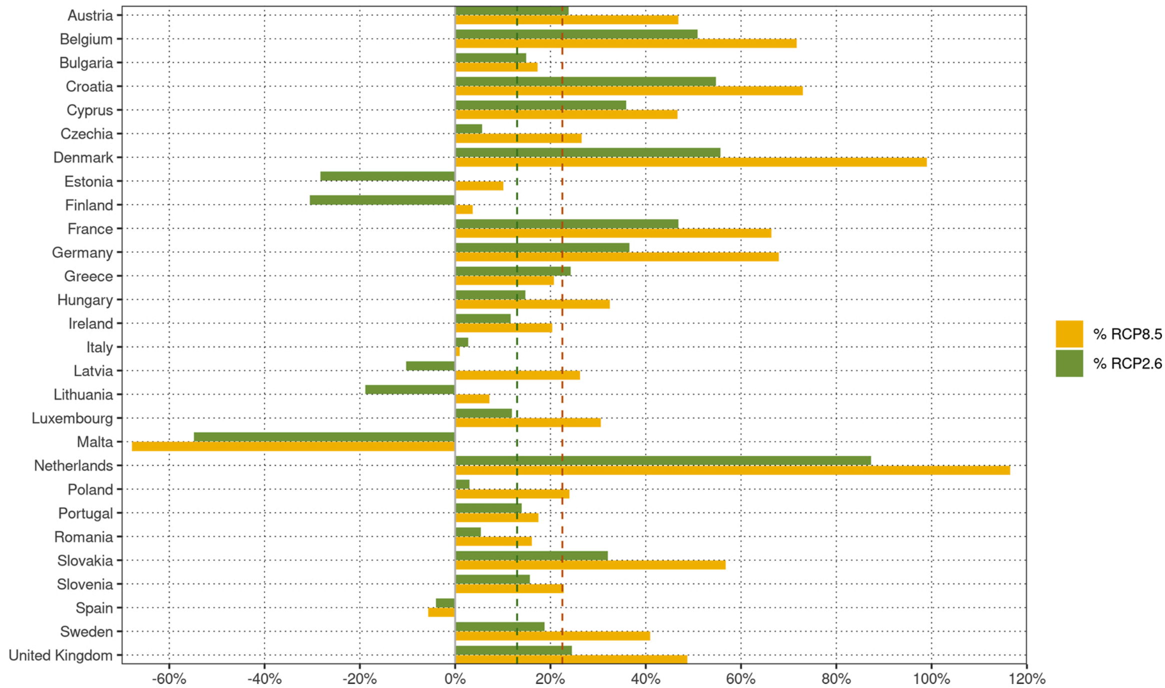


Fig. 7. Mean change in soil loss for each European country by 2050, expressed as percentage of the 2016 baseline soil loss, for two climate change scenarios (RCP2.6, RCP8.5). The dotted vertical lines represent the mean change (%) at EU for the RCP2.5 (green) and RCP8.5 (orange).

Table 1
The impact of different Agricultural Management Practices (AMPs) in reducing soil erosion rates for 3 different climate change (RCP) scenarios (2050). The reduction potential (last column) is the reduction % compared to the case where no AMPs are applied. Colour of the cells depends on the mean RCP value compared to the current baseline of 3.07 t ha^{-1} yr^{-1} (Green: decrease; yellow: increase 0-3%; orange: increase 3-10 %; red: increase > 10 %).

Scenario #	Agricultural Management Practice (AMP)	Detailed description of the AMP (% refer to the area)	Mean erosion rates per RCP scenario after application of AMP in 2050 (t ha^{-1} yr^{-1})			Reduction potential AMP (%)
			RCP2.6	RCP4.5	RCP8.5	
1	Flat application of green soil coverage (cover crops)	Apply 50% of cover crops in all agricultural lands	3.23	3.22	3.50	7.4%
2	Minimum green soil coverage (cover crops)	Introducing targeted soil cover where erosion rates are above 1t ha^{-1} yr^{-1}: 10% coverage if soil erosion is 1-2 t ha^{-1} yr^{-1}, 25% coverage if soil erosion is 2-5 t ha^{-1} yr^{-1} and 50% coverage if soil erosion is above 5 t ha^{-1} yr^{-1}	3.20	3.19	3.47	8.6%
3	Targeted green soil coverage (cover crops)	A stricter scenario compared to #2: 25% coverage if soil erosion is 1-2 t ha^{-1} yr^{-1}, 50% coverage if soil erosion is 2-5 t ha^{-1} yr^{-1} and 75% coverage if soil erosion is above 5 t ha^{-1} yr^{-1}	3.12	3.11	3.38	11.5%
4	Limited soil disturbance (reduced tillage)	Introducing targeted reduced tillage where erosion rates are above 1t ha^{-1} yr^{-1}: 5% of reduced tillage if soil erosion is 1-2 t ha^{-1} yr^{-1}, 10% of reduced tillage if soil erosion is 2-5 t ha^{-1} yr^{-1} and 20% of reduced tillage if soil erosion is above 5 t ha^{-1} yr^{-1}	2.97	2.96	3.22	17.1%
5	Combined minimum green cover and limiting soil disturbance (reduced tillage)	A combined approach of scenario #4 and #2: 10% of cover crops in areas where soil erosion <1 t ha^{-1} yr^{-1}; 5% of reduced tillage and 10% cover crops if soil erosion is 1-2 t ha^{-1} yr^{-1}; 10% of reduced tillage and 15% cover crops if soil erosion is 2-5 t ha^{-1} yr^{-1}; 20% of reduced tillage and 30% cover crops if soil erosion is above 5 t ha^{-1} yr^{-1}	2.84	2.84	3.08	22.5%

4.2. Data evaluation and uncertainties

The projections are presented as a range of values, considering the uncertainty within climate and economic models plus the potential for policy application. Increases in precipitation depth, surface runoff and the intensity of rainfall events in Western Europe may have a detrimental effect on soils by increasing soil erosion rates. Similar to our findings, reduced precipitation depth alongside increased rainfall intensity in future climate scenarios is projected across a major part of the Mediterranean (Donnelly et al., 2017). Prior to our study, the future rainfall erosivity was also estimated at a global scale using 14 models and all three RCP scenarios to model the global soil erosion projections in 2070 (Borrelli et al., 2020). In Europe, Panagos et al. (2017) applied the commonly used RCP4.5 HadGEM2-ES (Jones et al., 2011) projection to assess the 2050 erosivity at continental scale. In this preliminary study (Panagos et al., 2017), the future mean erosivity in the agricultural lands of the EU was estimated to be ca. + 23.6 % compared to the 2010 baseline.

Past rainfall erosivity has been estimated both at regional scale and for the whole European continent. In Europe, rainfall erosivity shows a limited increase of 4% during the last decades of the 20th century (Bezak et al., 2020). Most regional studies such as those in the Pannonian basin (Lukić et al., 2019), Tuscany (Vallebona et al., 2015), Rhone region (Diodato et al., 2016) and Czechia (Hanel et al., 2016) also showed a positive trend of rainfall erosivity during the last 30–50 years. Future erosivity has been modelled in a few studies in Europe such as those in Germany (Gericke et al., 2019) and Greece (Vantas et al., 2020), where both have estimated regional increases in line with our projections in those areas.

Projected future land use changes in the EU, estimated with the CLUE (Conversion of Land Use and its Effects) model, shows a decrease of arable lands which are either abandoned, sealed or afforested (Verburg and Overmars, 2009). Those land use dynamics account for the demand-driven changes which determine the local conversion processes and are in line with our projections of decreased arable land coverage. Other drivers such as climate change or loss of competitiveness in crop production will drive the cropland shrinkage in Europe (Schmitz et al., 2014). Even if the Land Use Land Cover (LULC) models have a high degree of uncertainty for future projections, there is consensus amongst most of the Computable General Equilibrium (CGE) models in predicting a decrease of cropland in EU (Alexander et al., 2017).

The outlook is based on existing policy framework and expected trends in the macro-economic environment. The expected changes in land use due to intensification of livestock production (Weindl et al., 2017) or diet changes are uncertainties within the future European land cover trends. In addition, It is also difficult to predict the land use changes due to the replacement of meat and dairy products with plant-derived foods (Temme et al., 2013). The trends in organic farming or shifts between food categories will also have an impact on land cover.

The projections of cover management (C-factor) include two types of uncertainties a) the land use dynamics projected by CAPRI and b) the C-factor assignment per crop and land use. Regarding the land use dynamics, the trends in CAPRI projections agree with other CGEs models. As CAPRI relies on historical trends, the land use projections capture the average outcomes under typical conditions. Therefore, we recognise that this simplification of the reality considers the future projections to be unaffected by short run fluctuations of weather, macroeconomic drivers, oil prices, etc. (Scholefield et al., 2011; Wirzke, 2012) (*supplementary material chapter 2*). In addition to the land use dynamics, we simulated the potential change of C-factor based on three types of scenarios. By assigning the lower C-factor per land use (e.g. 0.05 for pastures), we project a decrease of C-factor at 3.6 % in 2050 compared to the baseline. In case of assigning the higher C-factor (e.g. 0.15 for pastures), the projected C-factor change is -1.2 % while the mean C-factor assignment (e.g. 0.09 for pastures) results in a -2.1 % projected change (*supplementary material Tables S2 and S3*).

The rainfall erosivity projections have significant uncertainties as they are based on long-term climate model projections across different emissions pathways. The selection amongst the 19 different Global Climate Models may influence the outputs of soil losses as the erosivity has a wide range of values (*supplementary material Fig. S6)*. Therefore, we attempted to mitigate this uncertainty by considering an ensemble of 19 different Global Climate Models, each with 3 scenarios (RCP2.6, RCP4.5 and RCP 8.5). Thus, we count for a comprehensive range of plausible and published climate change projections based on which we derive the future rainfall erosivity (*supplementary material Table S4*). Finally, this analysis advances our knowledge compared to past studies which were limited to one or a few numbers of models.

On top of the uncertainty propagated by the land use and climate change projections, we acknowledge the limitations of the RUSLE model (*supplementary material Chapter 5).* Among others, RUSLE is known for the limited interactions between input factors, lack of deposition/sediment prediction, model upscaling issues etc. (Alewell et al., 2019). To better evaluate the performance of the RUSLE in our baseline, we performed a comparison with a) regional and local studies in EU which used RUSLE-based models; b) empirical data from plot database. The modelled baseline data on soil loss are compared well ($R^2 = 0.84$) with the 29 regional and local datasets using RUSLE (*supplementary material Chapter 5, Fig. S3*). In addition, we evaluated the performance of the potential erosion rates derived from RUSLE with a plot data from 40 locations in 13 countries having at least 4-years of measurements (*Fig. supplementary material S4*).

4.3. Data availability

The data (climate projections, land use projections, soil erosion projections) in all three scenarios will be available in the European Soil Data Centre (ESDAC, https://esdac.jrc.ec.europa.eu/).

5. Conclusions

By 2050, mean soil loss rates due to water erosion may increase by 13–22.5 % in agricultural areas of the EU and the UK compared to the 2016 baseline. Those projections have been shaped using a combined model framework of both land use and climate change. Compared to land use change, climate change showed a dominant effect on future soil erosion projections. To ensure comprehensiveness, we have considered climate projections for the year 2050 from 19 models applied in the EU plus the UK for three different RCP scenarios. Although the RCP2.6 and RCP4.5 climate change scenarios could result in similar mean values for the entire study area, we found consequentially different spatial variations in the patterns of soil loss (between 2016 and 2050). The less aggressive mitigation pathway RCP8.5 climate change scenario is alarming as it will aggravate soil loss in 84 % of the study area and increase the soil loss rates by at least 45 % in Western Europe. The Mediterranean basin shows smaller increases mainly due to the mixed impact of climate change on rainfall erosivity in this region.

The future projections of soil loss rates could be at least 3% higher if land use changes were ignored. In this study, the main drivers of land use change between 2016 and 2050 were crop composition dynamics, the transformation of cropland to grasslands and the shrinkage of EU agricultural area by 3.9 %. Therefore, it is recommended that projections of soil losses due to water erosion should consider both a wide range of climate change scenarios but also future land use changes.

As agro-environmental policies are the only mechanism to mitigate the future negative trend of soil loss in the EU, we performed a policy relevant scenario analysis. Among the scenarios, we included the uptake of management practices relevant to green soil coverage and minimum soil disturbance and have some quotations in the future Common Agricultural Policy (post-2020 CAP). The most effective policy instrument is to link CAP incentives to environmental performance in a targeted way. However, the application of soil conservation measures such as cover crops and reduced tillage should include at least 50 % of the hotspots (i.e., where soil losses exceed 5 t ha^{-1} yr^{-1}) to neutralize the future impact of climate change on water erosion. The post 2020 Common Agricultural Policy and other EU policy developments (EU Green Deal) may include a stronger soil conservation package with quantitative targets to mitigate the important soil erosion increase which is expected due to climate change in Europe.

Authors statement

Panos Panagos (PP) is first and contact author and he has developed the concept, develop the models, calculated the results, and drafted the paper and had the overall management of the project.

Cristiano Ballabio (CB) as second author was responsible for modelling future erosivity, data evaluation and drafted part of the future rainfall erosivity.

Mihaly Himics (MH) and Mariia Bogonos (MB) were responsible for modelling land use changes and drafted the part relevant to CAPRI model.

Simone Scarpa (SC) was responsible for data curation.

Jean Poesen (JP) and Francis Matthews (FM) revised the manuscript and proposed inputs in the modelling part.

Pasquale Borrelli (PB) as last author was responsible for Methodology, visualization, uncertainties estimation and revising the manuscript.

Declaration of Competing Interest

The authors confirm that there is no conflict of interest with the networks, organisations and data centres referred to in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.envsci.2021.07.012.

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