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MODELLING HOT SPOTS OF SOIL LOSS BY WIND EROSION (SoLoWind) IN WESTERN SAXONY, GERMANY

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ABSTRACT

While it needs yet to be assessed whether or not wind erosion in Western Saxony is a major point of concern regarding land degradation and fertility, it has already been recognized that considerable off-site effects of wind erosion in the adjacent regions of Saxony-Anhalt and Brandenburg are connected to the spread of herbicides, pesticides and dust. So far, no wind erosion assessment for Western Saxony, Germany, exists. The wind erosion model previously applied for Germany (DIN standard 19706) is considering neither changes in wind direction over time nor influences of field size. This study aims to provide a first assessment of wind erosion for Western Saxony by extending the existing DIN model to a multidirectional model on soil loss by wind (SoLoWind) with new controlling factors (changing wind directions, soil cover, mean field length and mean protection zone) combined by fuzzy logic. SoLoWind is used for a local off-site effect evaluation in combination with high-resolution wind speed and wind direction data at a section of the highway A72. The model attributes 3·6% of the arable fields in Western Saxony to the very-high-wind erosion risk class. A relationship between larger fields (greater than 116 ha) and higher proportions (51·7%) of very-high-wind erosion risk can be observed. Sections of the highway A72 might be under high risk according to the modelled off-site effects of wind erosion. The presented applications showed the potential of SoLoWind to support and consult management for protection measures on a regional scale. © 2016 The Authors. Land Degradation and Development published by John Wiley & Sons, Ltd.

KEY WORDS: multidirectional; field length; windbreaks; off-site effects; ILSWE

INTRODUCTION

Land degradation results in a reduction of the productive capacity of land (van Lynden *et al.,* 2004). Processes that are in the focus of discussion to cause land degradation are soil erosion by water, loss of organic matter, deforestation or changes in climate (Lee *et al.,* 1996; Montanarella, 2007; Cerdà *et al.,* 2010; Pérez-Cabello *et al.,* 2010; Bruun *et al.,* 2015; Kairis *et al.,* 2015; Prosdocimi *et al.,* 2016). However, there are other threats that can trigger land degradation that are much less known and result in the desertification of the landscapes (Munson *et al.,* 2011; Xu and Zhang, 2014; Vieira *et al.,* 2015; Xie *et al.,* 2015). Among those, wind erosion is one of the less studied processes (Dregne and Chou, 1992; Sterk *et al.,* 1999; Brotons *et al.,* 2010; Holmes *et al.,* 2012; Wang, 2014; Wang *et al.,* 2015; Borrelli *et al.,* 2016a). Recent evaluations on the European scale have shown that wind erosion cannot merely be neglected when discussing soil degradation status and soil fertility (Borrelli *et al.,* 2016a, 2016b).

Globally, 27% of the total land area (548 million ha) is potentially affected by wind erosion (Lal, 2001). In Europe, approximately 12% of the agricultural land is susceptible to soil erosion by wind (Borrelli *et al.,* 2015). The average annual soil loss by wind erosion on the European Union's arable land is predicted to be $0{\cdot}53\,\mathrm{Mg\,ha^{-1}\,y^{-1}}$ and for Germany's arable land to be $0{\cdot}26\,\mathrm{Mg\,ha^{-1}\,y^{-1}}$ (Borrelli *et al.,* 2016a). The focus of wind erosion studies in Germany is located in the Northern and Eastern parts of the country, where wind erosion is a major soil threat and environmental concern (BGR Bundesanstalt für Geowissenschaften und Rohstoffe, 2016). Approximately 30% of Northern and Eastern Germany's farmland is prone to wind erosion owing to its soil textural characteristics (Funk *et al.,* 2004). Wind erosion can cause an often non-visible loss of fine soil up to $40\,\mathrm{Mg\,ha^{-1}}$ per single event as was shown for fields in Kansas, USA (Chepil, 1960). Similar magnitudes were also observed in Brandenburg, Germany, where an average loss of 15-mm topsoil within a 4-year measuring period by wind erosion was recorded (Funk, 2004). Assuming a bulk density of $1\,\mathrm{Mg\,m^{-3}}$, the latter corresponds to a soil loss of $37{\cdot}5\,\mathrm{Mg\,ha^{-1}\,y^{-1}}$, which would clearly exceed the soil loss by water in this area estimated by Panagos *et al.* (2015). Even though both studies cannot directly be compared, this rough estimation of wind erosion magnitude gives a general idea on the possible detrimental impact of wind erosion.

One of the most susceptible regions not only within Germany but even within Europe is Western Saxony (Borrelli *et al.,* 2014, 2015). However, unlike for the adjacent states Saxony-Anhalt and Brandenburg where wind erosion was reported to be a considerable degradation risk (Funk, 2004; Helbig, 2015), no local or regional wind erosion assessment has been attempted for Western Saxony yet. In addition to the on-site effects resulting in the degradation of landscapes, and the off-site effects such as spread of

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pesticides, herbicides and dust (Glotfelty *et al.,* 1989; Riksen and de Graaff, 2001), wind erosion may also be a danger for human life. For instance, a wind erosion event at the highway A19 close to Rostock, Mecklenburg-West Pomerania, Germany, provoked visual obstruction in April 2011 and resulted in major collisions with 131 persons injured and eight casualties (Manhart *et al.,* 2012; Deetz *et al.,* 2016). Several other wind erosion events occurred in Northern and Eastern Germany with severe impacts on road traffic that were reported in newspapers (e.g. Aschersleben, Saxony-Anhalt – Geipel, 2011; Staßfurt, Saxony-Anhalt – Dörries, 2011; Neuruppin, Brandenburg – DPA, 2014; Neuruppin, Brandenburg – Klehn, 2014; Welsleben, Saxony-Anhalt – Helbig, 2015; Bensdorf, Brandenburg – Führer, 2016). Prevention of future on- and off-site effects of wind erosion depends on the identification of (i) wind erosion hot spots and (ii) spatial patterns of on- and off-site wind erosion effects.

To date, no reports on severe wind erosion events are available for Western Saxony; however, potential wind erosion risk is expected to be high because the natural conditions (topsoil texture, wind speeds, main wind direction and geographical location) and agricultural management practices (large and plain fields, and sparseness in windbreaks) are similar to those of the adjacent and regularly affected federal states of Saxony-Anhalt and Brandenburg. Furthermore, the sparseness in windbreaks coincides with strong and dry winds and low soil cover in the erosive season, which is in March and April (Toy *et al.,* 2002; Funk *et al.,* 2004; Hassenpflug, 2004). Even though the land degradation by wind erosion in consequence of the 1960s land reforms and land use change in the area of the former German Democratic Republic (Arndt, 2004; Baude and Meyer, 2006; Fritsche and Ertel, 2012) was immediately recognizable, monitoring or even mere observing of wind erosion had low priority for decades (Knauss, 2005).

The later spatial assessment of wind erosion risk for parts of Northern and Eastern Germany still follows the rather simplified norm DIN19706, although more sophisticated wind erosion models are available. In 1930s, the dust-bowl event in the USA (Tatarko *et al.,* 2013) triggered the development of empirical wind erosion models like the wind erosion equation (WEQ) (Chepil and Woodruff, 1963; Woodruff and Siddoway, 1965), the revised WEQ (RWEQ) (Fryrear *et al.,* 1998; Fryrear *et al.,* 2000), its GIS version (GIS-RWEQ) (Borrelli *et al.,* 2016a) and the erosion productivity impact calculator (Williams *et al.,* 1983). WEQ and RWEQ are widely used and extensively tested and have the ability to be scaled up from field to regional scale (Zobeck *et al.,* 2000; Youssef *et al.,* 2012; Guo *et al.,* 2013), but they are limited in their ability to account for multidirectionality of wind and variations in precipitation (Cole, 1983; Tatarko *et al.,* 2013). Subsequently, the recently developed Index of Land Susceptibility to Wind Erosion (ILSWE) (Borrelli *et al.,* 2014, 2015, 2016b) is a large-scale model that was applied at European scale. ILSWE serves as a conceptual model to define and parameterize factors of wind erosion and 'assesses the conditions and the frequency under which an area may become susceptible to wind erosion' (Borrelli *et al.,* 2016b). Process-oriented and more complex models like the wind erosion prediction system (WEPS) (Hagen, 1991; Wagner, 2013), wind erosion assessment model (WEAM) (Lu and Shao, 2001) or the Texas erosion analysis model (TEAM) (Gregory *et al.,* 1999) started to be developed in the 1990s. These models were usually not developed for European soils. Later, Wind Erosion on European Light Soils (WEELS) (Böhner *et al.,* 2003) was the first process-oriented assessment for European soils. Disadvantageously, all these models have an extremely large demand for high-resolution data, which limits their transferability and application in other than the tested and calibrated regions. Zou *et al.* (2015) gives a more in-depth review of wind erosion models.

A rather basic but commonly applied modelling approach (DIN19706) exists for wind erosion assessments in Germany (Blume, 2004) and the federal states Lower Saxony (Schäfer, 2015), Schleswig-Holstein (LLUR Landesamt für Landwirtschaft, Umwelt und ländliche Räume des Landes Schleswig-Holstein, 2011), Mecklenburg-West Pomerania (Frielinghaus *et al.,* 2002), Saxony-Anhalt (Deumelandt *et al.,* 2014) and Brandenburg (ZALF,). So far local, regional and national wind erosion modelling of German areas has been only published in so-called gray literature. For Saxony, such a regional wind erosion risk assessment has not been performed yet and assessments can only be derived from continental (Borrelli *et al.,* 2014, 2015, 2016a), national (Bug, 2014) or low-resolution regional (LfUG Sächsisches Landesamt für Umwelt und Geologie, 2007; Regionaler Planungsverband Westsachsen, 2007) models.

As the common empirical models on a regional scale are limited in transferability or require a local adjustment of the factors, process-oriented models are limited by the high data demand, and often it is not possible to downscale large-scale models; we aim to present to the international community the new Soil Loss by Wind erosion model (SoLoWind) for local and regional wind erosion assessments. SoLoWind is developed as a screening model. Screening models are 'simple in concept and designed to identify problem areas' (Morgan, 2005). They are 'indicative rather than precise' (Morgan, 2007), and as such their quality is rather evaluated by a sensitivity and plausibility check. The model was designed to overcome the limitations of unidirectionality of the DIN19706 model and non-transferability of the other aforementioned wind erosion models. SoLoWind is partly based on the DIN19706 model but includes new controlling factors like moisture and field length. Key components of SoLoWind are that (i) the multidirectionality of wind with respect to field length and windbreaks is considered and (ii) controlling factors are combined through fuzzy logic, which has the advantage to set fuzzy class breaks by probability functions (Lang and Blaschke, 2007) and classifies on a relative qualitative scheme instead of an ordinal scale (Mezősi *et al.,* 2015). In this way, the model should be able to locally identify those fields and objects, which are under risk to wind erosion to apply further prevention actions.

The objective of this study is to introduce the concepts of SoLoWind by (i) qualitatively assessing and mapping the spatial distribution of single arable fields under risk of wind erosion and (ii) combining SoLoWind with high-resolution local wind speed and direction data (derived from a separate orography model) to identify hot spots of wind erosion off-site effects in a sub-study area. We chose Western Saxony as our case study region, because of the expected high wind erosion susceptibility as discussed earlier.

MATERIAL AND METHODS

Study Area

The study area is located in the western part of Saxony, Germany, which has an extent of approximately 441,000 ha. It is characterized by a sequence of glacial lowlands, loess plains and loess hill country increasing in altitude from North to South (80 to 260 m asl) with sandy and silty topsoil. The landscape types for the study area modified according to Bernhardt *et al.* (1986) and Niemann & Stephan (1982) are presented in Figure 1. The climate is sub-continental. The average (1961 to 2010) annual rainfall, derived from a 1-km resolution map provided by the German Weather Service (DWD), for Western Saxony is 604 mm. The lowest average precipitation of 518 mm in conjunction with winter droughts due to the shielding effect of the Harz Mountains is located close to the border of Saxony-Anhalt (Airport Leipzig-Halle). Extratropical westerly winds are dominant with the prevailing wind direction of 240° South-West (Regionaler Planungsverband Westsachsen, 2007). Long-term average wind speeds in Western Saxony range between 1·6 and 4·1 m s^{-1} (derived from long-term annual wind speeds measured by DWD; 200-m resolution, 1981–2000), influenced by an altitudinal gradient of 0·3 m s^{-1} per 100-m height (Flemming, 1994). Long-term average wind speeds are lowest in the urban area of Leipzig and highest in the north-western region of the study area and on the summits of the loess hill country (Figure 1) (Regionaler Planungsverband Westsachsen, 2007). Measurements at nine meteorological stations in the study area (operated by DWD and the Saxon State Office Agency for the Environment, Agriculture and Geology) with hourly measured wind speeds and wind directions (at 10 m height) showed that the erosive season with gust speeds greater 5·4 m s^{-1} are predominantly from November to April. About 54% (239,590 ha) of the study area are agricultural fields [based on the field cadaster of the Integrated Administration and Control System (InVeKoS)]. The average size of arable fields has an extent of 26·5 ha with an obvious scarcity of windbreaks. Agricultural use is predominant in the fertile sandy-loess plain and loess hill country (Regionaler Planungsverband Westsachsen, 2007).

Soil Loss by Wind Erosion Model

Soil loss by wind incorporates major causal wind erosion factors (topsoil texture, organic content, soil moisture, wind speeds and wind directions, soil cover, field length and wind breaks) in the four modules natural wind erosion susceptibility (SUS), soil cover (COV), mean field length (MFL) and mean protection zones (MPZ) (Figure 2). All modules are calculated and evaluated separately and subsequently combined with fuzzy logic.

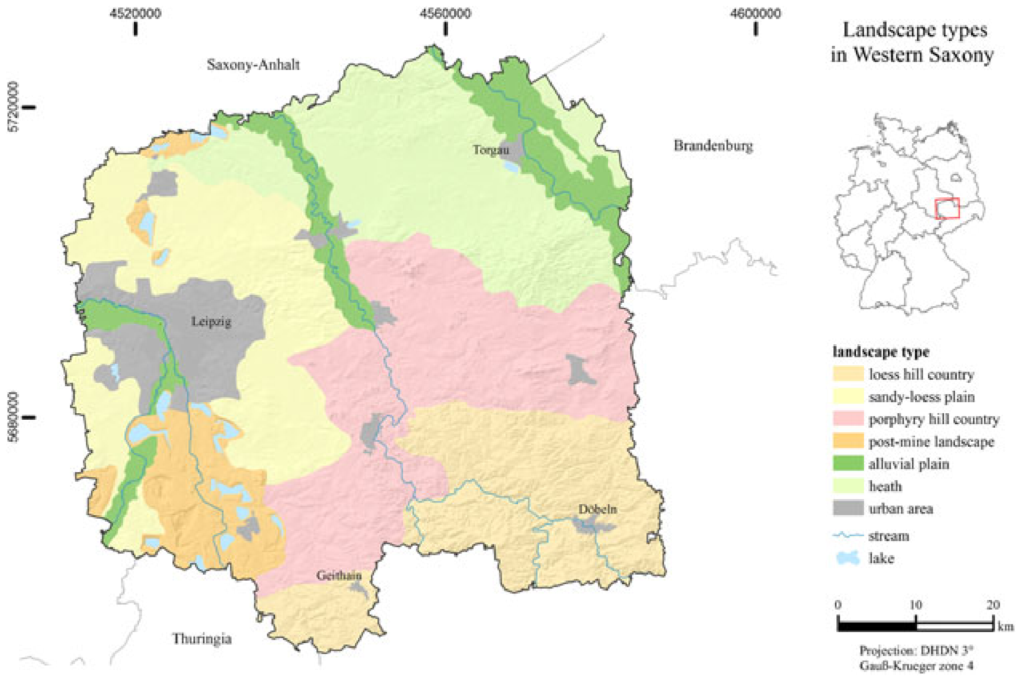

Figure 1. Landscape types in Western Saxony and urban centres modified according to Bernhardt *et al.* (1986) and Niemann & Stephan (1982). [Colour figure can be viewed at wileyonlinelibrary.com]

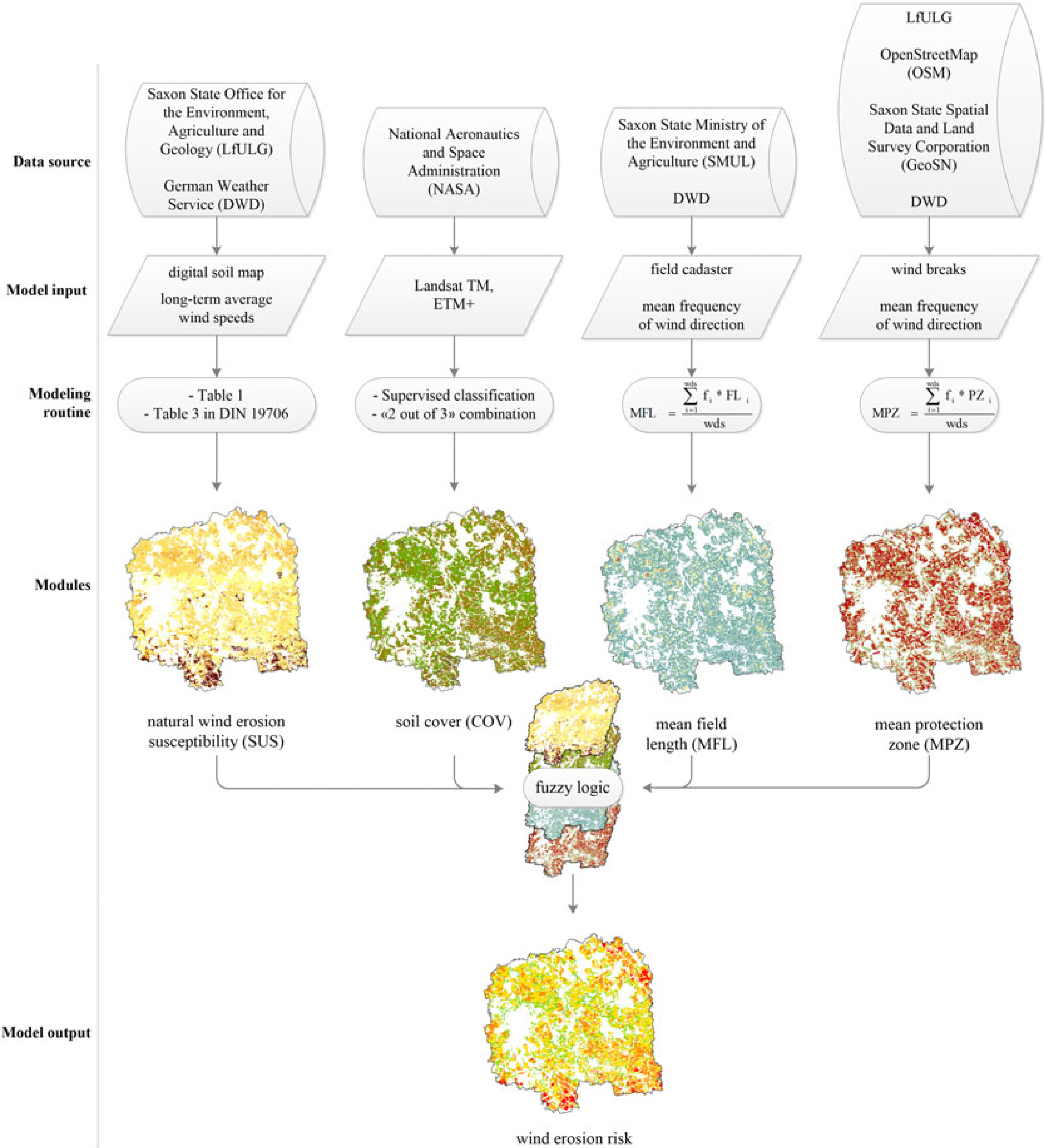

Figure 2. Datasets and framework of soil loss by wind (SoLoWind) and its modules natural wind erosion susceptibility (SUS), soil cover (COV), mean field length (MFL) and mean protection zones (MPZ). [Colour figure can be viewed at wileyonlinelibrary.com]

The first module, the natural wind erosion susceptibility module SUS, determines the regional soil erodibility according to Table I by the parameters soil texture, soil organic content and Ellenberg's soil moisture (*F*-value) of the topsoil layer. The derivation of soil erodibility classes (0–5; boldface in Table I) is based on an empirical relation implied in BGR Bundesanstalt für Geowissenschaften und Rohstoffe & Geologische Landesämter (1982). This approach includes an approximation factor for the site-specific soil moisture (*F*-value). In a second step within the module SUS, soil erodibility is combined with wind speeds according to Table III of DIN19706 (version 2013:02). In our example

Table I. Soil erodibility classes (0–5; in boldface) by wind according to soil texture, organic content and Ellenberg's *F*-value after BGR Bundesanstalt für Geowissenschaften und Rohstoffe & Geologische Landesämter (1982)

German textural classes	Description	Soil texture		Organic content in %	Mean Ellenberg F-value				
		Particle size in µm	Composition		7-8	6	5	4	3-2
T	Clay	<0.2	65-100% C, 0-35% Si, 0-35% S	/	**0**	**0**	**1**	**1**	**1**
U	Silt	2-63	0-8% C, 80-100% Si, 0-20% S						
L	Loam	/	8-45% C, 0-50% Si, 15-83% S						
Sl3	Medium loamy sand	63-2000	8-12% C, 7-40% Si, 48-85% S	>4	**0**	**1**	**2**	**3**	**3**
Sl4	Very loamy sand	63-2000	12-17% C, 13-40% Si, 45-75% S	<4	**0**	**2**	**2**	**3**	**3**
Sl2	Low loamy sand	63-2000	5-8% C, 5-25% Si, 67-90% S						
Su2	Low silty sand	2-63	0-5% C, 10-25% Si, 70-90% S						
Su3	Medium silty sand	2-63	0-8% C, 25-40% Si, 52-75% S	>4	**0**	**2**	**3**	**4**	**5**
Su4	Very silty sand	2-63	0-8% C, 40-50% Si, 42-60% S	<4	**0**	**3**	**4**	**4**	**5**
ffS	Very fine sand	63-125	<5% C, <10% Si, >85% FS						
gS	Coarse sand	630-2000	<5% C, <10% Si, <20% FS, <30% MS, >40% CS						
mS	Medium sand	200-630	<5% C, <10% Si, <20% FS, >70% MS, <15% CS						
msfS	Medium sandy fine sand	63-200	<5% C, <10% Si, 50-75% FS, 15-50% MS, <5% CS	>4	**0**	**3**	**4**	**5**	**5**
fsmS	Fine sandy medium sand	200-630	<5% C, <10% Si, 20-50% FS. 40-70% MS, <10% CS	<4	**0**	**4**	**5**	**5**	**5**
fS	Fine sand	63-200	<5% C, 10% Si, >75% FS, <15% MS, few grains CS						

C = clay, Si = silt, S = sand, FS = fine sand, MS = medium sand, CS = coarse sand, 0 = no soil erodibility, 1 = very low soil erodibility, 2 = low soil erodibility, 3 = medium soil erodibility, 4 = high soil erodibility, 5 = very high soil erodibility.

application, soil parameters and *F*-value were derived from the digital soil map of Saxony (1:50,000). For Western Saxony, long-term (1981 to 2000) average wind speeds in meter per second (in 10-m height, 200-m spatial resolution) were provided by DWD.

Further, a soil cover module COV that distinguishes between bare soil and covered soil in satellite images (according to the spectral information) is implemented in SoLoWind. The method assigned a specific class (bare, covered) to each image cell if 2 out of 3 years have similar spectral characteristics. This multi-year approach was chosen to account for inter-annual crop rotation. In the study area, the season from December to March showed the highest frequencies in erosive winds according to the evaluated wind speeds at nine different stations. Consequently, soil cover in March was chosen as the reference month owing to its high frequency in erosive winds and at the same time a phase of the year with high agricultural practice and low vegetation cover (seeding) (Toy *et al.,* 2002; Funk *et al.,* 2004; Hassenpflug, 2004). For a 3-year sequence (2010 to 2012) in March, various regions of interest (ROIs) were set: for 2010, 126; for 2011, a total of 143 ROIs; and for 2012, 173 ROIs. Digital orthophotos of the year 2012 (0·2-m spatial resolution) were used as ground truthing with 42 ROIs. For the soil cover mapping, a supervised minimum distance classification of Landsat satellite images (Landsat TM and ETM+, spatial resolution of 30 m) was used. A more detailed identification of the degree of coverage was not applicable with Landsat data in the respective research period because of missing ground truth data and the low spatial resolution.

The field lengths in module MFL are an indicator of intensity and transport capacity of wind forces on the topsoil (Hassenpflug, 2004; LLUR Landesamt für Landwirtschaft, Umwelt und ländliche Räume des Landes Schleswig-Holstein, 2011) and serve as an approximation for the wind erosion's avalanching effect (Chepil and Woodruff, 1963). The avalanching effect is most pronounced if the maximum length of the field coincides with the main wind direction. The field length of module MFL is calculated by a cumulative cell count approach using a conventional GIS flow accumulation algorithm (Figure 3). The cadastral map of all fields is rasterized to a constant raster and rotated to the desired wind direction (e.g. as in Figure 3 with a west–east orientation) because the flow accumulation approach only counts cells from left to right and cannot flow in any other direction than 90°. Flow accumulation has its initial counting cell at a left field border and cumulates the number of cells straightforward to the right until the opposite border is reached. It starts again to count by overpassing the next field border. The cumulative cell count is multiplied by the cell size to yield field length (meter) for each cell within a field. The resulting field length raster is rotated back to its initial position. All the steps are repeated for the 12 wind direction sectors (0° to 360°). For each sector, the individual long-term frequency of erosive winds (gust speeds above $5{\cdot}4\,\mathrm{m\,s^{-1}}$ and preceding 48 h rainless) need to be calculated. These frequencies (f_i) in each wind direction sector (wds)

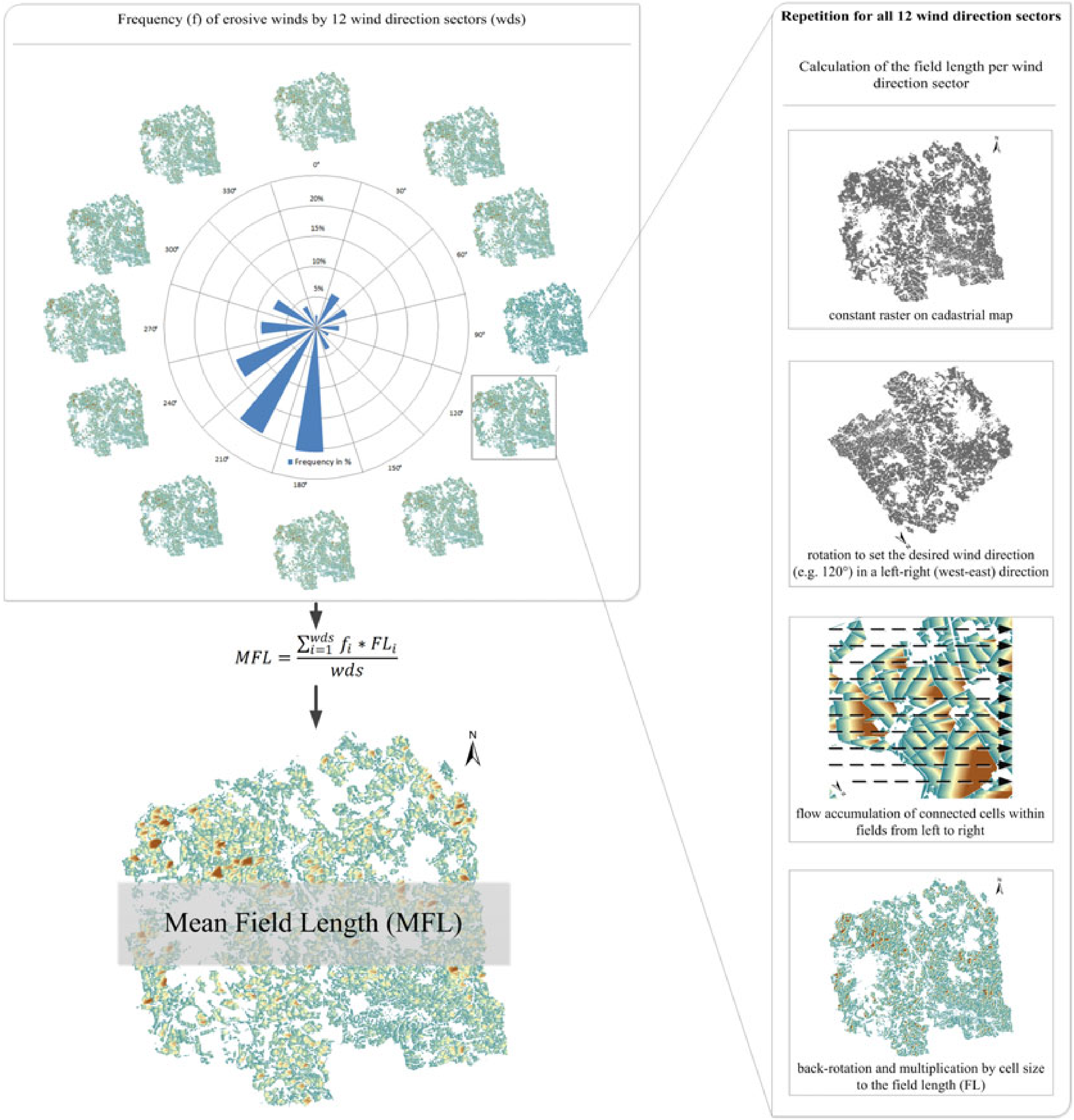

Figure 3. Concept of the mean field length module (MFL) by rotation, flow accumulation and averaging. [Colour figure can be viewed at wileyonlinelibrary.com]

serve as a weight factor for each (here: 12 according to 12 wind direction sections) field length raster (FL_i) in order to calculate a MFL raster according to the following equation:

$$MFL = \frac{\sum_{i=1}^{wds} f_i * FL_i}{wds} \quad (1)$$

For the presented two applications of the model, erosive events were derived from a total of nine gauging stations for the application to Western Saxony and Geithain for the sub-catchment application. The cadastral map was extracted from InVeKoS.

Finally, SoLoWind enables the user to evaluate the effectiveness of windbreaks, which are treated within a separate protection zone module MPZ. For the module calculation, all windbreaks like tree rows, hedges, groves, forests, buildings, bridges and field boundaries can be considered. The windward and leeward protection zones (Blume, 2004) are obtained by a GIS hillshade function using a specific altitude and azimuth for each wind sector. In this particular case, the illumination source of the hillshade tool can be understood as wind source. Therefore, windbreaks with defined heights have their specific wind shadow zone according to the altitude of the wind source. Azimuth can be understood as wind direction. The process is repeated for each wind direction sector (azimuth). Likewise in module MFL, the frequency (f_i) of erosive events of each wind direction sector (wds) serves as a weight factor for averaging the protection zones (PZ_i) to MPZ with Equation 2:

$$MPZ = \frac{\sum_{i=1}^{wds} f_i * PZ_i}{wds} \quad (2)$$

Here, we extracted the mentioned objects with its specific mean heights (Table II) from the biotope and land use mapping, the Official Topographic-Cartographic Information System, InVeKoS, OpenStreetMap and orthophotos.

The modules are combined by fuzzy logic, which was first introduced by Zadeh (1965; for detailed explanations, see also Klir and Folger, 1988; Zadeh and Kacprzyk, 1992; Kosko, 1993; Masulli *et al.,* 2013). The technique deals with uncertainties and vagueness of complex systems (Rihani *et al.,* 2009), which is often the case in wind erosion modelling (Böhner *et al.,* 2003; Gomes *et al.,* 2003; Goossens, 2003; Funk and Reuter, 2006; Borrelli *et al.,* 2016a, 2016b). The variables are transformed to fuzzy members, and the classes are converted into numerical values ranging from 0 (no membership) to 1 (full membership). Different underlying probability functions (e.g. linear, gaussian, triangular, trapezoid, exponential, logarithmic and polynomial) can be chosen instead of an additive linkage with high uncertainties (McBratney and Odeh, 1997; Mezősi *et al.,* 2015). We assumed a linear relationship for the qualitative classes of module SUS (in accordance with Climate Erosivity WF_m and Soil Erodibility EF in Borrelli *et al.,* 2016b). Although Mezősi *et al.* (2015) and Borrelli *et al.* (2016b) use a reciprocal and half-hyperbolic relationship of soil cover, a linear function was assumed for COV because it was classified as Boolean without intermediate values. According to NLÖ Niedersächsisches Landesamt für Ökologie (2003), classes of tolerable field lengths (module MFL) were also linear classified. It was assumed that the protection zone of any landscape component loses its effect with a linear trend (Combeau, 1977; Blume, 2004). All four modules as fuzzy members were combined with a fuzzy overlay by equal weights of one-quarter.

Table II. Average height and maximal protection zones of windbreaks (after Blume 2004) derived from BTLNK, InVeKoS, ATKIS, OSM and orthophotos

Type of windbreak	Average height (m)	Maximal protection zone (m) in leeward
Forest	20	500
Grove	15	375
Tree row	10	250
Bridge	10	250
Wetland	10	250
Building and urban space	10	250
Hedge	8	200
Field border	1	25

BTLNK, biotope and land use mapping; InVeKoS, Integrated Administration and Control System; ATKIS, Official Topographic-Cartographic Information System; OSM, OpenStreetMap.

Model Application

Wind erosion risk classes and plausibility check for Western Saxony

The modelled wind erosion risk map was classified into five equal interval risk categories. Fields with values in the first interval (0% to 20%) were classified as very low and second interval (greater 20% to 40%) as low risk to wind erosion; fields with values in the fourth interval (greater 60% to 80%) and the fifth interval (greater 80% to 100%) were classified as high and very high risk to wind erosion, respectively. Medium risk was assigned to the third interval (between 40% and 60%). Further, a zonal averaging of the cell values within each field was applied to achieve a more common mean field value for matching the results with cross compliance on soil erosion.

The model reliability was tested by (i) excluding individual modules, (ii) varying of the weighting of each module in the fuzzy logic routine and (iii) extracting the orientation of fields (in the fourth and fifth risk classes) by minimum bounding geometry to assess whether the longest axis of the field is parallel to the main wind direction (240°) of erosive winds and, therefore, more prone to a mobilization of topsoil by wind. Furthermore, snow fence positions served as a controlling indicator for wind exposed fields. Even though the process of snowdrift in winter might differ from aeolian mobilization during spring and early summer, high wind intensities and exposed fields are identified.

Combination of SoLoWind with small-scale orography modelling

The outputs of SoLoWind were linked to high-resolution wind speed and direction rasters, which enabled a more detailed evaluation on a local scale than SoLoWind alone. Station measurements of wind speeds and directions were regionalized by the influence of the relief with the orography model Wind Atlas Analysis and Application Program (WAsP) (by Trœn & Petersen, 1989, 1990). We used the measurements of the closest gauging station and a digital elevation model with a spatial resolution of 20 m for that modification. By the small-scale modelling, the frequency distribution of wind directions and associated wind speeds can be determined for a sub-region with a limited amount of gauging stations. This local assessment for an example sub-region results in the investigation of potential tracks of mobilized soil material and the identification of potential off-site effects (Riksen and de Graaff, 2001; Goossens, 2003) of wind erosion such as endangered objects, street bodies and landscape components by a semi-automated and visual evaluation.

Table III. Distribution of potential risk classes to wind erosion on arable land in Western Saxony

Potential risk classes to wind erosion	Proportion (%)
Very low	2·2
Low	20·6
Medium	46·6
High	26·9
Very high	3·6

RESULTS AND DISCUSSION

SoLoWind Application: Regional Wind Erosion Risk Modelling for Western Saxony

Soil loss by wind indicates that 22·8% of the arable fields in Western Saxony have very low or low and 30·5% fields have a high or very high risk of wind erosion (with 3·6% of fields having a very high risk of wind erosion; Table III, Figure 4).

Congruent with physical process understanding, larger fields (greater than 116 ha) show a higher proportion (51·7%) of very high risk. Only a small percentage (5·2%) of the 3·6% of very-high-risk fields was detected on fields smaller than 21 ha. More than one-third (37·3%) of high- and very-high-risk fields are orientated parallel (with its longest axis) to the main wind direction of 240°. The landscape type loess hill country in the south of the study area and alluvial plains along the rivers (Figure 1) have highest proportions in the top risk class (Figure 5). Alluvial plains are also one of the riskiest areas to wind erosion in the national model DIN19706 (Bug, 2014). These landscapes are characterized by the most mobile soil texture class from 0·08 to 0·1 mm with the lowest fluid threshold (necessary wind shear velocity to mobilize soil particles; Bagnold, 1941) and by intensified agricultural usage with bare soils in spring (according to module soil cover; COV). Owing to the management common in the region, both loess hill country and alluvial plains show bare soil on approximately 60% of all arable fields during March. A lower wind erosion risk occurs in urban landscapes, porphyry country, heath, sandy-loess plain and post-mining landscapes (Figure 1). Urban landscapes are least susceptible, owing to relative small fields and decelerating impact of buildings on wind speeds. In the other landscape types where the wind erosion risk is relatively low, a majority of fields is covered by vegetation according to the assessment in module COV. In addition, the topsoil of the sandy-loess plain and porphyry country has high amounts of clay aggregates decreasing soil erodibility. Heathland has a relatively low wind erosion risk (Figure 5) because it is shaped by lower moraines with generally permanent vegetation cover and additionally characterized by sand, which is more resistant to mobilization. Approximately two-thirds of all arable fields in the post-mining landscape are covered by vegetation in spring (module COV), and therefore, that landscape type is less risky in the erosive phase of the year.

By analysing each module separately, 30·9% of the cells of the module natural wind erosion susceptibility (SUS) are at very low susceptibility to natural wind erosion. Only 5·4% of the analysed agriculture land in Western Saxony is classified as having higher natural soil erosion susceptibility by wind. In the soil cover module COV, more than the

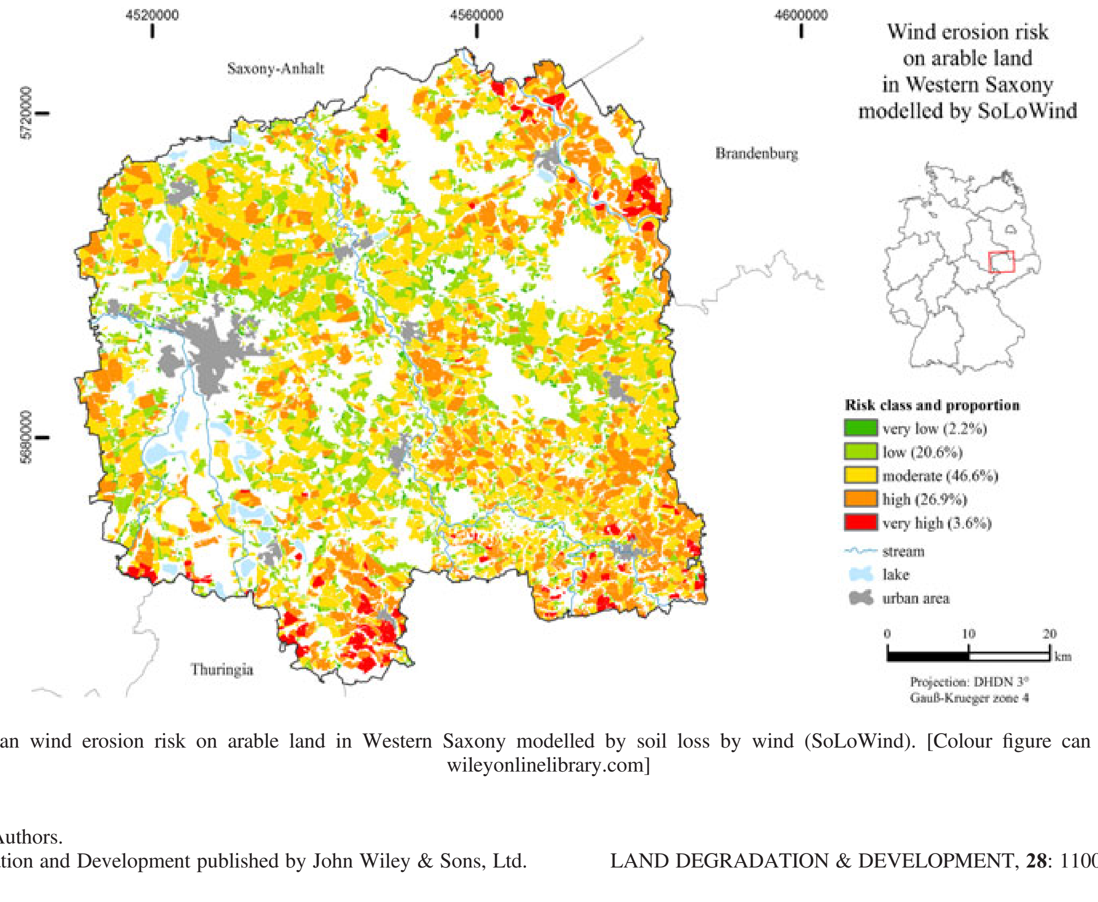

Figure 4. Mean wind erosion risk on arable land in Western Saxony modelled by soil loss by wind (SoLoWind). [Colour figure can be viewed at wileyonlinelibrary.com]

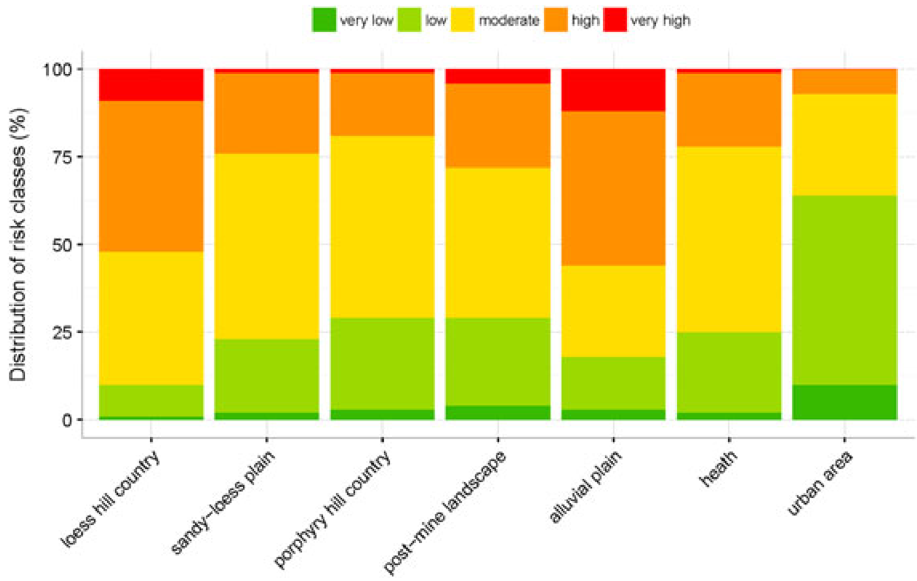

Figure 5. Distribution of risk classes to wind erosion per landscape type in Western Saxony. [Colour figure can be viewed at wileyonlinelibrary.com]

half of the arable land in the study area is assigned to be fully covered by vegetation in the investigated erosive periods from 2010 to 2012. Where field lengths are high, a protective effect of windbreaks is generally very low. Therefore, a similar risk pattern like for the MFL is visible for the MPZ. On a field scale, unprotected zones are located principally in the centre of fields because of an aggregation of field breaks at field borders. Owing to the large fields in the study area, approximately 40% of the study area is without any protection by field breaks. SoLoWind identified three main clusters with large proportions of high-risk classes in the study area. They are located in the regions of Geithain and Döbeln in the southern part and Torgau in the north-eastern part of Western Saxony (Figure 1).

Soil loss by wind results are very comparable with those of ILSWE. Both models assess the relative soil erosion susceptibility and do not quantify absolute amounts of eroded soil. However, the good comparability might still be surprising, because wind direction is not considered in ILSWE. Large fields and low numbers of windbreaks dominate in our study area, which might explain why wind direction is not crucially influencing the relative differences between fields. However, we would expect larger differences in study areas with smaller fields and irregular distribution of wind breaks, which will increase the dependency on wind direction and might influence wind erosion susceptibility considerably. As such, SoLoWind can be used as an additional sub-model of the continental ILSWE model to assign the wind erosion risk on a field scale. Both models follow a simplified qualitative approach but rely on different parameters and are applied on different scales. Hence, SoLoWind can be supplemented to ILSWE on a regional or local scale and might serve as a tool to verify large-scale models.

Each module was tested with a variation in weight during the fuzzy logic routine of SoLoWind's sensitivity check. The various overlays resulted in very robust results for all four modules. Finally, the comparison of localities of snow fences in Western Saxony indicates that 60·5% (138) of all fences (228) are adjacent (max. distance of 50 m) to high- and very-high-risk fields, which indicates that these fields are also affected by snowdrift. The latter supports the plausibility of our model results because both processes, wind erosion by soil and snow drift, are dependent on exposition and wind forces.

Owing to its modular structure, SoLoWind is suitable to assess the influence of land use management on wind erosion susceptibility. Soil erodibility can be reduced by increasing the content of organic matter (module SUS), and wind speeds can be decelerated by installing windbreaks and structuring the landscape (module MPZ). Moreover, a dense soil cover during the erosive periods (module COV) is the most effective and immediate method to reduce soil erosion by wind.

SoLoWind Application: Assessing Wind Erosion Off-Site Effects and the Evaluation of Windbreak Effectiveness at Local Scale

With our approach of considering the frequency distribution of wind direction on a local scale regionalized with the orography model WAsP (Figure 6), we can identify arable fields with regularly high wind speeds in the prevailing wind direction and the effect of the presence or absence of protecting windbreaks on endangered objects in the surrounding. For our sub-region, most frequently, the wind blows from the 165° to 195° directions. Windbreaks perpendicular to the 165° to 195° directions exist in the region (Figure 7), which decelerates wind speeds by lifting the wind field. Nevertheless, effective windbreaks on arable fields in the main wind direction next to highway A72 are missing in many

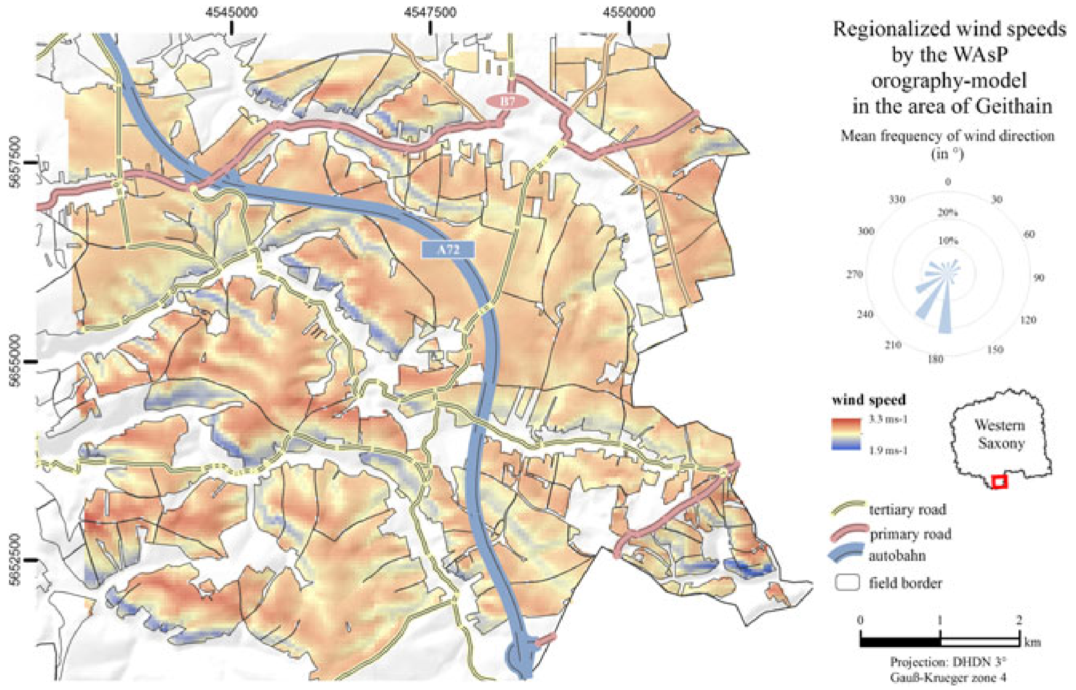

Figure 6. Regionalized wind speeds and direction according to the Wind Atlas Analysis and Application Program (WAsP) orography-model in the sub-region of Geithain. [Colour figure can be viewed at wileyonlinelibrary.com]

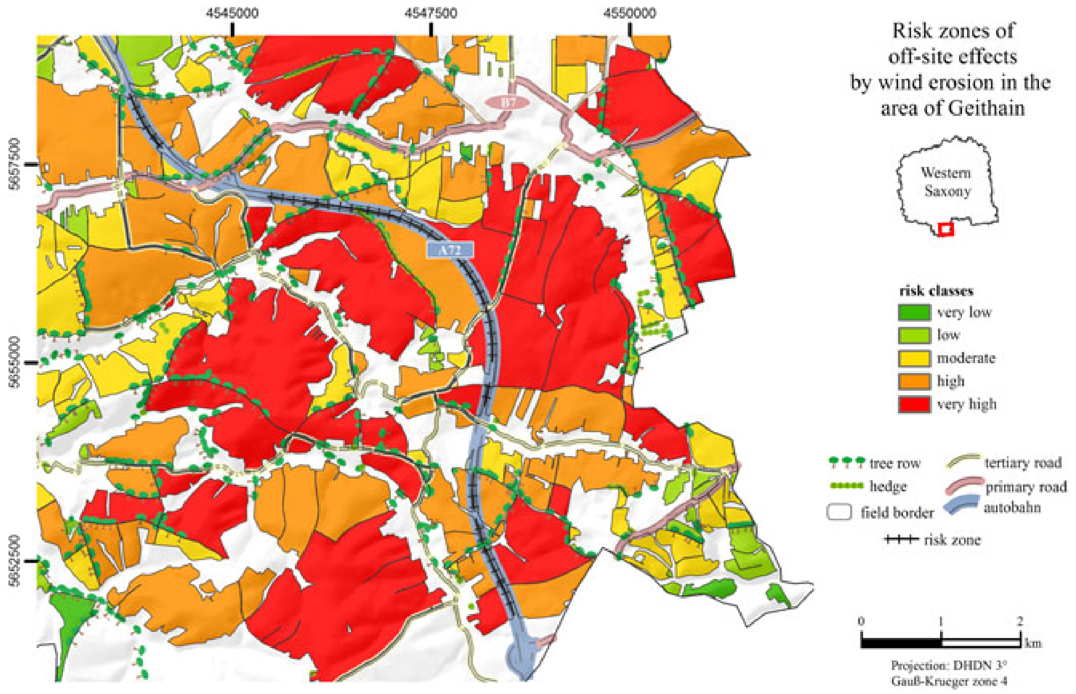

Figure 7. Risk zones of off-site effects by wind erosion in the area of Geithain under consideration of small-scale wind speeds and direction and windbreaks. [Colour figure can be viewed at wileyonlinelibrary.com]

segments. Therefore, highway A72 is specifically vulnerable in the vicinity to arable fields that are classified as risky (see risk zones in Figure 7). Moreover, the street body crosses the arable fields at ground level, which endangers traffic by reducing the visibility due to soil particles potentially mobilized by the wind. To our knowledge, protective windbreaks along the roadway are not planned by the Saxon State Office for Road Construction and Traffic even though soil erosion by wind would be 'strongly attenuated by the presence of nonerodible roughness elements on the surface' (Raupach *et al.,* 1993). The identified risk zones should be evaluated in the further planning and management to prevent future off-site effects. The local assessment can be transformed to other local sub-regions to evaluate the potential impact for soil loss of wind trajectories through the landscape.

CONCLUSIONS AND OUTLOOK

The soil loss by wind erosion model (SoLoWind) indicates the importance of windbreaks, which directly decelerate wind speed and can act as a measure to reduce SoLoWind. Either intra-field windbreaks or reduced field lengths have a protective effect. Our revised wind erosion screening model SoLoWind includes the consideration of the multidirectionality of the wind, the soil erodibility, the state of soil cover, the field length and windbreaks. SoLoWind can also be used to verify and refine large-scale models by integrating it on a regional scale as a sub-model to models like ILSWE. As such, ILSWE was designed to define and parameterize the most relevant factors and conditions of wind erosion and can be supplemented by the qualitative and more detailed assessment of SoLoWind on regional and local scales. Both models, SoLoWind and ILSWE, show comparable general results for the study area even though they are assessing the risk of wind erosion with different approaches and on different scales. SoLoWind is transferable to other study areas and allows for spatial wind erosion risk assessment with low data demand at the regional to local scale. Further, SoLoWind is suitable for wind erosion risk predictions under changing climates by considering different climate change scenarios as input data. The application of SoLoWind to Western Saxony showed that about one-third of all arable fields have either high- or very-high-wind erosion risk. As such, we conclude that as in the adjacent federal states, wind erosion is a serious land degradation threat for Western Saxony. Three main regions were identified with predominantly high and very high soil erosion risk by wind. Sections along the highway A72 that are potentially endangered by wind erosion off-site effects could clearly be determined and need to be protected to avoid influences on road traffic. SoLoWind clearly displays the connection between wind direction, wind frequency and landscape elements and can consequently serve as a planning tool to mitigate the impact of on- and off-site effects of wind erosion risk. We suggest that SoLoWind may serve as a planning tool for soil conservation strategies.

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