TOWARDS A PAN-EUROPEAN ASSESSMENT OF LAND SUSCEPTIBILITY TO WIND EROSION

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ABSTRACT

Understanding spatial and temporal patterns in land susceptibility to wind erosion is essential to design effective management strategies to control land degradation. The knowledge about the land surface susceptible to wind erosion in European contexts shows significant gaps. The lack of researches, particularly at the landscape to regional scales, prevents national and European institutions from taking actions aimed at an effective mitigating of land degradation. This study provides a preliminary pan-European assessment that delineates the spatial patterns of land susceptibility to wind erosion and lays the groundwork for future modelling activities. An Index of Land Susceptibility to Wind Erosion (ILSWE) was created by combining spatiotemporal variations of the most influential wind erosion factors (i.e. climatic erosivity, soil erodibility, vegetation cover and landscape roughness). The sensitivity of each input factor was ranked according to fuzzy logic techniques. State-of-the-art findings within the literature on soil erodibility and land susceptibility were used to evaluate the outcomes of the proposed modelling activity. Results show that the approach is suitable for integrating wind erosion information and environmental factors. Within the 34 European countries under investigation, moderate and high levels of land susceptibility to wind erosion were predicted, ranging from 25.8 to 13.0 M ha, respectively (corresponding to 5.3 and 2.9% of total area). New insights into the geography of wind erosion susceptibility in Europe were obtained and provide a solid basis for further investigations into the spatial variability and susceptibility of land to wind erosion across Europe. © 2014 The Authors. Land Degradation and Development published by John Wiley & Sons, Ltd.

KEY WORDS: soil degradation; soil protection; land susceptibility; wind erosive days; wind-erodible fraction of soil; wind erosion

INTRODUCTION

Soil erosion by wind is a primary land degradation process (Holmes et al., 2012; Wang & Shao, 2013) which affects natural environments and agricultural lands that have been unwisely exploited (Jönsson, 1994). About 28% of the global land area that experiences land degradation suffers from this wind-driven soil erosion process (Oldeman, 1994). In Europe, wind erosion affects the semi-arid areas of the Mediterranean region (López et al., 1998; Gomes et al., 2003; Moreno Brotons et al., 2009) as well as the temperate climate areas of the northern European countries (De Ploey, 1986; Eppink & Spaan, 1989; Goossens, 2001; Bärring et al., 2003). According to the European Environment Agency (EEA, 1998), about 42 million ha of European agricultural land may be affected by wind erosion. In agricultural lands, soil erosion by wind mainly results from the removal of the finest and most biological active part of the soil richest in organic matter and nutrients (Funk & Reuter, 2006). Repeated exposure to wind erosion can have permanent effects on agricultural soil degradation, making it difficult to maintain favourable soil conditions in the long run (Jönsson, 1994).

Wind erosion has always occurred as a natural land-forming process (Livingstone & Warren, 1996), but, today, the geomorphic effects of wind are locally accelerated by anthropogenic pressures (e.g. leaving cultivated lands fallow for extended periods of time, overgrazing rangeland pastures and, to a lesser extent, over-harvesting vegetation (Leys, 1999)). This becomes detrimental to the environment, farming activities (Warren, 2003) and infrastructures (Zhang et al., 2013). The unwise use and management of land, together with intensive crop cultivation, increasing mechanisation and increased field sizes, exacerbate the effects of wind erosion in the already most sensitive agricultural areas in Europe (Warren, 2003; Funk & Reuter, 2006). However, little is known about the extent and magnitude of wind erosion throughout Europe (Chappell & Warren, 2003). Recent investigations within the framework of EU projects (Wind Erosion on European Light Soils (WEELS) and Wind Erosion and Loss of Soil Nutrients in Semi-Arid Spain (WELSONS), Warren, 2003) provide reasons to suggest that the areas potentially affected by wind erosion may be more widely disseminated than previously reported by the European Environment Agency (EEA, 1998). Further studies have shown that the areas previously reported as being only slightly affected by wind erosion (EEA, 1998) are currently undergoing severe erosion processes (Böhner et al., 2003; Gomes et al., 2003). These findings indicate that the European-wide assessment of the distribution and severity of wind erosion provided by the EEA (1998) may no longer be representative. To reach the goal of the EU Thematic Strategy for Soil Protection (European Commission, 2006) and to tackle the new soil and biodiversity challenges that lie ahead of us (European

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Commission, 2011), we need to (i) gain a better understanding of where and under which conditions land degradation by wind erosion is most likely to occur, (ii) be able to estimate the environmental and economic costs of wind erosion and (iii) assess whether current and planned mitigation measures are effective and wisely distributed from a geographical perspective.

This paper provides a first pan-European assessment of land susceptibility to wind erosion and lays the groundwork for a comprehensive modelling approach. A conceptual model was developed to study the geography of wind erosion in Europe because most existing field-scale models require numerous parameters (Webb, 2008) or need further studies to be upscaled into region scales (Visser & Palma, 2004). First, the study is designed to define and parameterise the factors which determine the location and intensity of wind erosion (i.e. climate, soil characteristics, vegetation coverage and landscape roughness (Shao & Leslie, 1997)). Second, it assesses the conditions and the frequency under which an area may become susceptible to wind erosion by drawing on the Index of Land Susceptibility to Wind Erosion (ILSWE).

**METHODOLOGY**

**Study Area**

The study area includes the lands of the 28 Member States of the European Union (EU-28), three European Union candidate countries (i.e. Montenegro, Serbia, the Former Yugoslav Republic of Macedonia), three potential European Union candidate countries (i.e. Albania, Bosnia and Herzegovina, and Kosovo), Norway and Switzerland (Figure 1). The total land surface is about 4.9 million km$^2$, providing living space for a population of circa 540 million people (Eurostat, 2013). According to Eurostat (2013), two-fifths of the total land area of the EU-28 (approximately 40-1%) was put to agricultural use in 2010. Hence, for the study area an agricultural area of about 1.8 million km$^2$ can be inferred.

**Approach Overview**

Wind erosion is a complex geomorphic process governed by a large number of variables (Shao, 2008). Field-scale models such as the Wind Erosion Prediction System (WEPS—Wagner, 1996) employ up to some tens of parameters to predict soil loss. A pan-European assessment of land
susceptibility to wind erosion calls for a simplified and more practical approach (Zobeck et al., 2000; Funk & Reuter, 2006). Therefore, a limited number of key parameters which can express the complex interactions between the variables controlling wind erosion should be considered. It is generally accepted that wind erosion occurs when three conditions are occurring: the wind is strong enough, the soil surface is susceptible enough, and there is no surface protection from crops, residues or snow cover (Shao & Leslie, 1997). Under these conditions, the magnitude of an erosive event is governed by the eroding capacity of the wind and the inherent potential of the land to be eroded (Fryrear et al., 2000).

The preliminary pan-European assessment described in this paper is based on the combination of the most influential parameters, i.e. climate (wind, rainfall and evaporation), soil characteristics (sand, silt, clay, CaCO\textsubscript{3}, organic matter, water-retention capacity and soil moisture) and land use (land use, percent of vegetation cover and landscape roughness) (Figure 2). The spatial and temporal variability of these factors are appropriately defined through Geographic Information System (GIS) analyses. Harmonised datasets and a unified methodology were employed to suit the pan-European scale and avoid generating misleading findings that could result from heterogeneous input data. The selected soil erosion parameters were conceptually divided into three groups, namely (i) Climate Erosivity, (ii) Soil Erodibility and (iii) Vegetation Cover and Landscape Roughness. Sensitivity to the contributing group of factors was calculated using the fuzzy logic technique (Klir & Yuan, 1995), which allows the sensitivity range of each factor in Europe to be unambiguously defined (Mezõsi et al., 2013). Sensitivity ranges and threshold values of the input factors were ranked according to the relationships defined in the literature and derived by field experiments.

**Data Parameterisation and Processing**

**Climate erosivity**

The climate’s influence on the process of wind erosion of soil depends not only on the wind velocity but also on the intrinsic soil properties (Chepil, 1941), precipitation and temperature which, in turn, determine the surface soil conditions (Fryrear et al., 2000). Experimental data show that climatic erosivity can be expressed as the cubic measure of the annual averages of wind velocity (m s\textsuperscript{-1}) and the ratio of potential evaporation to precipitation (Skidmore, 1986). A climate erosivity factor must define the driving force of the process (wind velocity) and the other climate-related factors (amount and distribution of precipitation and evaporation), the interactions of which determine the intensity, frequency and duration of wind erosion events (Skidmore, 1986).

Daily time series of measured climate datasets (Biavetti et al., 2014) covering 30 years (1981–2010) of the Joint Research Centre Monitoring Agriculture Resources Unit (MARS), interpolated to a 25 × 25 km grid (approx. 5000 stations) were used to describe daily wind speed, surface and moisture conditions. The daily wind force values (erosivity) were determined by combining the effect of the daily values of wind velocity (U), corrected for the soil’s moisture conditions. An average daily threshold wind speed of 7 m s\textsuperscript{-1} was assumed (speed at 10 m height above ground) (Gross & Schäfer, 2004; Funk & Reuter, 2006, among others). A simplified topsoil moisture model was used to predict the daily water content in the uppermost soil layer (5 cm) of European soils:

\[ W_t = W_{t-1} + P - ET, \quad \text{forced in the interval } [0, AWC] \]

(1)

where \( W_t \) is the potential daily soil moisture content in the first 5 cm of the topsoil layer, \( W_{t-1} \) is the potential daily soil
moisture content of the previous day, P is the daily precipitation, ET is the daily potential evapotranspiration and AWC is the available water capacity (spatial resolution 25 × 25 km). AWC was calculated for the soil mapping units of the European Soil Database (Panagos et al., 2012) with pan-European pedotransfer functions (Tóth et al., 2013). The evapotranspiration values were computed using the MARS values of the Penman potential evaporation from a bare soil surface (mm day⁻¹) and the Penman potential transpiration from a crop canopy (mm day⁻¹). To partition the E and T values, the fraction of vegetated/bare soil was computed using two complementary biophysical parameters (Leaf Area Index (LAI) and the Fraction of Soil (FSoil)—Psolve, 2010) obtained from ENVISAT/MERIS imagery (European Space Agency). While a root depth of 80 cm was assumed, only the water potentially transpired by the uppermost 5 cm of the plant root was included in calculating the soil water balance. Finally, the days with high soil moisture content (>7%) (Chen et al., 1996) were filtered out, and a daily wind force (WF) value was computed for the remaining days, using the average daily wind speed (U) and an assumed threshold wind speed (Uₜ) of 7 m s⁻¹. The monthly wind force (WFₘ) was calculated as:

\[ WF_m = \frac{\sum_i (U_i - U_{th})^2}{s} \alpha \quad (2) \]

where WFₘ is the monthly wind force for erosive days α, and s is the number of erosive days in a month period. The monthly wind force grid data were then resampled at 250-m spatial resolution by applying a bilinear interpolation.

**Soil erodibility**

Wind erosion occurs when the shear wind forces at the surface exceed the energy that is required to mobilise the soil particles (friction velocity, uₘ > threshold friction velocity uₜh) (Shao, 2008). Following a simplified approach, a fixed threshold wind speed was assumed for the daily wind force values. The ability of soils to resist the wind forces was calculated using a soil erodibility factor (Böhner et al., 2003). The erodibility of European soil was estimated as the wind-erodible fraction of soil (EF), which is a simplification of Chepil’s (1941) work carried out by the U.S. Department of Agriculture Wind Erosion Research Unit (USDA-ARS) (Woodruff & Siddoway, 1965). The wind-erodible fraction of soil (EF) expresses the relationship between the soil loss by wind and the characteristics of the soil surface (Chepil & Woodruff, 1954). Field observations (soil sieving and wind tunnel experiments) revealed that aggregates that were larger than 0.84 mm in diameter were non-erodible under test conditions. As a result of these findings, the proportion of topsoil aggregates < 0.84 mm in diameter (i.e. the wind-erodible fraction of soil—EF) became a commonly accepted and widely applied measure of soil erodibility by wind (Woodruff & Siddoway, 1965; Fryrear et al., 2000).

The wind erodibility of European soils was computed by applying the multiple regression equation proposed by Fryrear et al. (1994) to predict the wind-erodible fraction of soils based on their texture and chemical properties:

\[ EF = \frac{29.09 + 0.31 S_s + 0.17 S_i + 0.33 S_c - 2.59 OM - 0.95 CaCO_3}{100} \quad (3) \]

where all variables are expressed as percentages. Sᵥ is the soil sand content, Sᵢ is the soil silt content, Sᵥ represents the ratio of sand to clay contents, OM is the organic matter content and CaCO₃ is the calcium carbonate content. Despite its frequent application in European contexts, researchers have revealed certain limits to the transferability of the equation (López et al., 2007). Still, it constitutes to be one of the most robust and widely tested equations that are defined in the literature to assess the intrinsic susceptibility of soil to wind erosion. The soil characteristics were obtained from the first topsoil survey carried out for the whole European Union (Land Use/Land Cover Area frame statistical Survey—LUCAS; Tóth et al., 2013). The wind-erodible fraction of soil (EF) was computed for 18,730 geo-referenced topsoil samples collected across 25 member states of the European Union. The predicton of the spatial distribution of the EF drew on a series of related but independent covariates, using a digital soil mapping approach (Cubist-rule-based model to calculate the regression, and Multilevel B-Splines to spatially interpolate the Cubist residuals) (Borreli et al., 2014a; Panagos et al., 2014).

**Vegetation cover and landscape roughness**

**Monthly vegetation condition.** It is well-recognised that permanent soil vegetation cover is the most effective way to prevent wind erosion (Wolfe & Nickling, 1993). The presence of the vegetation on the surface increases the turbulence close to the ground and therefore dissipates the wind’s kinetic energy. This results in a reduction of the wind velocity (Shao, 2008). Field experiments have shown that soil coverage of 40% can be regarded as sufficient to protect a susceptible soil area (Fryrear, 1985). Vegetation cover of about 20% can reduce the soil loss by half compared with a bare surface, while soil cover greater than 10% can effectively reduce wind erosion (Fryrear et al., 2000). Permanently bare soil and arable lands are the most seriously affected by wind erosion.

Since the effect of vegetation cover on wind erosion can be expressed using the percentage of the surface covered with non-erodible plant material (Fryrear et al., 2000), remote sensing data and GIS operations were combined to describe the spatiotemporal variation of vegetation throughout Europe. More precisely, two
complementary biophysical parameters derived from ENVISAT/MERIS images were adopted to describe the monthly vegetation cover and bare soil conditions: (i) the Leaf Area Index (LAI) and (ii) the Fraction of Soil (FSoil). The LAI is a well-known index that is largely employed for modelling soil erosion by water (Shao & Leslie, 1997). It is defined in broadleaf canopies as half developed areas of photosynthetically active elements of the vegetation per unit of horizontal ground area (LAI = leaf area m^2/ground area m^2). The FSoil parameter represents the fraction of soil that is visible from above, whether this corresponds to bare soil patches or holes in developed canopies (gap fraction). The per-pixel monthly vegetation cover (VSm) was estimated by calculating the mean of these two vegetation indices and was used to define a composite percentage of soil surface that is covered by vegetation.

**Landscape roughness.** Frictional effects, enhanced by the roughness of the land surface, reduce the wind velocity close to the surface (Fryrear et al., 2000). Accordingly, the roughness of a soil surface affects the wind erosion process by dissipating the wind erosivity and providing an efficient shelter effect (Shao, 2008). On a broader scale, the roughness of a landscape is determined by the size and the distribution of the rough elements that it contains. In principle, these are the dominant vegetation and built-up areas within the landscape (Funk & Reuter, 2006). To represent a potential effect of land use on wind energy, the aerodynamic roughness length in Europe (z_0 in m) was estimated on the basis of Corine land cover 2006 data and the TA–LUFT (2001) roughness classification (Funk & Reuter, 2006).

**Assessment of Land Susceptibility**

To assess the pan-European susceptibility of land to wind erosion, the main parameters which govern the erosive processes were expressed quantitatively and described using four factors, for which the spatial (Soil Erodibility and Landscape Roughness) and spatiotemporal (Climate and Vegetation Cover) variation was considered. The sensitivity values were calculated using fuzzy membership functions. This methodology assigned the sensitivity values on a pixel basis ranging from 0 to 1 (where 0 represents no sensitivity and 1 represents maximum sensitivity). The original values of the factors were reclassified on this scale through predefined fuzzy membership functions which were chosen based on the relationships between the selected factors and the soil loss ratio observed during field and wind tunnel experiments (Fryrear et al., 2000; Gross & Schäfer, 2004; Shao, 2008; Mezősi et al., 2013, among others). The functions used to reclassify the factors were (i) linear for the Climate Erosivity (WF_M), (ii) linear for the Soil Erodibility (EF), (iii) half-hyperbolic for the Vegetation Cover (VC_M) and (iv) logarithmic for the Land Roughness (LR). Monthly Index of Land Susceptibility to Wind Erosion values (ILSWE_M) (spatial resolution 500 m) was computed using a multiplicative equation (Equation (4)) and aggregated in the annual ILSWE (Equation (5)):

\[
\text{ILSWE}_M = \text{WF}_M \cdot \text{EF} \cdot \text{VC}_M \cdot \text{LR} \tag{4}
\]

\[
\text{ILSWE} = \sum_{j=1}^{12} (\text{ILSWE}_M) \j tag{5}
\]

According to Equation (4), the land susceptibility to wind erosion is the result of the multiplication of the wind erosion driving force (WF_M) for three decreasing factors (EF, VC_M and LR).

**Model Performance Evaluation**

In order to lay the groundwork for future studies to identify those areas that are susceptible to wind erosion in Europe, a procedure of verification was carried out to get feedback about the performance of the proposed spatial prediction approach. A thorough literature review revealed evidence of actual or potential wind erosion for 156 locations in Europe. These locations were accurately georeferenced in GIS. Overlay analyses were undertaken to determine the distribution of the 156 reference locations into the five classes of land susceptibility to wind erosion. A confusion matrix and Cohen’s Kappa Index of Agreement (KIA) were used to ensure a high consistency with the local and regional observations previously reported in the literature.

**RESULTS AND DISCUSSIONS**

**Analysis of Input Factors**

**Spatial distribution of erosive winds**

The analysis of the daily climate data provided by MARS (covering the period 1981–2010) revealed a spatiotemporal distribution of climate conditions that could promote wind erosion in certain areas of Europe. Figure 3A shows the spatial distribution of cumulated erosion days at a daily wind-speed threshold of 7 m s^-1. Large areas of northern European coastal regions and some Mediterranean coastal sectors (including the Balearic Sea, the Gulf of Lion, the Alboran Sea and the Aegian Sea, among others) are the regions most frequently affected by days potentially erosive. Figure 3B shows the spatial distribution of the potentially more erosive events. This second assessment is based on the assumed topsoil moisture balance. Comparing the two images, it becomes apparent that the erosive days show similar spatial patterns, but with different frequencies of occurrence. The decrease in erosive days due to the topsoil moisture reveals differences between the biogeographical regions (EEA, 2013a), with a remarkable decrease in the Atlantic and Continental regions occurred. The high precipitation levels in northern Europe strongly reduced the ability of the wind to remove soil particles (Bärring et al., 2003). By contrast, this mitigation effect appeared less pronounced in the Mediterranean region, where the driest soils are more vulnerable to the action of the wind.

A dimensionless wind force factor was estimated by applying Equation (2). An annual average wind force value
of 0.006 (after Fuzzy membership scoring) was calculated for the observed 30 years. Its spatial distribution varies greatly throughout the investigated area, ranging from zero (circa 20% of studied area) to about one (circa 0.3% of studied area) (SD 0.023). The highest values were observed in the Gulf of Lion, the Strait of Gibraltar and the Aegean Islands. Moderate to high values were found in northern Spain, northern France, along the coasts of the United Kingdom, the Netherlands, Denmark, Norway, southern Sweden, southern Italy, eastern Romania and the majority of the Mediterranean islands. The temporal variability of the wind force throughout the year shows higher values during winter and early spring. Still, different patterns were observed which may capture locally distributed temporal dynamics that differ from the aforementioned general conditions.

The spatial patterns of the wind force featured in the present study follow the general wind speed dynamics reported in the European Wind Atlas by Troen & Petersen (1989). However, the comparison of our results with the wind erosivity index of Europe proposed by Funk & Reuter (2006), which were based on 30-year average global climate data of the Climate Research Unit on a 0.5 x 0.5° grid, revealed significant dissimilarities. Despite a similar approach, the average annual global climate data proposed by Funk & Reuter (2006) did not report areas that our study showed to have high wind erosivity, such as the Greek Islands, most of the Spanish Peninsula, Ireland and western United Kingdom. On the other hand, the high and very high wind erosivity values reported by Funk & Reuter (2006) in eastern Germany and the Czech Republic were not confirmed by our analysis. Considering both wind scenarios (Figures 3A and 3B), eastern Germany and the Czech Republic are far from being the regions with the highest wind erosivity values. These findings leave room for further investigation to ascertain the reasons for such differences. Yet, the erosive wind day frequencies and wind force values generated for this study disclose new aspects about the spatial distribution of the wind erosivity across Europe. This, in turn, sheds more light on the geography of wind erosion.

Susceptibility of the soil to wind erosion

The soil analysis showed the prevalence of areas characterised by slight erodibility (83.5%) (after Shiyatyi, 1965), where the wind-erodible fraction of soil (EF) was estimated to be 40% and below. Soils with moderate (40% < EF ≤ 50%) and high (EF ≥ 50%) erodibility cover about 12.5% and 4% of the total surface, respectively. Lower EF values were found in the vast majority of the middle and low latitudes where, except for some hotspots, the EF rarely exceeds 40% in content. The Mediterranean countries (Cyprus, Spain, Malta and Italy) have the lowest average EF values (18.5%–22%) (Table I). The highest values were found in the North Sea and the Baltic Sea coastal regions. High values characterise Poland, Denmark, the Netherlands, northern Germany and to a lesser extent Belgium, Finland, Sweden, Latvia, Lithuania and Estonia. As inferable from Figure 4A, the distribution of the spatial EF patterns suggests a division of the European surface into three regions: (i) a northwestern region, mostly dominated by the highest EF values, (ii) a central eastern region, with average values interspersed with some high/low EF values and (iii) the Mediterranean area, mainly characterised by low EF values.

These findings are in line with the scenarios described by academic literature (Riksen & De Graaff, 2001; Gross & Schäfer, 2004; Kertész & Centeri, 2006). European soil degradation studies identified wind erosion as being a major...
threat to northern European soils (Warren, 2003). This is because the phenomenon unfolds significant effects especially on light sandy soils (Warren, 2003). The sandy glacial outwash soils of the northern European lowlands and the loess soils of the large Aeolian deposits in eastern Europe appear to be particularly susceptible to wind erosion (Gross & Schäfer, 2004). The map in Figure 3 illustrates the higher susceptibility to wind erosion of the northern European soils particularly well. Furthermore, regional observations in Lower Saxony and Hungary showed a promising correlation between soil susceptibility to wind erosion described by our analysis and in the literature (Borrelli et al., 2014b).

**Land cover and landscape roughness**

The monthly land cover (natural vegetation phenology) and land management conditions (agricultural activities) were described using biophysical parameters derived from ENVISAT/MERIS images. Figure 4B shows the annual average vegetated and bare soil conditions. It highlights the area that is poorly covered by vegetation during the year. The vegetation dynamics revealed by the spatial patterns are in line with the distribution of the main agricultural districts in Europe (EEA, 2013b). Figure 4B provides insights into the relationships between the general vegetation patterns, the different biogeographical zones as well as the drought and vegetation productivity dynamics (Cherlet et al., 2013). Figure 4C shows the outcomes of integrating the information into the model to represent the roughness of a landscape.

**Land Susceptibility**

Figure 5 presents the Index of Land Susceptibility to Wind Erosion (ILSWE) for 36 European countries using climate data for the period 1981–2010 and the land cover condition of 2012. The modelling outcomes were ranked into five classes using the quantile classification method. Approximately 78.5% of the land surface under investigation showed no susceptibility to wind erosion. The portion of the studied area with low and very low susceptibility accounted for 13.3%, whereas moderate susceptibility was reported for 5.3% (ca. 25.8 Mha). For the remaining 2.9% (ca. 13 Mha) of the studied area, high land susceptibility to wind erosion was modelled.

The results show that regions susceptible to wind erosion occur in most of the countries observed. Nevertheless, areas potentially affected by high erosion levels appear only in specific regions. In the Mediterranean area, susceptibility is high to moderate along the south-west coast of Spain (in the Spanish communities of Aragón, Castilla-La Mancha and Cataluña), in the Gulf of Lion (i.e. the French metropolitan regions of Languedoc-Roussillon and Provence-Alpes-Côte d’Azur) and on the Italian, French and Greek islands. In northern Europe, the most highly susceptible regions are found along the coastal area, i.e. in Nord-Pas-de-Calais and Normandy in France; and North Holland, Friesland and Groningen in the Netherlands. In the United Kingdom, some of the most susceptible areas were estimated in southwestern England and Scotland. Large parts of Denmark, particularly in the western sector of the peninsula and in the eastern archipelago, also show high susceptibility values. The region of Scania is the area with the highest susceptibility in Sweden. Severe susceptibility was also modelled along the Romanian and Bulgarian coasts and in the lowlands surrounding the Carpathian Mountains. For the more continental areas, the results show high susceptibility in the Pyrenean and Alpine regions, central Spain and northeastern Serbia. Few hotspots were identified along the coasts of Germany and Poland, in central France and central and southern Italy. The sectors of the study region that tend to have consistently low susceptibility values are the Baltic States, Finland, Slovenia, Portugal, southern Germany and Ireland.

The ILSWE values of land susceptibility to wind erosion for the observed countries are listed in Table II. The country values show that predicted land susceptibility is highest for

### Table I. Descriptive statistics of the wind-erodible fraction of soil for European countries

| Country          | Mean | Maximum | Standard deviation | Coefficient of variation [%] |
|------------------|------|---------|--------------------|-----------------------------|
| Albania          | 22.2 | 42.4    | 5.6                | 0.25                        |
| Austria          | 27.2 | 46.5    | 3.6                | 0.13                        |
| Belgium          | 32.0 | 61.2    | 6.9                | 0.21                        |
| Bosnia and Herzegovina | 21.2 | 46.0    | 5.2                | 0.24                        |
| Bulgaria         | 27.6 | 64.5    | 5.5                | 0.20                        |
| Cyprus           | 18.5 | 45.2    | 5.7                | 0.30                        |
| Croatia          | 25.2 | 54.3    | 8.2                | 0.32                        |
| Czech Republic   | 30.8 | 54.5    | 4.6                | 0.14                        |
| Denmark          | 41.1 | 61.4    | 5.7                | 0.13                        |
| Estonia          | 38.3 | 61.6    | 5.8                | 0.15                        |
| Finland          | 38.6 | 67.0    | 8.0                | 0.20                        |
| Former           | 26.8 | 49.5    | 5.4                | 0.20                        |
| Yugoslav Rep.-Macedonia | 24.4 | 60.5 | 7.5                | 0.30                        |
| Germany          | 35.0 | 69.0    | 10.2               | 0.29                        |
| Greece           | 23.7 | 61.3    | 7.3                | 0.30                        |
| Hungary          | 30.9 | 64.9    | 7.6                | 0.24                        |
| Ireland          | 27.0 | 41.7    | 2.8                | 0.10                        |
| Italy            | 22.0 | 52.6    | 6.0                | 0.27                        |
| Latvia           | 40.1 | 62.4    | 5.2                | 0.12                        |
| Lithuania        | 39.3 | 62.5    | 5.5                | 0.14                        |
| Luxembourg       | 24.6 | 37.9    | 3.1                | 0.12                        |
| Montenegro       | 19.3 | 51.1    | 5.4                | 0.28                        |
| Malta            | 21.8 | 36.7    | 4.8                | 0.22                        |
| Netherlands      | 40.0 | 67.1    | 9.8                | 0.24                        |
| Norway           | 34.0 | 65.5    | 5.1                | 0.15                        |
| Poland           | 45.2 | 68.8    | 8.4                | 0.18                        |
| Portugal         | 25.5 | 67.8    | 9.3                | 0.36                        |
| Romania          | 29.3 | 67.4    | 6.9                | 0.23                        |
| Serbia and Kosovo | 25.8 | 64.7    | 5.9                | 0.23                        |
| Slovakia         | 26.2 | 53.3    | 4.6                | 0.17                        |
| Slovenia         | 23.3 | 44.6    | 5.1                | 0.22                        |
| Spain            | 20.4 | 58.6    | 7.6                | 0.37                        |
| Sweden           | 34.5 | 63.8    | 6.2                | 0.17                        |
| Switzerland      | 24.1 | 45.0    | 3.7                | 0.15                        |
| United           | 27.7 | 54.9    | 4.0                | 0.14                        |
Denmark (16.2%), Spain (10.2%), Greece (7.9%) and to a lesser extent Romania (5.4%) and France (4.3%). By contrast, it seems that soil erosion by wind is not a significant environmental threat for Slovenia, Portugal and for the eastern Baltic States. Table III shows the estimated average annual land susceptibility values aggregated per biogeographical region (EEA, 2013a). These results suggest that the spatial variations in land susceptibility to wind erosion are strongly influenced by the general climatic and ecological conditions. The aggregation of the results per land use class highlights the role of human activities (Table IV). The predicted erosion susceptibility is highest for arable lands, where about 3.5% of the predicted high and moderate susceptibility can be observed. About 0.45% and 0.66% of pasturelands and poorly vegetated areas are affected by high to moderate susceptibility, respectively. Most of the area covered by forest and other forms of dense vegetation falls into the no hazard or low hazard classes. However, about 0.43% of forests show moderate to high susceptibility. Further observations of soil fraction values show a mean annual bare soil fraction of 64% for such forested areas. These results suggest a misclassification in the Corine land units (Borrelli et al., 2014b).

Figure 4. A) Map of wind-erosion susceptibility of European soils (500 m spatial resolution) based on the estimation of the wind-erodible fraction of soil (EF) (Chepil, 1941; Fryrear et al., 2000); B) average annual percentage of soil surface covered by vegetation derived by LAI and FSoil indices; C) landscape roughness length (z0 in m) in Europe derived from CORINE and land cover classification using TA–LUFT parameters (2001). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

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Model Performances

The cross-check results show that the areas that were predicted as susceptible to wind erosion coincide with the reference locations reported in the literature. The overall accuracy was 95.5% with a Kappa Index of Agreement (KIA) of 0.910. Accordingly, 109 (69.7%) of the 156 locations reported in literature were classified as being moderately/highly susceptible, while another 13 (8.4%) fell into areas defined as having low susceptibility (Figure 6). Another 27 (17.4%) of the literature sites fell into areas classified as being very lowly susceptible. Considering that quantitative measures of wind erosion are not available for most parts of Europe, and that the findings in the literature are heterogeneous in the scales and methods and are often limited to qualitative descriptions, the results obtained in this preliminary investigation show a good agreement with local and regional studies.

Overview and Future Research

The proposed scenario provides information on the mean annual susceptibility of land to wind erosion. It reveals different patterns in relation to previous pan-European assessments for large areas of the Mediterranean and northeastern European areas (Funk & Reuter, 2006; Reuter, 2009). By contrast, a good correlation between the model output and the information reported in local and regional studies was observed. These insights suggest that the simplified approach is well suited to detect the areas susceptible to wind erosion for the proposed scale and objective. The differences that arose in comparisons with the other pan-European assessments suggest a relevant scale dependency of the models. The coarser spatial and temporal resolution of the input data used by Funk & Reuter (2006) was found to be less able to effectively describe some areas that are susceptible to wind erosion. In their study, areas such as the Gulf of Lion, large parts of the Iberian Peninsula, the Carpathian region and the largest islands in the Mediterranean were not found to be among the most susceptible areas. These areas show most of the conditions favourable to wind erosion, e.g. low levels precipitation, soil moisture deficits, sparse
vegetation cover and, more importantly, very high wind speeds. The findings of our study of these areas suggest that the application of data that present a better fit to the European scale led to more accurate results. Regional observations and

Table II. Descriptive statistics of the land susceptibility to wind erosion for European countries

| Country               | None  | Very Low | Low   | Moderate | High  |
|-----------------------|-------|----------|-------|----------|-------|
|                       | [%]   |          |       |          |       |
| Albania               | 96.2  | 2.7      | 0.7   | 0.3      | 0     |
| Austria               | 86.6  | 4.3      | 5.5   | 3.5      | 0.2   |
| Belgium               | 85    | 5.2      | 7.5   | 2.4      | 0.1   |
| Bosnia and Herzegovina| 91    | 3        | 3.2   | 2.8      | 0     |
| Bulgaria              | 55    | 8.2      | 17.2  | 16.4     | 3.1   |
| Cyprus                | 25    | 10.1     | 29.5  | 29       | 6.4   |
| Croatia               | 91    | 3        | 3.2   | 2.8      | 0     |
| Czech Republic        | 77.5  | 12.9     | 7.8   | 1.8      | 0     |
| Denmark               | 18.4  | 7        | 25.7  | 32.6     | 16.2  |
| Estonia               | 98.8  | 1.1      | 0.1   | 0        | 0     |
| Finland               | 98.5  | 0.8      | 0.5   | 0.1      | 0     |
| Former Yugoslav       | 91.9  | 6.5      | 1.6   | 0        | 0     |
| Rep Macedonia         |       |          |       |          |       |
| France                | 75.4  | 8        | 7.3   | 5.1      | 4.3   |
| Germany               | 92.3  | 4        | 2.5   | 1        | 0.2   |
| Greece                | 65.2  | 8.1      | 10.1  | 8.6      | 7.9   |
| Hungary               | 90.1  | 6        | 3.1   | 0.9      | 0     |
| Ireland               | 88.1  | 5.8      | 3.4   | 2        | 0.7   |
| Italy                 | 73.2  | 8.5      | 9.1   | 6.3      | 2.9   |
| Latvia                | 99    | 0.6      | 0.2   | 0.1      | 0     |
| Lithuania             | 100   | 0        | 0     | 0        | 0     |
| Luxembourg            | 100   | 0        | 0     | 0        | 0     |
| Montenegro            | 92.4  | 5.6      | 1.9   | 0        | 0     |
| Netherlands           | 58.1  | 11.9     | 19.3  | 7.8      | 3     |
| Norway                | 72    | 7.2      | 9.3   | 7.8      | 3.7   |
| Poland                | 92.5  | 5        | 1.7   | 0.7      | 0.1   |
| Portugal              | 98.1  | 1.6      | 0.3   | 0        | 0     |
| Romania               | 66.5  | 5        | 9.7   | 13.5     | 5.4   |
| Serbia and Kosovo     | 76.9  | 4.7      | 6     | 8.6      | 3.8   |
| Slovakia              | 87.8  | 6.4      | 4.1   | 1.6      | 0.1   |
| Slovenia              | 99.9  | 0.1      | 0     | 0        | 0     |
| Spain                 | 52.9  | 12.2     | 14.2  | 10.5     | 10.2  |
| Sweden                | 90.8  | 2.4      | 3     | 2.4      | 1.3   |
| Switzerland           | 91.9  | 3.2      | 3.2   | 1.7      | 0     |
| United Kingdom        | 59.3  | 12.5     | 16.6  | 9.9      | 1.7   |

Table III. Average annual land susceptibility aggregated per biogeographical region (EEA, 2013a)

| Bio-geographical region | None | Very Low | Low | Moderate | High |
|-------------------------|------|----------|-----|----------|------|
|                         | [%]  |          |     |          |      |
| Alpine                  | 83.1 | 5.4      | 5.9 | 3.8      | 1.8  |
| Arctic                  | 20.2 | 4.0      | 29.3| 36.4     | 10.1 |
| Black Sea               | 48.2 | 0.8      | 4.6 | 9.7      | 36.7 |
| Continental             | 83.8 | 5.2      | 5.2 | 4.4      | 1.4  |
| Mediterranean           | 59.5 | 10.1     | 11.9| 9.6      | 8.9  |
| Pannonian               | 87.3 | 6.5      | 4.0 | 1.6      | 0.6  |
| Steppic                 | 20.1 | 2.4      | 17.0| 43.8     | 16.7 |
| Atlantic                | 69.5 | 10.1     | 11.6| 6.9      | 1.9  |
| Boreal                  | 97.6 | 1.0      | 0.8 | 0.5      | 0.1  |

Table IV. Descriptive statistics of the land susceptibility to wind erosion by land use

| Corine land type | None | Very Low | Low | Moderate | High |
|------------------|------|----------|-----|----------|------|
|                  | [%]  |          |     |          |      |
| Arabian           | 62.5 | 5.6      | 8.9 | 10.4     | 9.5  |
| Permanent crops   | 81.0 | 7.4      | 8.2 | 10.1     | 0.3  |
| Pastures          | 74.2 | 8.5      | 8.7 | 8.5      | 1.5  |
| Homogeneous areas | 93.7 | 3.1      | 1.5 | 1.5      | 0.8  |
| Forests           | 59.3 | 6.5      | 9.2 | 16.7     | 16.6 |
| Scrub/herbaceous vegetation | 69.5 | 8.7 | 9.2 | 16.7 | 16.6 |
| Open spaces with little or no vegetation | 81.0 | 7.4 | 8.2 | 10.1 | 0.3 |
| Others            | 91.4 | 9.4      | 1.5 | 1.5      | 0.8  |
cross-validation results provided encouraging outcomes with regard to the reliability of the study results and their suitability to consistently describe land susceptibility throughout Europe. This study provides additional knowledge about where and when wind erosion occurs in Europe. It highlights the fact that the intensity of erosion poses a threat to agricultural productivity. These outcomes helped to gain a better understanding of the geographical distribution of land degradation due to wind erosion in Europe.

Despite this paper’s significant contribution towards a better understanding of the dissemination and the potential threats of soil erosion by wind process, future research studies are encouraged to include further elements in the base model designed for this study. Future modelling approaches could optimise the spatial resolution of the climate data and topsoil moisture module. Considering the significant impact that the soil moisture content has in reducing the number of potentially erosive days, a snow cover factor needs to be incorporated in future modelling exercises. Moreover, further components should be included in the model to allow for the biophysical and land management differences within the heterogeneous environment of Europe. For instance, one could consider aspects such as (i) vegetation growth modules based on phenological analysis, (ii) a more accurate identification of bare soil conditions (e.g. tillage and sowing preparation), (iii) downscaling of the climate data by integrating local topographic controls, (iv) a description of the agricultural field size and boundary characteristics, (v) post-harvest residue cover management and (vi) agricultural field irrigation.

**Data Availability**

The European map of land susceptibility to wind erosion, as all the maps presented in this study, is available on the European Soil Data Centre (ESDAC) web platform (Panagos et al., 2012).

**CONCLUSIONS**

The analysis shows that the high soil erodibility of northern European countries does not necessary mean increased wind erosion in the entire region. The strong relationship observed between the topsoil moisture content and the number of erosive days in northern Europe suggests a noticeable mitigation effect for such regions. The proposed Index of

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**Figure 6.** Comparison of the Index of Land Susceptibility to Wind Erosion (ILSWE) with 155 locations described in the literature as being actually or potentially affected by wind erosion. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr
Land Susceptibility to Wind Erosion (ILSWE) indicates that, although the lands along the northern sea coasts showed high susceptibility to erosion, wind erosion seems to be a greater problem for southern European countries. Alarming wind erosion susceptibility values were observed in several locations throughout Mediterranean Europe. The local and regional control areas showed encouraging insights which indicate that the proposed maps may be suitable for both national and regional investigations into the spatial variability and analyses of land susceptibility to wind erosion. Our ongoing research activities aim to integrate the aforementioned modelling improvements in order to present a new phase of wind erosion susceptibility values for both national and regional investigations. These are essential prerequisites to improve the future performance of the model and to obtain reliable data on which researchers can provide a solid foundation for policy makers to design effective soil conservation strategies.

REFERENCES

Bärring L, Jönsson P, Mattsson JO, Åhman R. 2003. Wind erosion on arable land in Scania, Sweden and the relation to the wind climate—a review. Catena 52: 173–190.

Biasetti I, Karetos S, Ceglar A, Toreti A, Panagos P. 2014. European meteorological data: contribution to research, development, and policy support. Proceedings of SPIE 9229, Second International Conference on Remote Sensing and Geoinformation of the Environment (RS&G2014), 922907. DOI: 10.1117/12.2066286.

Böhner J, Schäfer W, Conrad O, Gross J, Ringeler A. 2003. The WEELS model: methods, results and limitations. Catena 52: 259–308.

Borrelli P, Ballabio C, Panagos P, Montanarella L. 2014a. Wind erosion in a semiarid agricultural area of Spain: the WELSONS project. Catena 94: 235–256.

Bärring L, Jönsson P, Mattsson JO, Åhman R. 2003. Wind erosion on arable land in Scania, Sweden and the relation to the wind climate—a review. Catena 52: 173–190.

Biavetti I, Karetsos S, Ceglar A, Toreti A, Panagos P. 2014. European meteorological data: contribution to research, development, and policy support. Proceedings of SPIE 9229, Second International Conference on Remote Sensing and Geoinformation of the Environment (RS&G2014), 922907. DOI: 10.1117/12.2066286.

Böhner J, Schäfer W, Conrad O, Gross J, Ringeler A. 2003. The WEELS model: methods, results and limitations. Catena 52: 259–308.

Borrelli P, Ballabio C, Panagos P, Montanarella L. 2014a. Wind Erosion Susceptibility of European Soils. Geoderma 232: 471–478.

Borrelli P, Modugno S, Panagos P, Marchetti M, Schütz B, Montanarella L. 2014b. Detection of harvested forest areas in Italy using Landsat imagery. Applied Geography 48: 102–111.

Chappell A, Warren A. 2003. Spatial scales of 137Cs-derived soil flux by wind in a 25 km2 arable area of eastern England. Catena 52: 209–234.

Chen W, Zhihao D, Zhenhuan L, Zuxao Y. 1996. Wind tunnel test of the influence of moisture on the erodibility of loessial sandy loam soils by wind. Journal of Arid Environments 34: 391–402.

Chepil WS. 1941. Relation of wind erosion to the dry aggregate structure of a soil. Journal of the Science of Food and Agriculture 21: 488–507.

Chepil WS, Woodruff NP. 1954. Estimations of wind erodibility of field surfaces. Journal of Soil and Water Conservation 9: 257–265.

Cherlet M, Ivits E, Sommer S, Tóth G, Jones A, Montanarella L, Belward AS. 2013. Land-productivity changes in Europe. Towards valuation of land degradation in the EU. Publications Office of the European Union: Luxembourg.

De Ploey J. 1986. Bodemerosie in de lage landen, een Europese milieuprobleem. Acco: Leuven.

Eppink LAAJ, Spaan WP. 1989. Agricultural wind erosion control measures in the Netherlands. Soil Technology Series 1: 1–13.

European Commission. 2006. Thematic strategy for soil protection. COM(2006) 231.

Eurostat. 2013. Population and population change statistics. [online] URL: http://epp.eurostat.ec.europa.eu/portal/page/portal/population/data/database. Accessed December 2013.

Fryrear DW. 1985. Soil cover and wind erosion. Transactions of the ASAE 28: 781–784.

Fryrear DW, Krammes CA, Williamson DL, Zobeck TM. 1994. Correlation of the wind erodible fraction of soils. Journal of Soil and Water Conservation 49: 183–188.

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

Funk R, Reuter HJ. 2006. Wind erosion. In Soil erosion in Europe, Boardman J, Poesen J. (eds). Wiley: Chichester; 563–582.

Funk R, Voelcker L. 1998. Einschätzung der potentiellen Winderosionsgefährdung in Mecklenburg-Vorpommern im Landesmaßstab mit der Revised Wind Erosion Equation. Mitteilungen der Deutschen Bodenkundlichen Gesellschaft 85: 557–560.

Gomes L, Arrue JL, López MV, Sterk G, Richard D, Gracia R, Frangi JP. 2003. Wind erosion in a semiarid agricultural area of Spain: the WELSONS project. Catena 52: 235–256.

Goossens D. 2001. The on-site and off-site effects of wind erosion. In Wind Erosion on Agricultural Land in Europe, Warren A. (ed.). Office for Official Publications of the European Communities: Luxembourg.

Gross J, Schäfer W. 2004. Quantification of erosion-induced dust emissions: Development of an application-oriented method. Wind Erosion and Dust Dynamics: Observations, Simulations, Modelling. ESW Publications: Wageningen.

Holmes PJ, Thomas DSG, Buteman MD, Wiggs GFS, Rabambhala M. 2012. Evidence for land degradation from aeolian sediment in the West-Central Free state province, South Africa. Land Degradation & Development 23: 665–670. DOI: 10.1002/ldr.2177.

Jönsson P. 1994. Influence of shelter on soil sorting by wind erosion—a case study. Catena 22: 35–47.

Kertész A, Centeri C. 2006. Hungary. In Soil erosion in Europe, Boardman J, Poesen J. (eds). Wiley: Chichester; 139–153.

Kile GI, Yuan B. 1995. Fuzzy sets and fuzzy logic. Prentice Hall: New Jersey.

Kosmas C, Danalatos N, Kosmas D, Kosmopoulos P. 2006. Greece. In Soil erosion in Europe, Boardman J, Poesen J. (eds.) Wiley: Chichester; 279–288.

Leys JF. 1999. Wind Erosion on Agricultural Land. In Aeolian Environments, Sediments and Landforms, Goudie AS, Livingstone I (eds). John Wiley & Sons Ltd: Chichester.

Livingstone I, Warren A. 1996. Aeolian geomorphology: an introduction. Wesley Longman Ltd: Addison.

López MV, Sabre M, Gracia R, Arrue JL, Gomes L. 1998. Tillage effects on soil surface conditions and dust emission by wind erosion in semiarid Aragon (NE Spain). Soil and Tillage Research 45: 91–105.

López MV, de Dios Herrero JM, Hevia GG, Gracia R, Buschiazzo DE. 2007. Determination of the wind-erodible fraction of soils using different methodologies, Geoderma 139: 407–411.

Mezői G, Blanka V, Bata T, Kovács F, Meyer B. 2013. Estimation of regional differences in wind erosion sensitivity in Hungary. Natural Hazards and Earth System Sciences Discussions 1: 4713–4750.

Moreno Brotons J, Romero Díaz A, Alonso Sarrazí F, Belmonte Serrato F. 2009. Wind Erosion on Mining Waste in Southeast Spain, Land Degradation & Development 21: 196–209. DOI: 10.1002/lde.948.

Oldeman LR. 1994. The global extent of soil degradation. In Soil Resilience and sustainable land use, Greenland DJ, Szabolcs I (eds). CAB International: Wallingford; 99–118.

Panagos P, Van Liedekerke M, Jones A, Montanarella L. 2012. European Soil Data Centre (ESDAC): response to European policy support and public data requirements. Land Use Policy 29: 399–338.

Panagos P, Meusburger K, Ballabio C, Borrelli P, Alewell C. 2014. Soil erodibility in Europe: A high-resolution dataset based on LUCAS. Science of Total Environment 479–480: 189–200.

Polive H. 2013. Biopar Product User Manual. MERIS FR Biophysical Products (Issue 1.10, BP-REP-BP053). Geoconsort: 40.

Reuter HJ. 2009. Wind erosion. Report on the project ‘Sustainable Agriculture and Soil Conservation’. European Commission.
Riksen MJPM, De Graaff J. 2001. On-site and off-site effects of wind erosion on European light soils. Land Degradation & Development 12: 1–11. DOI: 10.1002/ldr.423.

Shao Y. 2008. Physics and modelling of wind erosion. Springer: Cologne.

Shao Y, Leslie LM. 1997. Wind erosion prediction over the Australian continent. Journal of Geophysical Research, [Atmospheres] 102: 30091–30105.

Shiyatyi EI. 1965. Wind structure and velocity over a rugged soil surface. Vestnik Sel.-khoz. Nauki 10.

Skidmore EL. 1986. Wind erosion climatic erosivity. Climatic Change 9: 195–208.

Strauss P, Klaghofer E. 2006. Austria. In Soil erosion in Europe, Boardman J, Poesen J (eds). Wiley: Chichester; 205–212.

TA-Luft. 2001. Erste Allgemeine Verwaltungsvorschrift zum Bundes-Immissionsschutzgesetz. Technische Anleitung zur Reinhaltung der Luft – TA-Luft Stand 12.06.2001.

Tóth G, Weynants M, van Liedekerke M, Panagos P, Montanarella L. 2013. Soil databases in support of pan-European soil water model development and applications. Procedia Environmental Sciences 19: 411–415.

Troen I, Petersen EL. 1989. European Wind Atlas. Roskilde National Laboratory: Roskilde, Denmark.

Veïhe A, Hasholt B, Schiøtz IG. 2003. Soil erosion in Denmark: processes and politics. Environmental Science & Policy 6: 37–50.

Visser SM, Palma J. 2004. Up-scaling Wind and Water Erosion Models. Far from reality? In Wind and rain interaction in Erosion, Visser S, Cornelis W (eds). Tropical Resource Management Papers 50. Wageningen: The Netherlands.

Wagner LE. 1996. An overview of the wind erosion prediction system. In Procedure of International Conference on air Pollution from Agricultural Operations, pp. 73–75.

Wang YQ, Shao MA. 2013. Spatial variability of soil physical properties in a region of the Loess Plateau of PR China subject to wind and water erosion. Land Degradation & Development 24: 296–304. DOI: 10.1002/ldr.1128.

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

Webb NP. 2008. Modelling Land Susceptibility to Wind Erosion in Western Queensland, Australia. (PhD dissertation). The University of Queensland: Australia.

Wolfe SA, Nickling WG. 1993. The protective role of sparse vegetation in wind erosion. Progress in Physical Geography 17: 50–68.

Woodruff NP, Siddoway FH. 1965. A wind erosion equation. Soil Science Society of America 29: 602–609.

Zhang K, Qu J, Han Q, Xie S, Kai K, Niu Q, An Z. 2013. Wind tunnel simulation of windblown sand along China’s Qinghai-Tibet Railway. Land Degradation & Development 25: 244–250. DOI: 10.1002/ldr.2137/abstract.

Zobeck TM, Parker NC, Haskell S, Guoding K. 2000. Scaling up from field to region for wind erosion prediction using a field-scale wind erosion model and GIS. Agriculture, Ecosystems & Environment 82: 247–259.