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A NEW ASSESSMENT OF SOIL LOSS DUE TO WIND EROSION IN EUROPEAN AGRICULTURAL SOILS USING A QUANTITATIVE SPATIALLY DISTRIBUTED MODELLING APPROACH

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ABSTRACT

Field measurements and observations have shown that wind erosion is a threat for numerous arable lands in the European Union (EU). Wind erosion affects both the semi-arid areas of the Mediterranean region as well as the temperate climate areas of the northern European countries. Yet, there is still a lack of knowledge, which limits the understanding about where, when and how heavily wind erosion is affecting European arable lands. Currently, the challenge is to integrate the insights gained by recent pan-European assessments, local measurements, observations and field-scale model exercises into a new generation of regional-scale wind erosion models. This is an important step to make the complex matter of wind erosion dynamics more tangible for decision-makers and to support further research on a field-scale level. A geographic information system version of the Revised Wind Erosion Equation was developed to (i) move a step forward into the large-scale wind erosion modelling; (ii) evaluate the soil loss potential due to wind erosion in the arable land of the EU; and (iii) provide a tool useful to support field-based observations of wind erosion. The model was designed to predict the daily soil loss potential at a ca. 1 km^2 spatial resolution. The average annual soil loss predicted by geographic information system Revised Wind Erosion Equation in the EU arable land totalled 0·53 Mg ha^{-1} y^{-1}, with the second quantile and the fourth quantile equal to 0·3 and 1·9 Mg ha^{-1} y^{-1}, respectively. The cross-validation shows a high consistency with local measurements reported in literature. © 2016 The Authors. *Land Degradation and Development* published by John Wiley & Sons, Ltd.

KEY WORDS: soil degradation; GIS-RWEQ; Soil Thematic Strategy; European Union; wind erosion modelling

INTRODUCTION

Soil erosion by wind (wind erosion) is a serious environmental problem (Lal, 1994) often resulting in severe forms of soil degradation (Dregne & Chou, 1992; Warren, 2003; Zhang *et al.,* 2014). Wind erosion occurs in dry conditions when the soil is exposed to wind (Zobeck, 1991; Webb *et al.,* 2006). It is a wind-forced movement of soil (Bagnold, 1941; Shao, 2008) where the finest particles, particularly organic matter, clay and loam, are entrained and transported over long distances before being redeposited elsewhere (Chepil, 1946). The accumulation of matter stripped through the action of wind during the postglacial period constituted an importing geomorphic process (Livingstone & Warren, 1996). It formed to the fertile loess soils that cover large areas of Europe and North America, where highly productive farming has developed ever since (Roose, 1996; Haase *et al.,* 2007). In recent times, however, intensive farming has increased the frequency and magnitude of this geomorphic process with consequences especially for sensitive lands, important for food production (Dostal *et al.,* 2006; Funk & Reuter, 2006; Wang *et al.,* 2015). Land management practices such as intensive crop cultivation, increased mechanisation, enlargement of field sizes, removal of hedges, high residues/biomass exploitation of vegetation and consecutive bare fallow years in cultivated lands exacerbated both environmental and economic effects of wind erosion (Chepil & Woodruff, 1963; Williams & Young, 1999; Riksen & de Graaff, 2001; Warren & Bärring, 2003; Houyou *et al.,* 2014; Colazo & Buschiazzo, 2015; Gao *et al.,* 2015). Increased soil loss rates due to wind constitute an on-site challenge that decreases the ability of soils to sustain vegetation and livestock (Goossens, 2003). At the same time, it also causes off-farm impacts related to the spread of dust, herbicides and pesticides (Riksen & de Graaff, 2001; Goossens, 2003).

In fact, wind erosion is also a phenomenon relevant for Europe (Warren, 2003; Verheijen *et al.,* 2009) although this land degradation process has been overlooked until very recently (Funk & Reuter, 2006). Wind erosion proceeds unnoticed in the short term (Chepil, 1960). Still, a considerable part of the topsoil, rich in nutrient and organic matter, is removed and damages agricultural productivity in the long term (Lyles, 1975) with a consequently increased use of fertilisers. Riksen & De Graaff (2001) reported that wind erosion may affect about one million hectares in the western part of Denmark (ca. 38% of the utilised agriculture area), 170·000 ha in Sweden (ca. 5·5%), almost two million ha in North Germany (ca. 12%), 260·000 ha in the UK (ca. 1·5%) and 97·000 ha in the Netherlands (ca. 5·2%).

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The state-of-the-art literature presents wind erosion as a process that locally affects the temperate climate areas of the northern European countries as well as the semi-arid areas of the Mediterranean region (Eppink & Spaan, 1989; López *et al.,* 1998; Funk & Engel, 2015, among others). Actual observations, field measurements and modelling assessments, however, are all extremely limited and highly unequally distributed across Europe. To gain a better understanding of the wind erosion situation in Europe, the Soil Resource Assessment working group of the Joint Research Centre carried out the first European Union assessment of land susceptibility to wind erosion (Borrelli *et al.,* 2014b; Borrelli *et al.,* 2016). By means of a modelling exercise, the spatiotemporal variations of the most influential wind erosion factors (i.e. climatic erosivity, soil erodibility, vegetation cover and landscape roughness) were combined to highlight the regions that are potentially affected by this process.

Today's challenge is to integrate the insights of local experiments and field-scale models into a new generation of large-scale wind erosion models. While naturally being less accurate than field-scale models, they still provide essential knowledge about where and when wind erosion occurs and disclose the level of risk for agricultural productivity in specific areas.

The Revised Wind Erosion Equation (RWEQ; Fryrear *et al.,* 2000) is a tool extensively tested to perform field-based predictions of soil loss due to wind erosion. A number of studies have found good agreement between the yields predicted by RWEQ and the field measures (Buschiazzo & Zobeck, 2008; Youssef *et al.,* 2012). The significant relationship between the observed and predicted transport capacity and soil loss (Zobeck *et al.,* 2001), as well as the limited need for input data compared with mechanistic wind erosion models like the Wind Erosion Prediction System (Hagen, 2004), makes RWEQ a suitable tool for a large-scale prediction of the wind erosion potential (Zobeck *et al.,* 2000; Youssef *et al.,* 2012; Guo *et al.,* 2013).

In this study, a geographic information system (GIS) version of the RWEQ (named GIS-RWEQ) is presented to quantitatively assess soil loss by wind over large study areas and to evaluate the reliability of its results. The GIS-RWEQ model and available datasets were used to compute soil loss rates in the arable land of the 28 member states of the European Union (EU-28) between January 2001 and December 2010. The GIS-RWEQ model reproduces the main components of RWEQ in a GIS environment. RWEQ, a combination of empirical and process modelling broadly tested in the USA by the United States Department of Agriculture Agricultural Research Service, has proven its potential for upscaling (Zobeck *et al.,* 2000). Therefore, it has also been employed for large-scale wind erosion assessments outside the USA (Visser *et al.,* 2005; Youssef *et al.,* 2012; Guo *et al.,* 2013; Gong *et al.,* 2014). Its comprehensive modelling scheme, tested for various types of soil, along with its rather low demand of input data, makes it a suitable equation for the initial assessment of soil loss due to wind erosion in Europe. As for water erosion (Panagos *et al.,* 2016), the decision to use a model developed for the USA as a basis is due to the lack of wind erosion models developed and tested for European environments.

MATERIALS AND METHODS

Study Area

For the purposes of the model, the arable land of the EU-28 were selected. More specifically, the study area covered the following CORINE 2006 land cover unit: non-irrigated arable land (code 2.1.1) and permanently irrigated land (code 2.1.2). The resulting modelling area amounted to ca. 96·1 million hectares.

The Revised Wind Erosion Equation Model

The RWEQ is a combination of empirical and process-based modelling developed to estimate the soil loss for agricultural fields in the USA (Fryrear *et al.,* 1998; Fryrear *et al.,* 2000). The equation estimates the amount of soil eroded and transported by wind within the first 2-m height for a specified time period. RWEQ was extensively tested in the Great Plain area (Fryrear *et al.,* 1999). Its input factors derive from both field and laboratory studies (Woodruff & Siddoway, 1965). The actual transport model was developed and calibrated through field data of mass transport.

The equation is relatively simple and requires a limited amount of input data, which makes it suitable for upscaling (Zobeck *et al.,* 2000; Youssef *et al.,* 2012; Guo *et al.,* 2013). Wind is the basic driving force in the model. Independent of the type of soil, the model predicts the eroded soil up to the capacity that could be transported by the wind. The soil loss (SL) for a specific field is calculated including the downwind trend in soil loss and sediment flux within the field. Following Fryrear *et al.* (2000), the model estimates the mass transport (Q_x (kg m^{-1})) at a specific downwind distance (x (m)) away from the upwind border as

$$Q_x = Q_{\max}\left[1 - e^{-\left(\frac{x}{s}\right)^2}\right] \tag{1}$$

where s is the critical field length (m) at which the 63% maximum transport capacity ($Q_{\max}$ (kg m^{-1})) is reached. $Q_{\max}$ and s are estimated as

$$Q_{\max} = 109.8\left(WF{\cdot}EF{\cdot}SCF{\cdot}K'{\cdot}COG\right) \tag{2}$$

$$s = 150.71\left(WF{\cdot}EF{\cdot}SCF{\cdot}K'{\cdot}COG\right)^{-0.3711} \tag{3}$$

where *WF* is the weather factor, *EF* is the soil erodible fraction, *SCF* is the soil crust factor, *K′* is the soil roughness and *COG* is a combined crop factor. The average SL expressed in (kg m^{-2}) at a specific point (x (m)) in the field is

$$SL = \frac{2_x}{s^2} Q_{\max} e^{-\left(\frac{x}{s}\right)^2} \tag{4}$$

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Conceptual Scheme

In the original version of RWEQ (Fryrear *et al.,* 2000), the model's simulation region is a specific field with given size, shape, orientation, climate and vegetation cover dynamics. The input data required to run the model are generally directly measured data. In this paper, a simplified GIS-based application of the RWEQ model is proposed and called GIS-RWEQ. It follows a spatially distributed approach based on a grid structure, running in R and Python scripts. The model scheme is designed to describe the daily soil loss potential at a large scale.

For its application at EU-28 scale, the spatiotemporal pattern and dynamic changes of the environmental factors necessary to build the input layers were obtained by means of remote sensing techniques (ENVI and eCognition), GIS applications and statistic operations (ArcGIS 10.2; R statistics). The simulation region of the GIS-RWEQ model was represented by a grid cell (ca. 1 × 1 km, a MODIS ca. 250 m cell-size multiple). The soil loss potential was computed on a daily base for each simulation sub-region across the entire period between January 2001 and December 2010, by combining soil properties and daily data of rainfall, wind speed, evapotranspiration, soil moisture and crop canopy cover (Figure 1). The material and methods employed for the delineation of the simulation subregions and the application of GIS-RWEQ are reported in the Supporting Information.

Model Implementation

Running GIS-RWEQ for the entire EU-28 demanded a high computational power and several terabytes of data storage capacity. The model input factors were pre-processed in a GIS environment (AcrGIS, ENVI and eCognition), whereas the calculations were carried out through R and Python scripting. The large amount of data (ca. 7,300 layers per year) was handled by tailing the study area (617 tiles 100 × 100 km) and creating loops of data processing. Despite the use of multi-tasking calculation in a Linux server, 25 days of calculations were needed to obtain the final results.

Model Performance Evaluation

The outcomes of the proposed modelling approach were subjected to a validation procedure to assess the model performance. A subset of the literature locations suffering from wind erosion reported by Borrelli *et al.* (2016) was employed. Out of 156 locations accurately georeferenced in GIS, 90 were found to be located within EU-28 arable land. These study sites, mostly reporting qualitative assessments of wind erosion, were spatially overlaid with the GIS-REWQ map, assigning them the long-term average annual soil loss predicted by the GIS-RWEQ model.

The underlying validation criteria is that the studies on wind erosion are likely distributed in areas where this process is relevant and, consequently, where also the model should predict high soil losses.

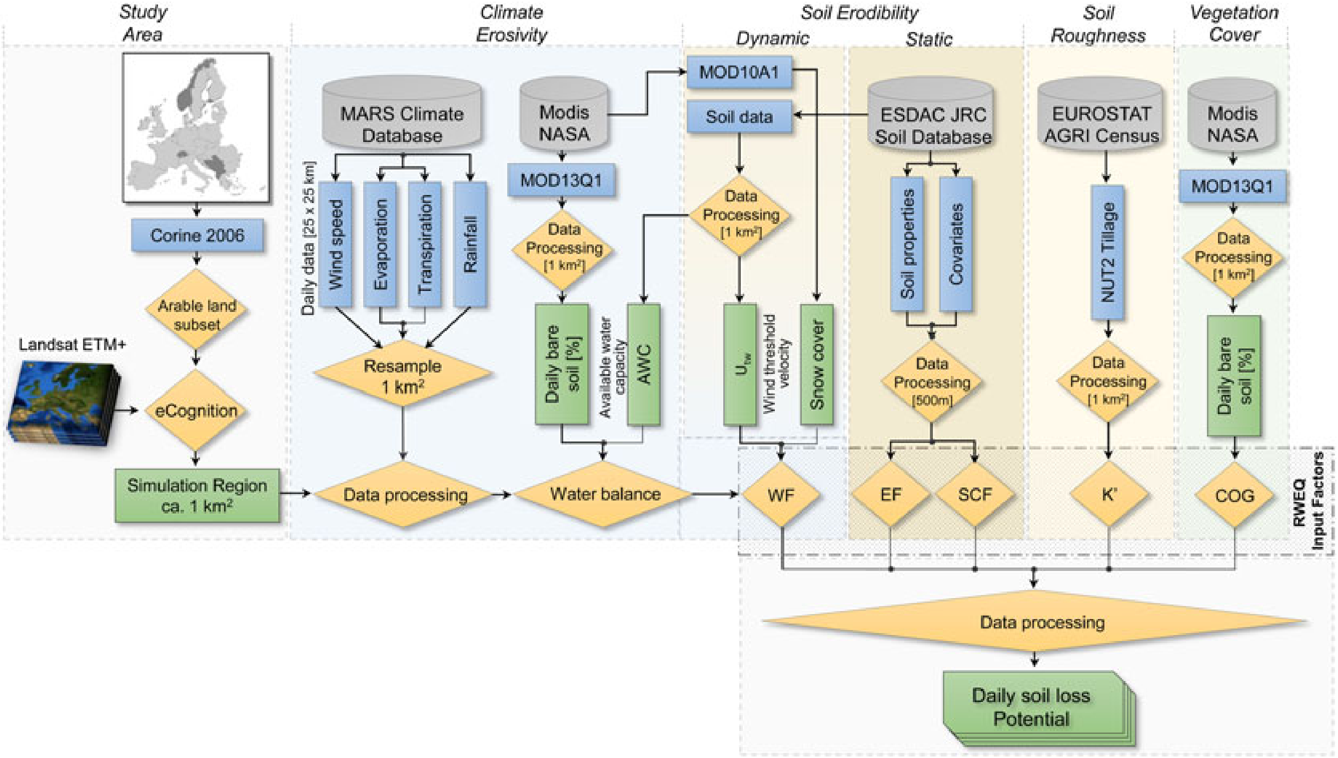

Figure 1. Workflow of the geographical information system Revised Wind Erosion Equation application at pan-European scale. The symbols of the Revised Wind Erosion Equation input factors stands for WF, weather factor; EF, wind-erodible fraction of soil; SCF, soil crust factor; K′, soil roughness factor and COG, combined crop factors. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

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RESULTS

Geographical and Temporal Occurrence of Wind Erosion

The soil loss potential due to wind erosion was estimated by the GIS-RWEQ for the 1·17 million cells (ca. 1 km spatial resolution) into which the arable land of the EU-28 was subdivided. The average annual soil loss rates predicted for the period 2001–2010 totalled 0·53 Mg ha^{-1} y^{-1}, with the second quantile and fourth quantile equal to 0·3 and 1·9 Mg ha^{-1} y^{-1}, respectively. The spatial pattern of soil erosion was divided into six classes defined according to the soil loss data distribution (quintiles) (Figure 2). Approximately a third (36·3%) of the investigated arable land showed no sign of erosion (Figure 3). About 33·7% and 8·2% of the study area, respectively, were subject to very low and low soil erosion, whereas 12·2% were characterised by slight erosion. For the remaining 9·7% of arable land, moderate (5·3%) and high (4·4%) soil loss rates were predicted.

The modelling outcomes suggest that wind erosion is a common process in most countries. A cross-country analysis (Table I) showed the highest annual soil loss rate in Denmark (3 Mg ha^{-1} y^{-1}), the Netherlands (2·6 Mg ha^{-1} y^{-1}), Bulgaria (1·8 Mg ha^{-1} y^{-1}) and to a lesser extent also in the UK (1 Mg ha^{-1} y^{-1}) and Romania (0·95 Mg ha^{-1} y^{-1}). As illustrated in Figure 2, the areas, potentially affected by evident soil loss rates, showed a clumped spatial distribution. In northern Europe, the locations most susceptible to wind erosion were found along the North Sea coasts of Denmark, UK, the Netherlands, Germany, France and Belgium. Noticeable soil loss rates were also predicted along the coast of the Baltic Sea, especially in the western sector, Czech Republic, Slovakia and Hungary. In the Mediterranean area, higher erosion rates occurred in a zonal distribution. Here, regions with higher soil loss rates were located in the Spanish regions of Aragón, Castilla y Leon, the Italian regions of Apulia, Tuscany and Sardinia, in the Provence in France and the Greek regions of Central and Eastern Macedonia and Thrace. In Eastern Europe, high erosion rates appeared in the Romanian and Bulgarian lowlands surrounding the Carpathian Mountains and along the Black Sea coastline. About 35% and 21·1% of the Bulgarian and Romanian arable lands, respectively, potentially experienced soil loss rates greater than 1·5 Mg ha^{-1} y^{-1}.

The modelling results indicated a pronounced temporal variability of soil loss rates. While different patterns across the countries could be observed, the temporal distribution

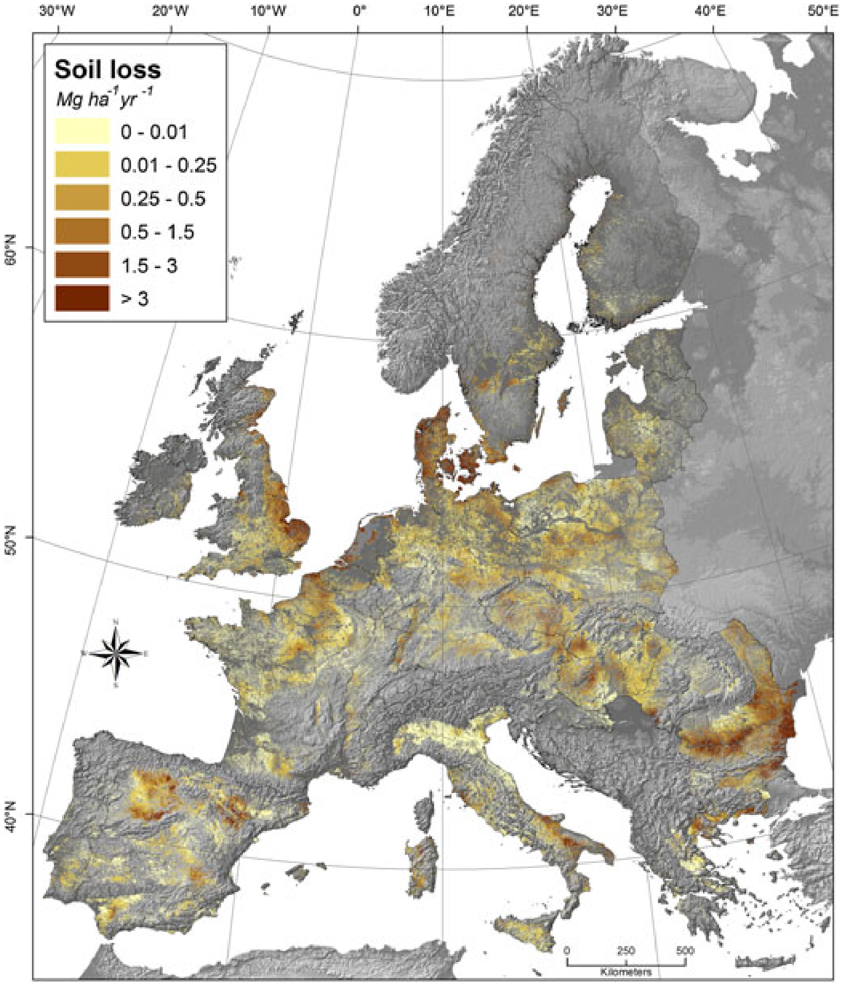

Figure 2. Potential wind soil loss modelled for the European arable land. Spatial resolution ca. 1 × 1 km cell size. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

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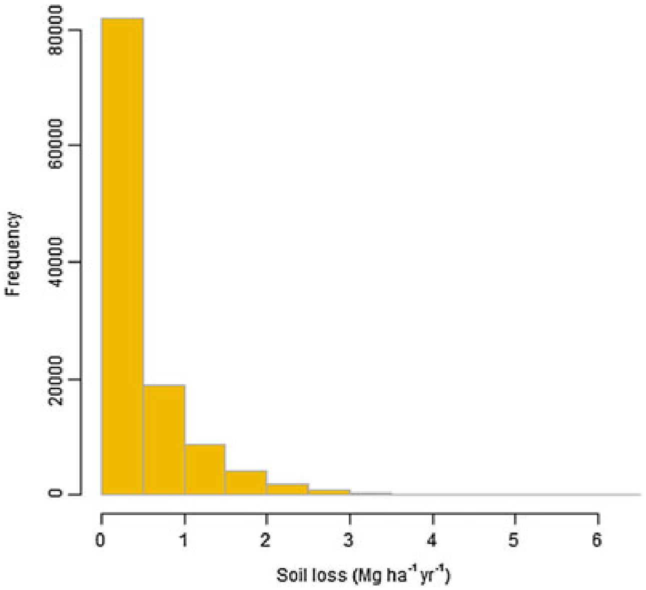

Figure 3. Histogram of wind soil loss rates for the European Union arable land. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

of wind erosion throughout the year at a European level showed the highest values during the winter period. Soil loss rates were at their peak between December and February, accounting for approximately 57% of the total losses. In spring, the monthly soil loss values decreased hitting their minimum in May (Figure 4). As expected, the temporal dynamics of soil erosion were closely correlated with the weather factor (WF) patterns (Figure 4). The average monthly WF totalled 23·3 kg m-width^{-1}. The most severe monthly WF was observed during the period between January (44·1 kg m-width^{-1}) and March (41·4 kg m-width^{-1}). Figure 5 illustrates a comparison between the average annual WF computed for this study (Eq. 2 of the Supporting Information) and the potential annual WF value calculated assuming the RWEQ threshold wind velocity. The annual average of the WF potential totalled 643 kg m-width^{-1} (Figure 5a). This is a value three times higher than the one computed for this study (278·6 kg m-width^{-1}; Figure 5b). The most remarkable decreases of the WF occurred in the Atlantic and Continental regions, which is mainly because of high soil moisture conditions. By contrast, in the Mediterranean area, the WF values maintained intensities and spatial patterns similar to the scenario modelled.

Table I. Descriptive statistics of the potential soil loss for the European counties.

Country	Mean	Maximum	Soil loss > 3 Mg ha^{-1} y^{-1}
	Mg ha^{-1} y^{-1}		[%]
Austria	0·26	5·2	0·2
Belgium	0·31	8·4	1·5
Bulgaria	1·84	20·7	17·6
Croatia	0·00	1·2	—
Cyprus	0·00	0·5	—
Czech Republic	0·45	7·2	1·8
Denmark	3·01	39·9	36·3
Estonia	0·27	15·3	2·3
Finland	0·33	16·5	3·0
France	0·19	18·8	1·0
Germany	0·26	33·1	1·1
Greece	0·55	37·4	3·7
Hungary	0·27	10·2	0·8
Ireland	0·25	15·8	1·9
Italy	0·27	22·8	2·0
Latvia	0·07	7·9	0·2
Lithuania	0·10	8·1	0·1
Luxembourg	0·02	0·8	—
Malta	—	—	—
The Netherlands	2·60	36·7	30·4
Poland	0·18	11·6	0·2
Portugal	0·06	7·4	0·1
Romania	0·95	16·4	8·5
Slovakia	0·39	10·6	1·3
Slovenia	0·01	0·4	—
Spain	0·43	20·6	3·4
Sweden	0·74	26·1	5·8
UK	1·03	29·2	10·7

With regard to the inter-annual variability, the model simulated highest values of soil loss of 0·74, 0·77 and 0·6 Mg ha^{-1} y^{-1} in 2001, 2002 and 2004, respectively. Across the entire study period, the average annual soil losses ranged from 0·32 to 0·77 Mg ha^{-1} y^{-1} (σ 0·14 Mg ha^{-1} y^{-1}).

The effect of the vegetation cover on the soil loss budget, assessed through the soil retention capacity (SL_{sv}) (Gong *et al.,* 2014), amounted to 11·37 Mg ha^{-1} y^{-1}. Accordingly, the potential soil loss under permanent bare soil conditions was estimated to be 11·9 Mg ha^{-1} y^{-1}. In fact, this is 22 times higher than the soil loss modelled in the official modelling. Under the simulation of permanent bare soil conditions, the highest increase of soil loss was observed during the period between May and July. Monthly average soil loss rates showed values ranging from 0·41 Mg ha^{-1} month^{-1} (July) to 1·73 Mg ha^{-1} month^{-1} (March).

Model Performance

The cross-check of the modelling results showed that the predicted soil loss rates were generally in agreement with the wind erosion sites reported in literature. In the European arable land, 85 of the 90 locations reported in literature (94·4%) were classified by the GIS-RWEQ model as being susceptible to erosion. Thereof, 23·3% of the literature sites fell into areas modelled as high erosion areas (>3 Mg ha^{-1} y^{-1}), whereas 48·9% fell into areas where slight to moderate erosion was predicted (0·5–3 Mg ha^{-1} y^{-1}). The remaining 22·2% literature sites fell into areas classified as being very low to low erosive (0·01–0·5 Mg ha^{-1} y^{-1}).

DISCUSSIONS

The Paradigm of Wind Erosion in Europe

Soil erosion by wind is a serious environmental threat to which European decision-makers currently pay little attention. Although there are numerous informative studies across Europe, these are mainly carried out at field or local scale (López *et al.,* 1998; Böhner *et al.,* 2003; Funk &

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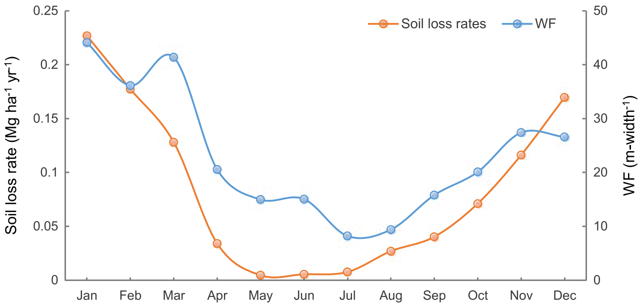

Figure 4. Monthly averages of soil loss and weather factor (WF) values. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

Engel, 2015). While meaningful from the local perspective, the number of studies and their spatial distribution has not been sufficient to gain a comprehensive understanding of the current wind erosion dynamics in Europe. As a result, wind erosion has been overlooked as a land degradation process in recent years (Funk & Reuter, 2006). For a too long time, the knowledge about the '*where*' and the '*when*' of wind erosion in Europe relied on rough approximations carried out during the early nineties (EEA - European Environment Agency, 1998; Jones *et al.,* 2012) by combining heterogeneous methods of field observations and measurements (van Lynden, 1995). Recent studies (Böhner *et al.,* 2003; Gomes *et al.,* 2003; Warren, 2003; Funk & Reuter, 2006; Borrelli *et al.,* 2016) provided reasons to believe that the dynamics of wind erosion are more complex than previously assumed. The current incomplete state of knowledge about wind erosion may seriously limit the development of effective EU policies and measures aiming to mitigate this threat.

Interestingly, there is a huge imbalance between the literature about wind and water erosion in Europe, in terms of knowledge depth, number of peer-reviewed publications as well as the amount of ongoing field experiments. During the last few decades, water erosion prediction models have successfully been coupled with GIS, thus allowing the upscaling of soil erosion assessment from field level to watershed or even global level. Field-scale water erosion models such as the universal SL equation (Wischmeier *et al.,* 1971) were linked to GIS and applied from regional (Borrelli *et al.,* 2016) to global scale (van Oost *et al.,* 2007). At the same time, quantitative attempts to integrate wind erosion prediction models into GIS environments were less straightforward, with most applications reaching beyond field scale.

As a result, for over two decades, the dynamics of wind erosion processes in Europe have been described through the global data proposed by Oldeman (1994), the European-wide assessment proposed by the International Soil Reference and Information Centre (Van Lynden, 1995) and the European Environment Agency (EEA - European Environment Agency, 1998; Jones *et al.,* 2012). With the introduction of the Index of Land Susceptibility to Wind Erosion (ILSWE) approach, Borrelli *et al.* (2016) reported innovative insights into the spatiotemporal dynamics of wind erosion processes in Europe. The GIS-RWEQ model, compared with the semi-quantitative approach previously proposed, provides a more comprehensive and thorough modelling scheme capable of making a quantitative estimate of soil loss.

Geographical Information System Revised Wind Erosion Equation — A New Approach for Large-scale Quantitative Estimates

In this study, the RWEQ model was selected because it has proven to be an effective tool (Buschiazzo & Zobeck, 2008;

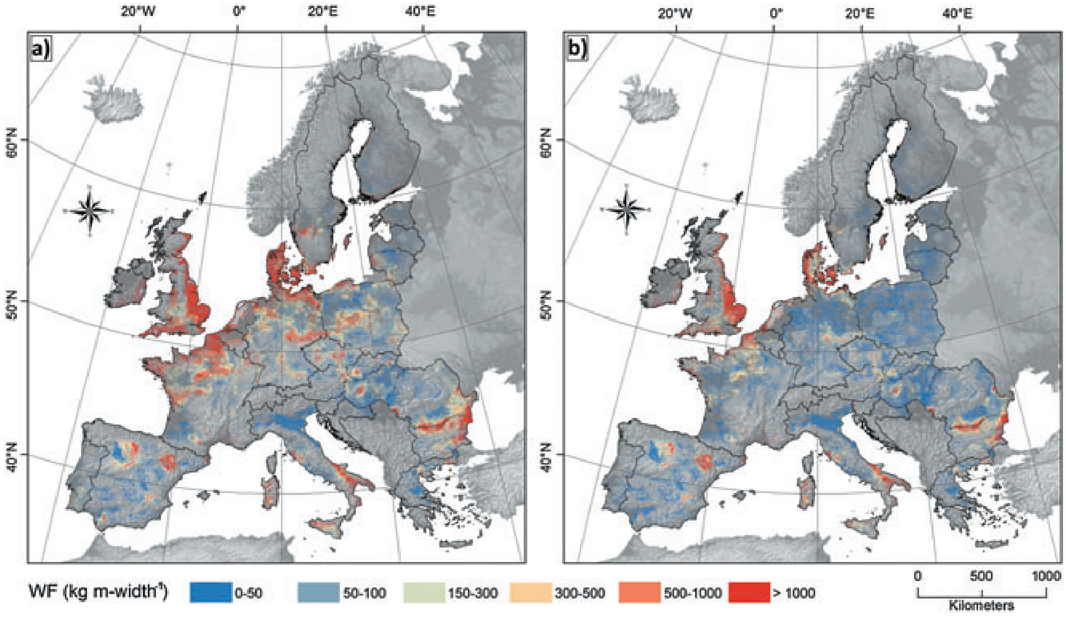

Figure 5. Average annual weather factor (WF). Spatial distribution of the potential wind factor (without topsoil moisture adjustment) (left). Spatial distribution of the current modelling wind factor adjusted for the proposed topsoil moisture content (right). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

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Youssef *et al.,* 2012), with a straightforward modelling scheme and only a limited amount of input data. The first attempt to up-scale RWEQ was carried out in Texas by Zobeck *et al.* (2000), where the RWEQ software was employed to predict the soil loss for a number of representative fields. The results were spatialised using GIS techniques. This study showed good results and demonstrated the feasibility of up-scaling from field to regional scale using GIS tools. Although accurate, the proposed methodology still strongly depended on the original RWEQ software and could not be applied to double-digit square kilometre study area sizes. Later approaches aimed to fully integrate the RWEQ scheme into GIS environments (Guo *et al.,* 2013; Gong *et al.,* 2014). This, however, resulted in an inevitable simplification of the model scheme, in order to overcome the challenges of computing the input parameters for large study areas. Despite modelling limits such as the lack of a thorough approach to spatially assess the soil erodibility, the use of a static threshold for the wind velocity, the disregard of vegetation cover on evapotraspiration or the neglect of the spatial changes in field sizes and shapes within the study area, these models unveiled important aspects about the dynamics of wind erosion in the observed areas.

The development of the conceptual GIS-RWEQ framework followed the path paved by previous modelling exercises (Guo *et al.,* 2013; Gong *et al.,* 2014). Given the considerably larger study area compared with former studies, a number of modelling assumptions had to be made as well. The GIS-RWEQ scheme, however, is able to perform a more comprehensive GIS transformation than the previous large-scale RWEQ applications, thus making it a more dynamic exercise. GIS-RWEQ was designed to (i) predict the daily soil loss potential for 1·17 million simulated subregions with their individual field geometry being extracted by remote sensing operations (average field area, length, width and direction); (ii) assess the daily vegetation cover dynamics; (iii) take into account the potential effect of the local soil tillage operations on the soil roughness factor; and (iv) implement a dynamic threshold wind velocity thereby accounting for soil properties, soil moisture content and a snow cover.

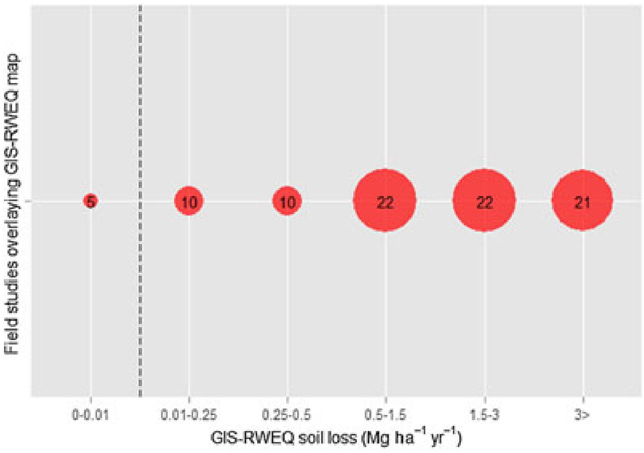

Figure 6. Distribution of the soil loss rates predicted for the 90 wind erosion-sensitive locations reported in literature into the six soil loss classes. GIS-RWEQ, geographical information system Revised Wind Erosion Equation. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

Model Performances

The cross-check analysis showed that the results are promising and that the approach undertaken is suitable for the integration of a more comprehensive RWEQ modelling scheme into GIS. During the evaluation of the model performances, it turned out that 94·4% of the 90 wind erosion-sensitive locations reported in literature were also classified by the GIS-RWEQ model as being affected by wind erosion. For the majority of these locations, moderate to high soil erosion rates were predicted (Figure 6). Further analyses showed that the results were consistent with the observed data of the local studies collected during the Wind Erosion on European Light Soils (WEELS) assessment.

More in-depth comparisons were made for five locations studied within the European Union project ‘WEELS’ (Böhner *et al.,* 2003). The first site considered was the Breckland district in the UK, with an area of ca. 1,000 km^2 well-known for its wind erosion susceptibility (Riksen & De Graaff, 2001). Here, GIS-RWEQ confirmed the high vulnerability to wind erosion of the area by predicting an average soil loss of 3·25 Mg ha^{-1} y^{-1}. The second site was an experimental area of about 25 km^2 in the Suffolk County, in East Anglia. Using radioisotope caesium-137 as a tracer for wind erosion, Chappell & Warren (2003) reported a long-term net soil loss of 0·6 Mg ha^{-1} y^{-1}. In this experimental area, GIS-RWEQ predicted a soil loss of 2·5 Mg ha^{-1} y^{-1} (σ 2·2 Mg ha^{-1} y^{-1}) for the period 2001—2010. This value is slightly higher than the one reported by Chappell & Warren (2003), but it is not far from the average soil erosion rate predicted in the area by Böhner *et al.* (2003), using the WEELS model at 25 × 25 m spatial resolution for the period 1970—1998 (1·56 Mg ha^{-1} y^{-1}). The third site under consideration was Grönheim, in Lower Saxony. Here, Goossens *et al.* (2001) estimated a total dust transport between 0·16 and 0·2 Mg ha^{-1} y^{-1}, while the high spatial resolution application of the WEELS model (Böhner *et al.,* 2003) predicted an average soil loss of 0·43 Mg ha^{-1} y^{-1} for the period between 1981 and 1993. Again, GIS-RWEQ predicted a soil loss ratio in the same order of magnitude reported by the local investigations (0·15 Mg ha^{-1} y^{-1}). The last two locations taken into account were Exloërmond, in the Netherlands and Scania in Sweden. Although no quantitative soil erosion data were reported in literature for these two locations, both sites were described as being subject to a serious wind erosion threat in the WEELS project (Riksen & De Graaff, 2001; Böhner *et al.,* 2003; Riksen, 2004). The GIS-RWEQ model predicted soil erosion rates of 1·42 (σ 2·54) and 1·23 Mg ha^{-1} y^{-1} (σ 1·39) for Exloërmond and Scania, respectively, thus confirming the sensitivity of the areas to wind erosion.

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Scope, Limitations and Future Directions

The proposed methodology constitutes a significant step for closing the research gap in large-scale wind erosion assessments. This dynamic tool is also of high relevance to inform national and European policy-makers in supporting the decision-making process. In light of these considerations, the meaningful results obtained by the cross-validation of the modelling outcomes clearly support the relevance of the proposed model as a basis for future wind erosion research. GIS-RWEQ's capacity to provide quantitative estimates allows for its outcomes to be embedded into other modelling platforms in order to comprehensively assess how these wind erosion processes affect the soil organic carbon content (van Oost *et al.,* 2007; Gao *et al.,* 2015; Borrelli *et al.,* 2016; Lugato *et al.,* 2016) and their economic losses due to wind erosion (Riksen & De Graaff, 2001). Researchers are thus invited to use GIS-RWEQ as a basis for future investigations in order to drive wind erosion research into a new era.

Despite the large scope of the study area, the most important input factors of the RWEQ model were maintained in the proposed GIS-RWEQ model. At this scale, however, the effect of the topographical (hillslopes) and landscape features (e.g. wind barriers/shelterbelts) on wind speed could not be considered because suitable methods and database are not available. With regard to the crop canopy (combined crop factors), this input factor was simplified by not considering the residues (SLR_s and SLR_f) and their decomposition. Accordingly, daily combined crop factors values were given by the fraction of soil surface covered with crop canopy derived by MODIS imagery.

Still, enhancements in the input data could further improve the accuracy of the model. Important input parameters such as wind speed, rainfall and evapotraspiration were derived by data interpolation of an original 25 × 25-km grid. Although these are the best daily data currently openly available, the spatial resolution is rather coarse and suboptimal for the evaluation of the wind erosion dynamics. Moreover, the database used did not provide information regarding the wind direction and occurrence of wind gusts. The former limited the model's capacity to fully use the field characteristics extracted through Landsat imagery segmentation (Figure 7). Regarding the later, the absence of wind gusts limited our ability to assess extreme erosion events in order to better calibrate the daily wind values. Without information on wind gusts and sub-daily wind speed data, the estimated values of the daily wind erosive force could have been subject to underestimations. The soil movement rates are proportional to the cube of average wind speed (Skidmore, 1986). As a consequence, an extreme wind event concentrated in a short time interval would not adequately be represented by the daily average. Another limitation of the model is related to the structure of the soil moisture module. The soil water content affects the threshold wind speed that is necessary to erode the soil (Chepil, 1946). To represent the erodibility continuum, which is related to the type of soil and its moisture conditions (Webb & Strong, 2011), the threshold wind velocity for wet soil condition (U_{tw}) used the exponential relationships reported in the relevant literature (Bisal & Hsieh, 1966; Chen *et al.,* 1996; Fécan & Bergametti, 1998). In specific circumstances, the incoming solar radiation and evapotranspiration could quickly dry the outermost layer of soil, so that wind erosion could follow a rainstorm event within a few minutes (Fryrear *et al.,* 2000). The current daily scale of the model does not allow for the consideration of erosion events occurring during rainy days. This may also be a source of possible soil loss underestimations. This would mainly affect the humid regions of northern Europe where the soil moisture module often increases the threshold wind velocity for wet soil condition (U_{tw}) thus limiting the soil loss occurrence (as illustrated in Figure 5).

Figure 7. Example of the field segmentation results created using eCognition. Location: Groningen province, the Netherlands. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

Importantly, the aforementioned limits could be overcome by applying the GIS-RWEQ model at regional or landscape scale. Thereby, climate data of higher spatiotemporal detail could be used, including sub-daily wind speed data and wind gusts information, which could be interpolated based on advanced techniques of spatial interpolation (Thornton *et al.,* 1997; Panagos *et al.,* 2015). Alternatively, an attempt to overcome the limits related to the daily averages could be based on the investigating of possible statistical relations between wind erosion force sub-hourly values and daily average wind speed data (Guo *et al.,* 2012), taking into account climatic region specific approaches (Naipal *et al.,* 2015). Sub-daily information would also help to address the aforementioned limit related to the current topsoil moisture module. In addition, regional-scale applications of the model could account for further and more accurate land use and land cover features, for example, wind barriers, shelterbelts, riparian vegetation, tree lines and buildings.

CONCLUSIONS

This study proposed a GIS-based methodology combined with the field erosion model RWEQ to assess the potential of wind erosion at large scale. The scheme of this widely applied field wind erosion prediction model was integrated with local measurements, observations and field-scale model exercises to create a new regional-scale wind erosion model for Europe and evaluate its outcomes. With the proposed modelling, it became possible to provide answers to the 'where', the 'when' and the magnitude of wind erosion in European arable lands. This is an important step to make the complex matter of wind erosion dynamics more tangible for decision-makers. It also supports further research on a field-scale level

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