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The new assessment of soil loss by water erosion in Europe

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ABSTRACT

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 European Commission's Soil Thematic Strategy has identified soil erosion as a relevant issue for the European Union, and has proposed an approach to monitor soil erosion. This paper presents the application of a modified version of the Revised Universal Soil Loss Equation (RUSLE) model (RUSLE2015) to estimate soil loss in Europe for the reference year 2010, within which the input factors (Rainfall erosivity, Soil erodibility, Cover-Management, Topography, Support practices) are modelled with the most recently available pan-European datasets. While RUSLE has been used before in Europe, RUSLE2015 improves the quality of estimation by introducing updated (2010), high-resolution (100 m), peer-reviewed input layers. The mean soil loss rate in the European Union's erosion-prone lands (agricultural, forests and semi-natural areas) was found to be 2.46 t ha^{-1} yr^{-1}, resulting in a total soil loss of 970 Mt annually.

A major benefit of RUSLE2015 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) and support practices (contour farming, maintenance of stone walls and grass margins). The policy interventions (GAEC, Soil Thematic Strategy) over the past decade have reduced the soil loss rate by 9.5% on average in Europe, and by 20% for arable lands. Special attention is given to the 4 million ha of croplands which currently have unsustainable soil loss rates of more than 5 t ha^{-1} yr^{-1}, and to which policy measures should be targeted.

1. Introduction

The land degradation process due to the rate of soil loss exceeding that of soil formation has helped shape today's physical landscape (Alewell et al., 2015). Soil erosion is among the eight soil threats listed within the Soil Thematic Strategy of the European Commission (EC, 2006). During the past decade, the problem of soil erosion has become part of the environmental agenda in the European Union (EU) due to its impacts on food production, drinking water quality, ecosystem services, mud floods, eutrophication, biodiversity and carbon stock shrinkage (Boardman and Poesen, 2006). Soil erosion by water accounts for the greatest loss of soil in Europe compared to other erosion processes (e.g. wind erosion). Recent policy developments in the European Commission (the Soil Thematic Strategy, the Common Agricultural Policy, Europe 2020, and the 7th Environmental Action Programme) call for quantitative assessments of soil loss rates at the European level. As the measurement of actual soil loss rates at the continental scale (by means of e.g. experimental plots, Caesium-137 measurements, the sampling of sediment loads in the runoff from small catchments) is not financially feasible, soil erosion modelling approaches are used to make such assessments. Besides the policy requests, a continental assessment of soil loss may help to: (a) quantify the impacts of soil loss at such a large scale, (b) assess the main effects of climate, vegetation and land use changes on soil erosion rates, and (c) prioritise effective remediation programmes (Lu et al., 2003).

The main factors affecting the rates of soil erosion by water are precipitation, soil type, topography, land use and land management. In a recent inventory, Karydas et al. (2014) identified 82 water-erosion models classified on different spatial/temporal

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scales with various levels of complexity. The most commonly used erosion model is the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) and its revised version (RUSLE) (Renard et al., 1997) which estimates long-term average annual soil loss by sheet and rill erosion. It should be noted that soil loss caused by (ephemeral) gully erosion is not predicted by RUSLE (Poesen et al., 2003). Despite its shortcomings, RUSLE is still the most frequently used model at large scales (Renschler and Harbor, 2002; Kinnell, 2010) as it can process data input for large regions, and provides a basis for carrying out scenario analysis and taking measures against erosion (Lu et al., 2003). In addition, a recent collection of soil loss data in Europe by the European Environmental Information and Observation Network (EIONET) found that all participating countries used USLE/RUSLE (Panagos et al., 2014a) to model soil loss.

The objective of this study is to provide an up-to-date soil loss map of the European Union using the RUSLE model. This map aims to:

(a) use the most updated input layers of precipitation, soil, topography, land use and management,
(b) help predict the effects of policy scenarios,
(c) be replicable, comparable and utilised at a broader scale (other than soil erosion modelling).

2. Methodology

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

$$E = R \times K \times C \times \mathrm{LS} \times P \quad (1)$$

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), LS: slope length and slope steepness factor (dimensionless), and P: support practices factor (dimensionless).

The RUSLE2015 model introduces some improvements to each of the soil loss factors, adapting them to the latest state-of-the-art data currently available at the European scale. The main difference from previous studies that modelled soil loss at the European scale using RUSLE (e.g. Van der Knijff et al., 2000; Bosco et al., 2015) is the improved quality of input layers. Each input factor has been estimated in a transparent way. The assessment procedures for the soil erodibility factor (Panagos et al., 2014b), the rainfall erosivity (Panagos et al., 2015a), the cover-management factor (Panagos et al., 2015b), the topographic factor (Panagos et al., 2015c) and support practices factor (Panagos et al., 2015d) have recently been published, and the corresponding datasets are available from the European Soil Data Centre (Panagos et al., 2012). The 5 factors are described in the supplementary material and the corresponding publications. For the estimation of input factors, RUSLE2015 made use of the most updated and freely available datasets at the European scale (Fig. 1).

The K-factor is estimated for the 20,000 field sampling points included in the Land Use/Cover Area frame (LUCAS) survey (Toth et al., 2013) and then interpolated with a Cubist regression model using spatial covariates such as remotely sensed data and terrain features to produce a 500 m resolution K-factor map of Europe (Panagos et al., 2014b). The R-factor is calculated based on high-resolution temporal rainfall data (5, 10, 15, 30 and 60 min) collected from 1 541 well-distributed precipitation stations across Europe (Panagos et al., 2015a). The 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) (Panagos et al., 2015b). The LS-factor (Panagos et al., 2015c) is calculated using the recent Digital Elevation Model (DEM) at 25 m and applying the equations proposed by Desmet and Govers (1996). The 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 (Panagos et al., 2015d).

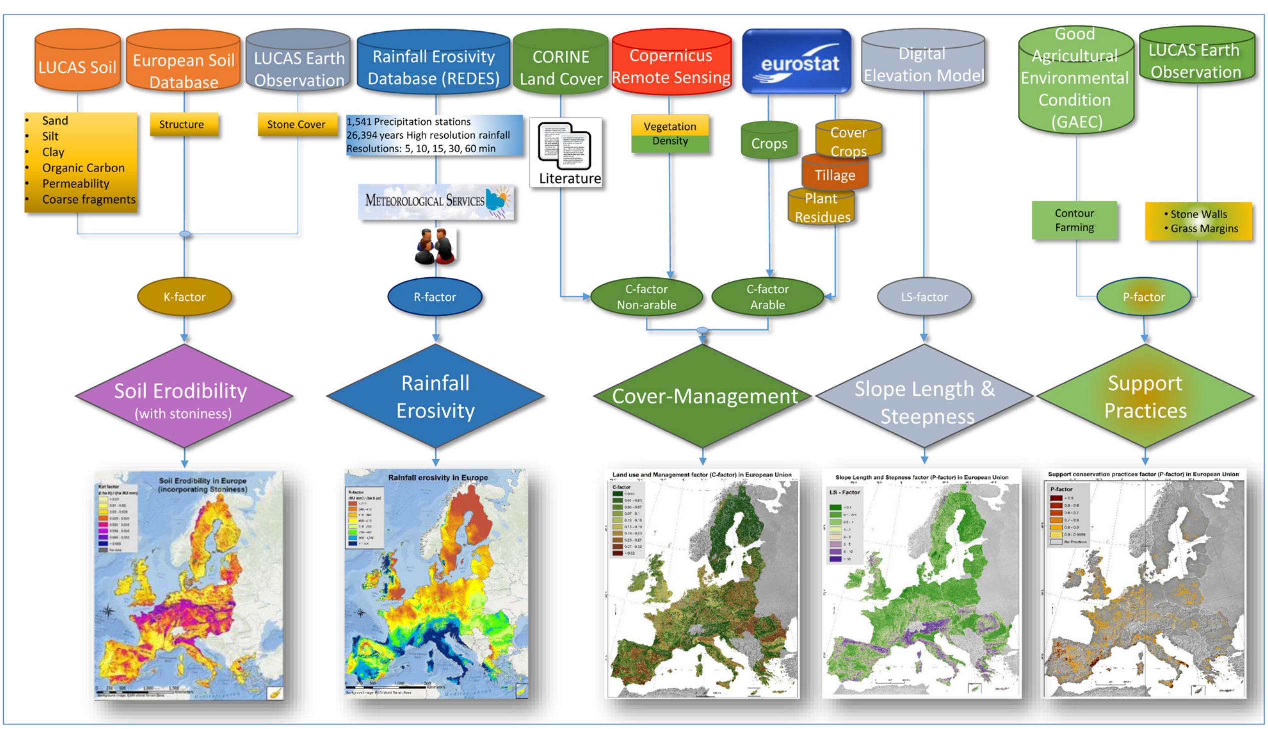

Fig. 1. Input datasets used for the estimation of soil loss factors for Europe in RUSLE2015.

3. Results and discussion

3.1. Map of soil loss in the European Union

A map of soil loss in the European Union was produced using RUSLE2015 at 100 m resolution (Fig. 2). This resolution depends on the data availability of the input factors. The scale of 100 m pixel size was selected as being the most appropriate because the *C*-factor layer (at 100 m resolution) can be altered as a result of policy interventions that affect land use. The 100 m resolution also falls between the coarse resolution values of the *K*-factor (500 m), the *R*-factor (500 m), the *P*-factor (1 km), and the very high resolution

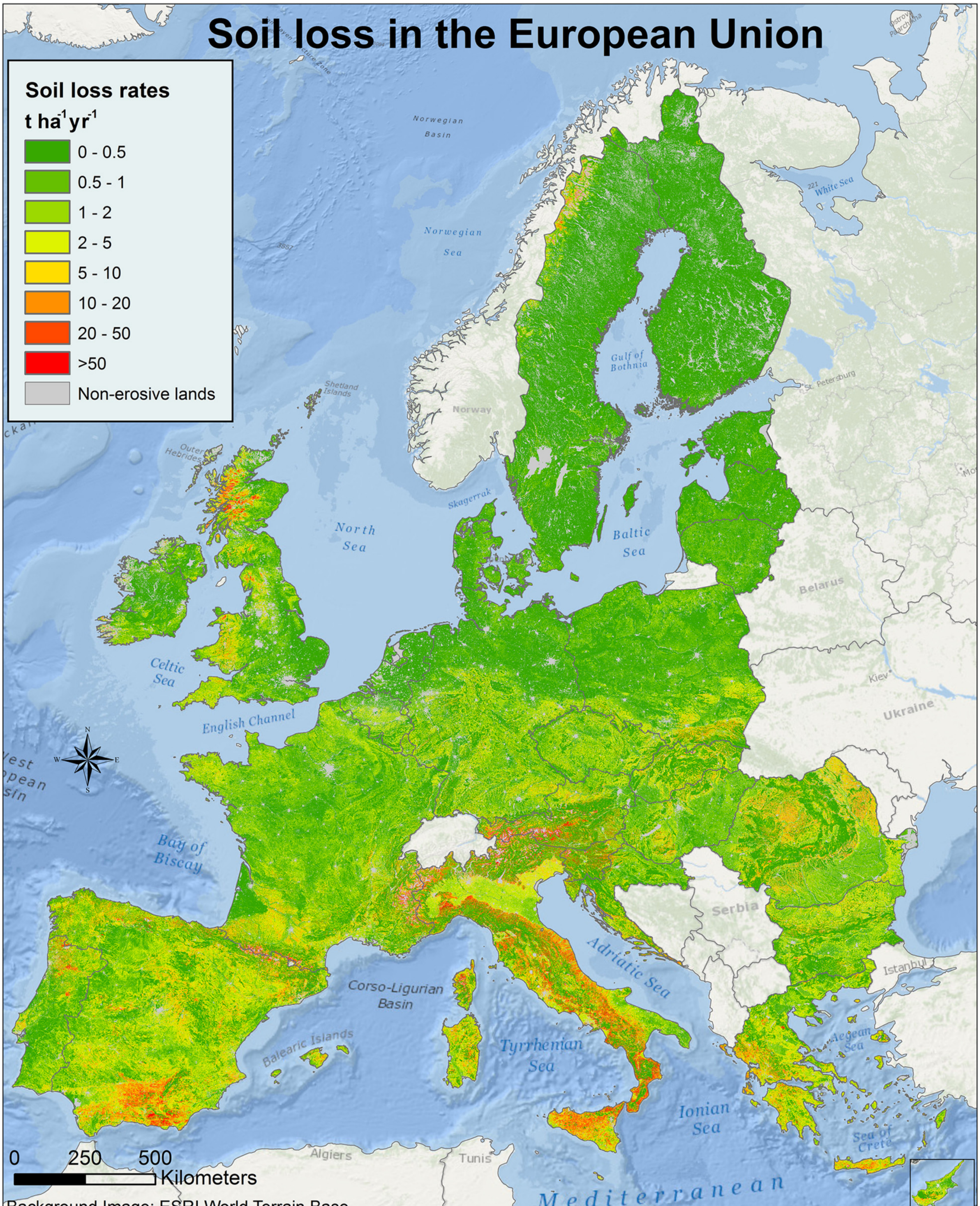

Fig. 2. Map of soil loss rates in the European Union (Reference year: 2010) based on RUSLE2015.

of the LS-factor (25 m). Soil loss potential is estimated for 90.3% of the EU surface (3941×10^3 km^2 out of a total 4366×10^3 km^2), as the remaining 9.7% consists of surfaces that are not prone to soil erosion, such as urban areas, bare rocks, glaciers, wetlands, lakes, rivers, inland waters and marine waters.

2010 was chosen as the reference year of the soil loss map of the European Union, as this is the most recent year for which most of the input factors are estimated: the *R*-factor is based on the Rainfall Erosivity Database at the European Scale (REDES) which includes the first decade of the 21st century; most of the input to the *K*-factor comes from the LUCAS 2009 soil survey database; the *C*-factor is based on CORINE land cover (2006), Copernicus Remote sensing data (2011–2012) and Eurostat databases (crop statistics, tillage practices, cover crops, plant residues) which use 2010 as their reference year; the LS-factor is estimated with the recently published (2014) Digital Elevation Model; and the *P*-factor is based on the GAEC database (2010) and the LUCAS field observations (2012).

The mean annual rate of soil loss due to water erosion for the reference year 2010 is 2.46 t ha^{-1} yr^{-1} for the potentially erosion-prone land cover in the EU. The total annual soil loss in the EU is 970 Mt. The average rate of soil loss falls to 2.22 t ha^{-1} yr^{-1} if the non-erosion-prone areas are included in the statistical analysis. In both cases, the average annual rate of soil loss is significantly higher than the average rate of soil formation in Europe of 1.4 t ha^{-1} yr^{-1} (Verheijen et al., 2009).

The variation of the rate of soil loss (*E*) in the EU is very high due to different topographic, climatic, land use, management and soil conditions. The maximum soil loss rate of 325 t ha^{-1} yr^{-1} (Maetens et al., 2012), observed in experimental plots, has been imposed for very few pixels (<0.001%) in order to avoid model outliers.

3.2. Regional assessments

The highest annual soil loss rates (*E*-values) are observed in the Mediterranean areas (medium/high *C*-factor, high *R*-factor and LS-factor), while lower *E*-values are predicted for Scandinavia and the Baltic States (Fig. 2). The combination of high rainfall erosivity (*R*-factor) with relatively steep slopes (LS-factor) also results in elevated *E*-values in the Alpine areas, the Apennines, the Pyrenees, the Sierra Nevada, western Greece and western Wales and Scotland. The effect of low levels of vegetation cover (*C*-factor) is most visible in southern Spain and eastern Romania. The impact of soil erodibility (*K*-factor) is particularly prevalent in the Loess Belt (Belgium, southern Germany and southern Poland). Support practices (*P*-factor) only have an effect at the local level and are not visible on the EU soil loss map. However, this information is available on the *P*-factor map (Panagos et al., 2015d), which is a useful decision-making tool for supporting good agricultural practices.

The highest mean annual soil loss rate (at country level) is found In Italy (8.46 t/ha), followed by Slovenia (7.43 t/ha) and Austria (7.19 t/ha) (Table 1), due to a combination of high rainfall erosivity (Panagos et al., 2015a) and steep topography (steep and long slopes). The mean rates of soil loss of the other Mediterranean countries (Spain, Greece, Malta and Cyprus) are also higher than the pan-European average. The lowest mean annual soil loss rates were found in Finland (0.06 t/ha), Estonia (0.21 t/ha) and the Netherlands (0.27 t/ha). All the Scandinavian and Baltic states have mean annual soil loss rates of less than 0.52 t/ha (Table 1).

Large countries with high mean soil loss rates, such as Italy and Spain, have the highest share of total soil loss in the EU. The estimated total soil loss of eight of the Mediterranean EU Member States (IT, ES, FR, GR, PT, HR, SI and CY) is 67% of the total soil loss in the European Union (28 countries).

Annual soil loss is further assessed by biogeographical regions which are classified based on climatic and ecological criteria (EEA, 2011). The highest mean soil loss rate (5.27 t ha^{-1} yr^{-1}) is predicted for the Alpine climatic zone (Alps, Pyrenees, and Southern Carpathians) due to the combined effect of rainfall erosivity and topography. The Mediterranean climatic zone also

Table 1
Average soil loss rate (*E*-value) per country (all lands, arable lands), effect of Good Agricultural Environmental Condition (GAEC) practices, and share of EU soil loss.

Country		Overall Mean	Mean in arable lands	Mean in arable lands without GAEC	GAEC effect	% of the total soil loss in EU
		E (t ha^{-1} yr^{-1}) (%)				
AT	Austria	7.19	3.97	5.23	31.8	5.65%
BE	Belgium	1.22	2.06	2.71	31.8	0.30%
BG	Bulgaria	2.05	2.47	3.77	52.5	2.21%
CY	Cyprus	2.89	1.85	2.82	52.6	0.25%
CZ	Czech Republic	1.65	2.52	3.30	31.0	1.24%
DE	Germany	1.25	1.75	2.51	43.5	4.15%
DK	Denmark	0.50	0.61	0.68	11.4	0.20%
EE	Estonia	0.21	0.70	0.88	25.3	0.09%
ES	Spain	3.94	4.27	5.56	30.3	19.61%
FI	Finland	0.06	0.46	0.64	37.9	0.18%
FR	France	2.25	1.99	2.78	39.5	11.85%
GR	Greece	4.13	2.77	3.63	31.1	5.31%
HR	Croatia	3.16	1.67	1.80	7.5	1.74%
HU	Hungary	1.62	2.10	2.35	12.0	1.42%
IE	Ireland	0.96	1.32	1.52	15.7	0.55%
IT	Italy	8.46	8.38	9.80	16.9	24.13%
LT	Lithuania	0.52	0.95	1.02	7.5	0.32%
LU	Luxembourg	2.07	4.54	6.19	36.3	0.05%
LV	Latvia	0.32	1.01	1.11	10.1	0.20%
MT	Malta	6.02	15.93	18.72	17.5	0.01%
NL	Netherlands	0.27	0.54	0.68	24.7	0.08%
PL	Poland	0.96	1.61	1.79	11.2	2.92%
PT	Portugal	2.31	2.94	3.55	20.6	2.01%
RO	Romania	2.84	3.39	3.88	14.3	6.31%
SE	Sweden	0.41	1.12	1.31	16.6	1.57%
SI	Slovenia	7.43	4.63	5.33	15.0	1.49%
SK	Slovakia	2.18	3.54	4.09	15.6	1.03%
UK	United Kingdom	2.38	1.04	1.49	43.2	5.14%

has a high soil loss rate (4.61 t ha^{-1} yr^{-1}) due to having the highest *R*-factor in Europe. The mean soil loss rates of the largest part of the EU, covered by the Atlantic and the Continental climatic zone, are 1.78 and 1.98 t ha^{-1} yr^{-1}, respectively, which are much lower than the rates for the Alpine and Mediterranean regions. Finally, the lowest annual soil loss rates (0.16 t ha^{-1} yr^{-1}) are found in the Boreal zone which has very little rainfall erosivity, flat topography and high vegetation density.

3.3. Land cover/use assessment

The map of soil loss in the European Union (Fig. 2) was analysed by land cover/use type using the major 2nd level CORINE land cover classes (CLC, 2014). CORINE was used for the land cover assessment as this is the most well-known land cover classification in Europe. The mean rate of soil loss from the arable lands of the EU (2.67 t ha^{-1} yr^{-1}) is 10% higher than the overall soil loss rate (2.46 t ha^{-1} yr^{-1}). Permanent crops have a high mean soil loss rate (9.47 t ha^{-1} yr^{-1}), as most of the vineyards and olive trees are located in hilly Mediterranean areas with high rainfall erosivity. The mean annual soil loss rate in pastures is 2.02 t ha^{-1} yr^{-1}, mainly due to higher vegetation densities and, as a consequence, lower *C*-factors. The heterogeneous agricultural areas have a higher overall mean rate of soil loss (4.21 t ha^{-1} yr^{-1}) than do arable land areas, despite the fact that their *C*-factor is lower. The latter is due to the differences in topography (which influence the LS factor), as the arable lands are typically located in flat or gently sloping areas. The agricultural areas, including arable lands, permanent crops, grasslands and heterogeneous agriculture lands and covering 46.7% of the EU surface area (or 52% of the potentially erosion-prone region studied), have a mean soil loss rate of 3.24 t ha^{-1} yr^{-1}. These agricultural lands account for 68.3% of total soil losses (Fig. 3).

The forests and semi-natural CORINE land-cover/use classes are very heterogeneous in terms of soil loss estimates. Despite the fact that they occupy more than 30% of the EU land, forests have by far the lowest rate of soil loss (0.07 t ha^{-1} yr^{-1}), contributing to less than 1% of the total soil loss in Europe. Areas covered with shrub and herbaceous vegetation have a mean soil loss rate of 2.69 t ha^{-1} yr^{-1}. Within this land-cover group, natural grassland areas have a mean soil loss rate of 4.41 t ha^{-1} yr^{-1}, mainly due to their location on steep areas. Very high soil loss rates (40.16 t ha^{-1} yr^{-1}) have been estimated for sparsely vegetated areas, which are mainly bad-lands in high attitudes with scattered vegetation. Those sparsely vegetated areas explain the high rates of soil loss in southern Spain. However, this is the most uncertain land-cover group due to the uncertainty of the *C*-factor and the ambiguity in CORINE land cover classification.

3.4. Comparison of predicted soil loss rates with other data sources and uncertainties

In 2010, the European Soil Data Centre (ESDAC) of the European Commission collected soil loss data from national institutions in Europe through the European Environment Information and Observation Network (EIONET). The result of this data collection exercise was the EIONET-SOIL database which includes data at 1-km pixel size for eight countries: Austria, Belgium, Bulgaria, Germany, Italy, the Netherlands, Poland, and Slovakia (Panagos et al., 2014a). Denmark was included in a later phase.

The intersecting pixels of the mean soil loss rates estimated by RUSLE2015 were compared with the mean EIONET soil loss data. Despite their different modelling approaches, the mean estimates of the Pan-European Soil Erosion Risk Assessment (PESERA) model (Kirkby et al., 2008) and the predicted loss rates from erosion plots in Europe (Cerdan et al., 2010) were also included in the comparison (Table 2), as both datasets have been used extensively

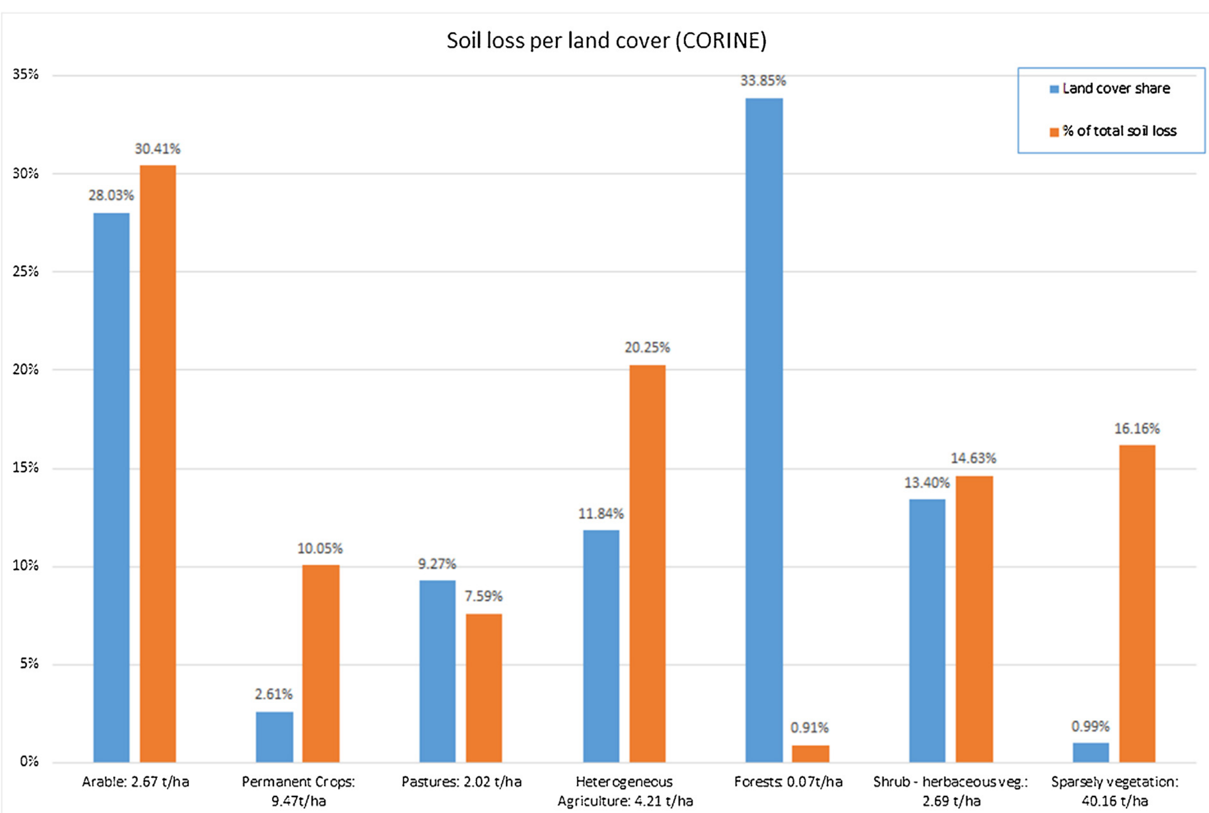

Fig. 3. Rates of mean soil loss per land cover group and corresponding shares of soil loss.

Table 2
Comparison of RUSLE2015, European Environment Information and Observation Network for soil (EIONET-SOIL), Pan-European Soil Erosion Risk. Assessment (PESERA) (Kirkby et al., 2008) mean soil loss estimates and aggregated soil loss plot measurements (Plot, Cerdan et al., 2010).

Country		RUSLE2015	EIONET-SOIL	PESERA	Plot	Soil loss ratio RUSLE2015: EIONET-SOIL
		$t\,ha^{-1}\,yr^{-1}$				
AT	Austria[a]	3.50	2.01	1.24	1.6	1.7
BE	Belgium	1.25	3.70	1.10	1.4	0.3
BG	Bulgaria	2.11	1.92	0.61	1.9	1.1
DE	Germany	1.44	1.41	1.30	1.9	1.0
DK	Denmark[b]	0.50	0.33–0.61 (0.47)	3.29	2.6	1.1
IT	Italy	8.77	6.95	2.69	2.3	1.3
NL	Netherlands	0.27	0.26	0.08	0.4	1.0
PL	Poland	1.25	1.46	0.83	1.5	0.9
SK	Slovakia	2.15	1.06	1.29	3.2	2.0

[a] Austria: only for agricultural lands.
[b] Denmark: As the EIONET-SOIL data were given in classes, a range has been estimated (mean value in parentheses).

during the past decade in Europe. The soil loss ratio (Table 2) was calculated by dividing RUSLE2015 results by the EIONET-SOIL data in the common intersecting pixels.

The PESERA model tends to estimate generally lower erosion rates than all other approaches due to its sediment module (Panagos et al., 2014a), with the exception of overestimating soil erosion in flat areas (Denmark, the Po Valley in Italy). Rainfall intensity is not included in the soil erosion map of Europe produced by Cerdan et al. (2010), which is based on a plot database, leading to lower estimates for soil loss rates in countries with high rainfall erosivity (Italy, Austria). The RUSLE2015 mean loss rates and spatial patterns are very close to the reported EIONET-SOIL data in Germany, the Netherlands, Bulgaria, Poland and Denmark. The RUSLE2015 soil loss results are slightly higher than those of EIONET-SOIL for Italy, and even higher for agricultural land areas of Austria. The EIONET-SOIL values reported for Belgium are much higher than those of RUSLE2015, especially in the Wallonian forests, while the EIONET-SOIL values reported for Slovakia are lower than those of RUSLE2015. The very good correspondence of RUSLE2015 mean annual soil loss rates with the country estimates from EIONET-SOIL in six EU Member States seems to confirm the accuracy of the modelled results. The reasons for the differences found between the RUSLE2015 and country estimates for two Member States (Slovakia, Belgium) should be further investigated.

The major benefit of RUSLE2015 is its high-quality input layers due to

(a) the assessment of soil erodibility based on the sampling of topsoils in the field and laboratory analysis of soil properties, plus the *K*-factor data verification with local and regional published studies,
(b) the participation of the Member States in the extensive data collection of high-resolution precipitation data,
(c) the use of the first ever high-resolution Digital Elevation Model at 25 m,
(d) the combination of the CORINE Land Cover database with remote sensing vegetation density data, plus the use of crop and management practices statistical data, and
(e) the first ever assessment of good management practices using LUCAS survey observations and the GAEC database.

The *C*-factor estimation based on the quite old and static CORINE land cover data was ameliorated by the use of two additional databases (Vegetation density, Management practices statistical data). The vegetation-coverage density derived from remote-sensing datasets of the Copernicus Programme improved the assigned *C*-factor values at each pixel in non-arable lands (Panagos et al., 2015b). The calculation of the *C*-factor in arable lands included statistical data such as crop composition, soil-tillage practices, cover crops and plant residues.

The major sources of uncertainty are found in some highly erosion-prone CORINE land-cover classes (e.g. sparsely vegetated areas) that demonstrate high variability between Mediterranean regions (bad-lands) and northern Europe (mixed vegetation with rocks). The use of remote sensing data on vegetation density has proven to be useful for fine-tuning the erosion-factor values. The soil loss predictions in steep and arid areas can be further improved by separating the effects of erodible soil from the effects of rock and gravel surfaces.

3.5. Policy making and future scenario analysis

The European Union, which accounts for 2.9% of the global land area, contributes 1.3% of the total global annual soil loss estimate of 75 Gt (Pimentel et al., 1995). Pan-European assessments such as the current study help to guide investments designed to protect soil against erosion by water and to prioritise actions for effective remediation. The EU soil loss mapped by land cover/use, country, climatic zone and soil loss class facilitates the identification of hotspots on which efforts to prevent further soil degradation should be focused. In a cost-benefit analysis, Kuhlman et al., 2010 showed that the implementation of anti-erosion measures (terracing, stone walls, grass margins, contour farming, reduced tillage, cover crops and plant residues) in severely erosion-prone agricultural areas ($E > 10$ t ha^{-1} yr^{-1}) could have an economic benefit (on- and off-site) of 1.35 billion Euros.

The distribution of soil loss rates is positively skewed with a median value of 1.27 t ha^{-1} yr^{-1}. The soil loss rates of about 76% of the total European land area are less than 2 t ha^{-1} yr^{-1}; this is considered to be sustainable, given the generally accepted soil formation rates (Verheijen et al., 2009). The remaining 24% of the European land area, which has soil loss rates above 2 t ha^{-1} yr^{-1}, contributes to almost 87% of total soil loss in Europe (Table 3). Soil protection measures should definitely be taken in the 5.2% of the European land areas that suffer from severe soil loss ($E > 10$ t ha^{-1} yr^{-1}) and that contribute to 52% of the total soil loss in Europe. An example of such a measure is the afforestation or re-vegetation of sparsely vegetated areas that have very high soil loss rates.

Focusing on arable lands, the soil loss rate of 12.7% of EU croplands (14×10^6 ha) is greater than 5 t ha^{-1} yr^{-1} (Table 3). A layer of at least 0.4 mm is eroded annually from those cropland areas (Montgomery, 2007), to which emerging management practices should be applied in order to ensure the agricultural sustainability of the EU.

Table 3
Analysis of soil loss rates per class (in whole study area of 3941×10^3 km^2, focusing on croplands).

Soil loss Class t ha^{-1} yr^{-1}	% of total area	Mean soil loss rate in the class (t ha^{-1} yr^{-1})	% contribution to total soil loss	% of cropland
0–1	63.5%	0.24	6.1%	44.4%
1–2	12.3%	1.43	7.2%	23.0%
2–5	12.8%	3.18	16.8%	19.9%
5–10	6.2%	7.00	17.8%	7.6%
10–20	3.2%	13.79	18.2%	3.6%
20–50	1.6%	29.51	19.0%	1.4%
>50	0.4%	88.67	14.9%	0.1%
Total	100.0%	2.46	100.0%	100.0%

Soil erosion is among the agro-environmental indicators developed by the European Commission services for monitoring agricultural and environmental policies. The map of soil loss in the EU (Fig. 2) supports the statistical service Eurostat with aggregated data at various geographic levels (national, regional, provincial). The Directorate-General for Agriculture and Rural Development (DG AGRI), which is responsible for the implementation of Common Agricultural Policy (CAP) in the EU, focuses on soil erosion in agricultural lands and requests indicators of soil erosion in agricultural lands. An example of such indicators is the annual soil loss rate in arable lands at the NUTS3 (Nomenclature of Territorial Units for Statistics level 3) (Fig. 4). The percentage of agricultural land affected by erosion is one of the Green growth indicators of the Organisation for Economic Co-operation and Development (OECD).

The RUSLE2015 model structure can simulate scenarios of land management, land use change, and climate change. As such, the model becomes a useful tool for policy makers to both assess past performance and estimate soil loss changes based on future scenarios.

Human activity and agricultural practices are the main drivers for soil erosion trends (Garcia-Ruiz et al., 2013). In terms of land management, we focused on agricultural lands as the *C*-factor can be changed by farmers' interventions. Under the EU's Common Agricultural Policy (CAP), farmers receive direct payments on the condition that they follow particular management practices that are beneficial to the environment. Agro-environmental standards are set in the requirements for Good Agricultural and Environmental Condition (GAEC) introduced by the CAP reform in 2003 and implemented by the Member States after 2005 (Angileri et al., 2009). The GAEC includes mandatory soil protection measures against erosion, and proposes the limitation of bare soils, the promotion of reduced tillage and a minimum soil cover, contour farming in sloping areas, the maintenance of terraces and stone walls, and the increased use of grass margins (Matthews, 2013).

The implementation of GAEC in the agricultural lands of Member States has helped to reduce soil loss rates. Since no statistical data were available about reduced tillage, soil cover, contour farming, terracing and grass margins before the GAEC implementation in 2003, we hypothesised that those management practices were previously not applied or were only applied to a very limited extent. Their impact during the past decade (2003–2010) was to reduce soil loss by water erosion in arable lands from 3.35 t ha^{-1} yr^{-1} to 2.67 t ha^{-1} (−20.2%). The greatest effects of GAEC implementation were reported in Cyprus, Bulgaria, Germany, the United Kingdom and France, with a reduction of more than 30% in the mean rates of soil loss from agricultural lands. GAEC implementation had the least impact on Eastern European countries (new EU Member States after the 2004 enlargement), where the mean rates of soil loss from agricultural lands fell by less than 13.5%. If no GAEC requirements had been applied in the EU, the mean soil loss rate in the study area (agricultural lands, forests and semi-natural areas) would have been 2.71 t ha^{-1} yr^{-1}. Compared to the current estimated mean annual rate of 2.46 t ha^{-1} yr^{-1}, this implies that overall soil loss in the EU was reduced by 9.5% during the past decade due to policy measurements (GAEC).

The management practice with the greatest impact on soil loss rates were the reduced and no tillage practices which are currently applied in more than 25% of the agricultural lands of the EU (Panagos et al., 2015b). The management practices of keeping plant residues on the soil surface and using cover crops, which are both incorporated in the RUSLE2015 *C*-factor, had very limited contribution to soil loss rate decline (ca. 1% each), mainly due to their limited extent of implementation in EU agricultural lands. Of the support practices (*P*-factor) applied in EU agricultural lands during the past decade, the use of grass margins had the greatest effect (>1%) in reducing soil loss rates, while the impact of contour farming was insignificant (0.15%) due to its very limited application in Europe (Panagos et al., 2015d).

A sensitivity analysis of the cover-management factor (*C*-factor) allows future scenarios of land use to be developed based on the changes in crop rotation that may be imposed by EU policies. A prime example is the EU Biofuels Directive (BFD) which will push for the transformation of cereal croplands (*C*-factor: 0.20) into energy croplands such as sugar beet, sunflowers and maize (*C*-factor: 0.38), and will also result in reducing crop residues. Changing 10% of cereals to energy crops as a result of the BFD requirements (Frondel and Peters, 2007) would lead to an increase in the *C*-factor of 3.8% in arable lands and a 2.2% increase in mean soil loss rates.

To predict future rainfall erosivity, we used one of the most frequently applied future scenarios of the Intergovernmental Panel on Climate Change (IPCC, 2013) Fifth Assessment Report, HadGEM2 (Martin et al., 2011), which assumes a medium increase in greenhouse gas concentrations and a global air temperature increase of 1.4 degrees in the period 2045–2065 (Representative Concentration Pathways – RCP 4.5). We have run the Gaussian Process Regression (GPR) geo-statistical model for the rainfall erosivity in Europe (Panagos et al., 2015a) taking as input the WorldClim's future predictions for precipitation, temperature and seasonality in Europe (Hijmans et al., 2005). According to the HadGEM2 (RCP 4.5) scenario and *R*-factor geo-statistical model GPR (Panagos et al., 2015a), an average increase of 10–15% in rainfall erosivity is estimated till 2050 in Europe and, as a result, a similar increase will occur in soil loss rates. The major increase is predicted in northern Europe (coasts of the North Sea and the English Channel), the Alps, north-western France and eastern Croatia. The Nordic countries (Finland, Sweden), Baltic States and eastern Poland are expected to have a decrease of rainfall erosivity. Small changes in rainfall erosivity are expected in Central Europe (Slovakia, western Poland) and other parts of Europe, while the Mediterranean basin shows mixed trends.

We selected the projections of land use change for the year 2050 based on the pan-European Land Use Modelling Platform (LUMP) (Lavalle et al., 2013). LUMP translates policy scenarios into land-use changes such as afforestation and deforestation, pressures on natural areas, abandonment of productive agricultural areas, and urbanisation. According to LUMP, all agricultural land uses will be reduced by 2050 (croplands will decrease by 1.2%, permanent crops by 0.2% and pastures by 0.6%), and semi-natural areas will also decrease by 1%. Urban areas will increase by 0.7% and forest areas by 2.2%. Forest lands, which are the least erosion-prone (with mean annual soil loss of 0.065 t/ha), will replace erosion-sensitive land uses (permanent crops, arable, pastures and

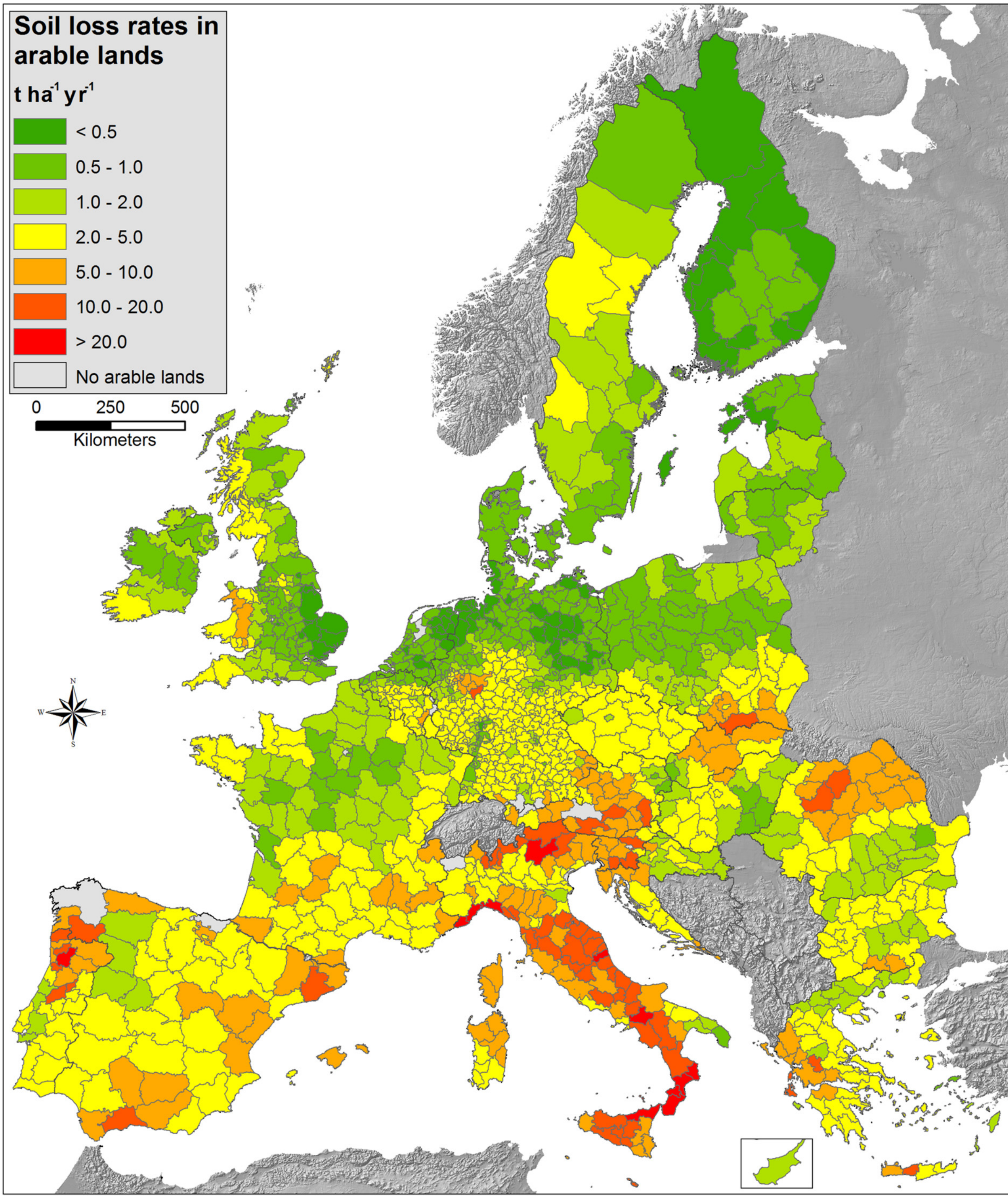

Fig. 4. Mean soil loss rates at province (NUTS3) level for arable lands in the EU.

semi-natural). In total soil loss terms, the future land use changes projected by LUMP will result in a 5.8% reduction in soil loss. However, LUMP should take into consideration the imminent threat of peak phosphorous levels, with the only noteworthy P resources left in the Western Sahara and Morocco after 2013 (Elser and Bennett, 2011). Given this threat, the EU Member States will most likely start to increase their area of arable land considerably in the near future.

The policy implications of this soil loss map (Fig. 2) will affect important pillars of EU soil protection other than just erosion. The soil organic carbon (SOC) cycle, for instance, is strongly affected by erosion, since large quantities of sediments and SOC are moved and re-deposited over the landscape, especially in agricultural areas. The feedbacks of these geomorphological–biogeochemical cycles are so complex that the debate is still open as to whether arable land functions as a source or sink of carbon dioxide (CO_2) (Kirkels et al., 2014). RUSLE2015 will certainly help to improve the scientific knowledge of one component of the global carbon budget, which has to date often been neglected due to lack of data. For instance, using the top SOC stock estimates in European agricultural land provided by Lugato et al. (2014) and the soil erosion estimated by RUSLE2015, we calculated an overall SOC detachment of 14.8 Mt annually. Compared to the total 17.63 Gt of SOC in agricultural lands (Lugato et al., 2014), this results in a 1% SOC detachment in 12 years. This rough estimate, which aims to highlight the order of magnitude of the process, shows that landscape and biogeochemical processes need to be integrated into a unique framework which can predict the multiple effects of the implementation of agricultural policies such as the GAEC. In the future, the soil loss map can improve the knowledge about phosphorus budget in agricultural soils.

3.6. RUSLE2015 evaluation and data availability

The application of RUSLE2015 and the map of soil loss in the EU overcome the problems outlined by previous pan-European assessments (e.g. Cerdan et al., 2010; Bosco et al., 2015), i.e. lack of high-resolution pan-European datasets, lack of homogeneity in available data, absence of management practices and lack of rainfall intensity datasets. The model is presented in a transparent way and the input layers have been peer-reviewed following the principles described in the literature. The transparency of the model ensures comparability with other regional/national data sources, replicability of the results with future databases, and usability by policy makers and scientists. An additional benefit of the RUSLE2015 model is its ability to carry out scenario analyses based on past and future land-management and land-use changes, and climate change.

The 100 m resolution map of soil loss in the Europe Union based on the year 2010 and its input layers are available from the online European Soil Data Centre (http://esdac.jrc.ec.europa.eu). The issue of data availability is important both for decision makers and modellers in various environmental domains such as agricultural production, food security, carbon sequestration, biodiversity, ecosystem services and water management. However, it is better not to take decisions at pixel level (100 m resolution) where it is recommended to use local measurements. It should also be pointed out that the soil loss rates presented in this paper are long-term averages and should not be compared with event-based observations, given the large seasonal variability of the *R*- and *C*-factors. Moreover, users should take into account the fact that an additional model component is needed to predict sediment yields from catchment areas. The future development of RUSLE2015 will include the temporal distribution of soil loss and a sedimentation module.

4. Conclusions

This paper describes the application of a modified RUSLE model (RUSLE2015) using the latest high-resolution input layers at the European scale, to produce the soil loss map of the European Union at 100m resolution for the reference year 2010. RUSLE2015 shows that, excluding non-erosion-prone areas (urban, bare rocks, glaciers, water bodies), the EU has a mean annual soil loss rate 2.46 t ha^{-1}. The total annual soil loss of the EU is estimated at around 970Mt. The results of RUSLE2015 compared well with national data reported in the EIONET-SOIL database. RUSLE2015 was found to be the most suitable modelling approach for estimating soil loss at the European scale (in terms of validation, usability, replicability, transparency, and parameterisation).

The mean soil loss rate in the EU exceeds the average soil formation rate by a factor of 1.6. The highest soil loss rates are found in the Mediterranean areas and in the Alpine regions of Slovenia and western Austria, mainly due to a combination of high rainfall erosivity and steep topography. Soil protection measures should focus on the 24% of European lands that experience mean annual soil loss rates of over 2 t ha^{-1}.

A spatial analysis by land cover type demonstrated that croplands have a mean annual soil loss similar to that of shrublands, while pastures show significantly lower rates, and forests areas are practically non-erodible. The highest soil loss rates are found in sparsely vegetated areas. A special focus was given to arable lands, where management practices and support measures implemented in the context of the Common Agricultural Policy reduced the soil loss rate by 20%. Such measures have helped to reduce overall EU soil loss by 9.5% in total during the past decade. The land management and agricultural practices applied in the EU over the past decade are much improved compared to those used previously (e.g. 20 years ago). The soil loss map delineates hotspots that will require special protection measures. In the 12.7% of arable lands that experience unsustainable rates of soil loss (>5 t ha^{-1} yr^{-1}), policy makers can promote anti-erosion measures by financing land management practices such as reduced tillage, the planting of cover crops, keeping plant residues at the soil surface, the maintenance of stone walls, and the increased use of grass margins and contour farming.

Based on the land-use changes predicted for the year 2050 by the LUMP model, RUSLE2015 estimates a decrease in soil loss rates mainly due to an increase of forest area at the expense of semi-natural and pasture areas. By contrast, the expansion of arable land area creates an uncertainty in future soil loss estimates. The increase of grass margins, the maintenance of stone walls and the application of contour farming foreseen by the Common Agricultural Policy can further reduce soil loss rates in arable lands. On the other hand, the pressure from other policies (e.g. the Biofuels Directive) to cultivate (mainly erosion-prone) energy crops may increase soil loss rates if no additional management practices are applied. RUSLE2015 is a useful tool for simulating the effects of these policy developments, land use changes and land management practices on the rates of soil loss due to water erosion.

Conflict of interest

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

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.envsci.2015.08.012.

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