New methods of assessing wind erosion risk: Innovative approach to soil protection respecting windbreak effect

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Abstract: Research and development of new soil protection methods helps to maintain sustainable soil management and prevent the degradation of valuable agricultural resources. Wind erosion is a significant environmental issue that can severely degrade landscape, impact agricultural productivity and deteriorate air quality through increased dust emissions and atmospheric pollution. The main goal of this paper was to provide a methodological protocol for mapping and assessing wind erosion risk, taking into account protective effect of both existing and intended windbreaks. Based on the Potential Wind Erosion Risk (PWE) map, which takes into account soil and climatic conditions affecting wind erosion risk, a new map of potential wind erosion risk (RPWE) was created with the inclusion of the effect of windbreaks and their protected zones on the tolerated length of plots. Using this method, it is possible to assess wind erosion risk, model the design of new wind barriers and evaluate their effectiveness. The presented method has been developed into a web application that provides all outputs online. The assessment builds on long-term studies of wind erosion potential and methods for spatial representation of land susceptibility to wind erosion. Assessment of the current state of erosion risk with existing windbreaks as well as modelling the state when some are removed or newly planted, is fundamental when building a resilient and healthy environment. The newly developed method contributes to worldwide global land degradation prevention and offers new insights into the methodological approach for assessing wind erosion.

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1. Introduction

Wind erosion as a significant environmental issue

Damage caused by wind erosion manifests itself not only in the removal of soil particles, fertilizers and plant protection products, but also in the exposure of plant roots and the cutting of tender stems of young plants. In addition, extensive wind erosion has serious consequences for air quality. The intensification of wind erosion leads to an increase in dust emissions and atmospheric pollution by suspended particles (*Xi and Sokolik, 2016; Yulevitch et al., 2020; Chen et al., 2023; Lackóová et al., 2023*). In the Czech Republic, 9% of PM10 particulates come from agriculture (*CHMI, 2024*). With climate change and the drying of the agricultural landscape emissions of these pollutants will become more important. Along with intensive suburbanization, when residential zones expand into the original agrarian landscape (*Pénzes et al., 2023*), the danger of exposure of residents to a new and so far neglected risk with potential health impacts is increasing.

Harmful wind erosion is mostly recorded in dry and warm areas, intensively farmed and mostly flat (*Fryrear et al., 2000; Podhrázská et al., 2008; Borrelli et al., 2014*). In Europe, although wind erosion is not as extensive and serious a problem as it is in drier regions of the world, it can locally cause very significant economic and ecological damage (*Riksen and de Graaff, 2001*). For example, even in the Czech Republic the climate gradually becoming more arid due to rising temperature and uneven rain distribution throughout the year (*Středová et al., 2013*). In some regions of the Czech Republic the wind erosion can occur throughout the year but is most damaging in the spring that follows a dry, snow-poor winter, when strong winds blow dried topsoil from bare or sparsely vegetated fields or in autumn, when the soil surface is no longer protected by vegetation. According to *Ministry of Agriculture of the Czech Republic (2020)* approximately 25% of Czech arable land is potentially threatened by wind erosion which represents an area greater than 569000 hectares. The situation is all the more serious as the highest threaten are the most fertile areas of the country, which are intensively used for agriculture and play a significant role in ensuring the food self-sufficiency and security.

Concept of windbreaks as a mitigation measure

Powerful anti-erosion measure at the level of the agricultural landscape is the establishment of windbreaks, which, in addition to directly protecting the soil by reducing wind speed, also have a number of other ecosystem functions, such as increasing the biodiversity and permeability of the landscape, improving moisture conditions by reducing evaporation in the immediate vicinity of the windbreaks, etc. (*Weninger et al., 2021*). Windbreaks' structure depends on their purpose, expected benefits and characteristics of the specific site and will determine the carbon storage potential that these stands can provide (*Ballesteros-Possú et al., 2019*). In addition to anti-erosion effect, windbreaks protect roads, provide wildlife habitat, improve landscape aesthetics, and mitigate odour, dust, and pesticide drift (*Tyndall and Colletti, 2007*). They have been shown to reduce peak particle concentrations during dust events, thereby reducing the risk of human exposure to high levels of PM pollution (*Chang et al., 2021*). Windbreaks also mitigate climate change representing an effective strategy for sequestering more carbon on agricultural land (*Schoeneberger, 2009*) and thus constitute a part of so-called "climate-smart landscapes".

Anti-erosion effect of windbreaks is given by their appropriate allocation in the landscape, health state of constituting woods, and their structural diversity and inner structure (*Podhrázská et al., 2021*). *Středová et al. (2012)* proved that fully foliaged windbreak reduces winds speed up to a distance of 200 to 250 m on leeward side. Advanced method of windbreaks structure evaluation is based on optical porosity (*Loeffler et al., 1992; Vacek et al., 2018*). The efficiency of windbreaks can be measured in field experiments or based on computer simulations. Field experiments are always limited by unstable weather conditions, instruments, lack of samples and other factors (*Bitog et al., 2012*). *Yang et al. (2021)* noted that evaluation of windbreaks can be even based on remote sensing images and GIS. This is a very suitable solution that enables automated continuous evaluation, since the state of the windbreak is not constant over time. For example, the phenology of woody plants changes not only during the year, but also in the long term due to climate change (*Mrekaj et al., 2024; Lukasová et al., 2020*).

Challenges in assessing wind erosion risk

Complexity of assessing wind erosion risk lies in the variety of factors controlling this type of soil erosion, like soil type, wind patterns, and landscape features. All factors contributing to wind erosion are generally described by *Borelli et al. (2014, 2016, 2017)* and for central Europe specified by *Středová et al. (2021).*

Susceptibility of soils to the wind erosion (i.e. potential risk) is given by soil and climatic conditions. Based on aggregated pedological information the soils were classified from the most at risk (sandy soils) to not at risk (soils with a high content of clay particles). Although these clay soils are generally less vulnerable to wind erosion, under certain conditions they can also become significantly threatened, as low winter temperatures cause a significant breakdown of soil aggregates (*Stout and Zobeck, 1996; Bullock et al., 2001; Stout, 2007; Pi et al., 2020; Chepil, 1953, 1954; Hinman and Bisal, 1968*, etc.). Susceptibility of all soil to wind erosion increases with their dry surface and the occurrence of erosively dangerous winds. By synthesizing all relevant factors such as soil factors (wind erodible fraction, soil-crust, surface-roughness and vegetation cover) and climatic factors (mean monthly wind speed, evapotranspiration and the precipitation) a map of potential wind erosion risk was created (PWE). Map distinguishes six categories of risk. The entire methodological procedure was published by *Doležal et al. (2017)* and *Středová et al. (2021).*

The risk of wind erosion increases when specific landscape elements with a windbreak effect are missing. A comprehensive method of wind erosion risk assessment must therefore take into account their presence. It would make it possible to claim a protected proportion of land spared from the erosive effects of wind. The final interactive output provides a useful tool for all relevant stakeholders of landscape management. It facilitates the design of suitable windbreaks or the modelling of erosion risk when the windbreaks should be removed.

Objectives and Scope of this study are:

i) define a methodological approach for incorporation of windbreaks' effect into wind erosion risk classification;
ii) estimation of potential wind erosion (PWE) risk taking into account windbreaks' effect;
iii) implementation of the results into the interactive web application.

2. Material and methods

The paper introduces an innovative approach to wind erosion risk assessment taking into account the effect of windbreaks. It combines several methodological protocols and map layers authorized and certified by national authorities and published by authors team members of the paper (i.e. *Podhrázská and Novotný, 2007; Podhrázská et al., 2008; Podhrázská et al., 2015; Doležal et al., 2017; Kučera et al., 2021a; Kučera et al., 2021b; Kučera at al., 2023*).

Because these protocols are essentially practically oriented and intended for end users dealing with practical landscape management, there is a lack of comprehensive communication for the scientific community. To fill the gap, we introduce a scientifically focused output of the applied methodology.

The whole methodological procedure described in this chapter has been illustrated using the example of the Czech Republic (Central Europe).

2.1. Employed inputs

Input map layer A: Potential wind erosion (PWE) risk

So called PWE risk map (Fig. 1) combines relevant soil and climatic parameters in order to distinguish 6 PWE risk categories (from the lowest to the highest risk): 1 – subtle exposure, 2 – slight exposure, 3 – moderate exposure, 4 – high exposure, 5 – very high exposure, 6 – the highest exposure. As stated in the introduction, the methodological procedure of PWE risk map was published in *Doležal et al. (2017)* and *Středová et al. (2021).*

Input map layer B: Protective zones of windbreaks

Methodological protocol of *Podhrázská and Novotný (2007)*, and *Podhrázská et al. (2008)* defines windbreaks' protective zone according to their structure and direction of prevailing erosive winds following results of *Středová et al. (2012).* They, based on a robust set of field measurements, provided nomogram relating wind speed reduction to windbreak parameters. In order to define the protective zones (Table 1) the comprehensive evaluation of existing vegetation barriers was needed. Such a database employing input data of Ministry of Agriculture (Forests of the Czech Republic; LPIS-ESE, i.e. land parcel identification system – ecologically significant element, the

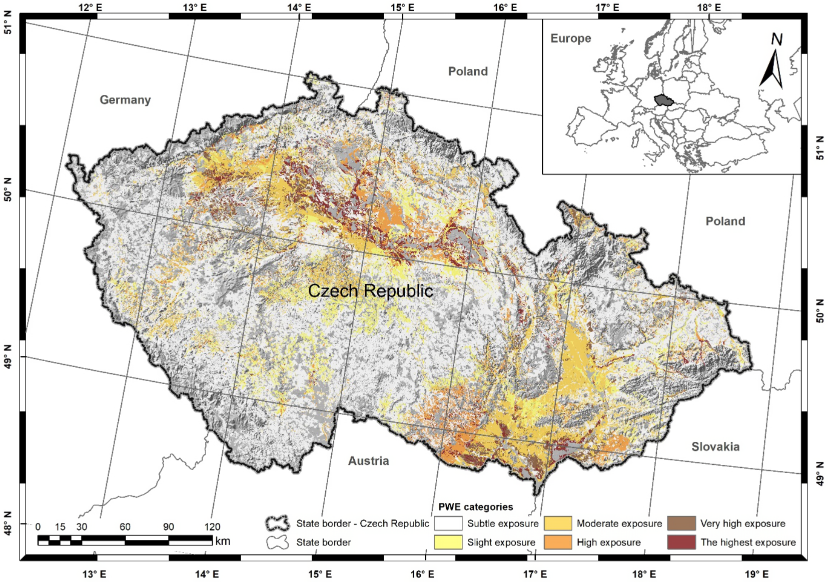

Fig. 1. Potential wind erosion (PWE) risk in the Czech Republic.

database lists all agricultural parcels, hereinafter referred to as "plots"), the Ministry of Environment (windbreak planting database) and ZABAGED have been built and continuously updated for many years (*Kučera and Podhrazska, 2020; Kučera et al., 2021a*) and includes approx. 2900 windbreaks and 2200 other vegetation barriers. Each vegetation barrier is categorized according to *Podhrázská et al. (2008)* and *Doležal et al. (2017)* regarding its effectiveness.

Table 1. The protective zones of windbreaks.

Type of windbreak	**leeward side [m]**	**windward side [m]**
fully developed windbreak	300	100
other vegetation barriers	150	50

The protective zones' definition also requires knowledge of prevailing directions of erosive winds (Fig. 2) evaluated by *Kučera et al. (2023)*, using wind rosettes related to the maximum wind gust and its direction in 2 or 1 second. The percentage of 15-minute and 10-minute wind gusts above a threshold wind speed were used. Based on wind-tunnel experiments, *Pasák et al. (1984)* determined the lowest/critical value of 3.3 m s^{-1} as the threshold wind speed to initiate soil particles transport. However, wind is standardly measured at a height of 10 m, and it can be easily interpolated to any height of 0 to 10 m using models with the estimated parameters mentioned by *Chen et al. (1998).* Wind speed of 3.3 m.s^{-1} at ground level corresponds to 10 m.s^{-1} at a height of 10 m. The resulting wind direction encompasses spring and autumn winds as they are the most dangerous in terms of wind erosion. Interpolation tools (kriging and nearest neighbour method) in ArcGIS Desktop were used to determine the areas. The Czech Hydrometeorological Institute station locations and the 4th generation Digital Elevation Model (DMR 4G, © ČÚZK) were used as base layers (2023).

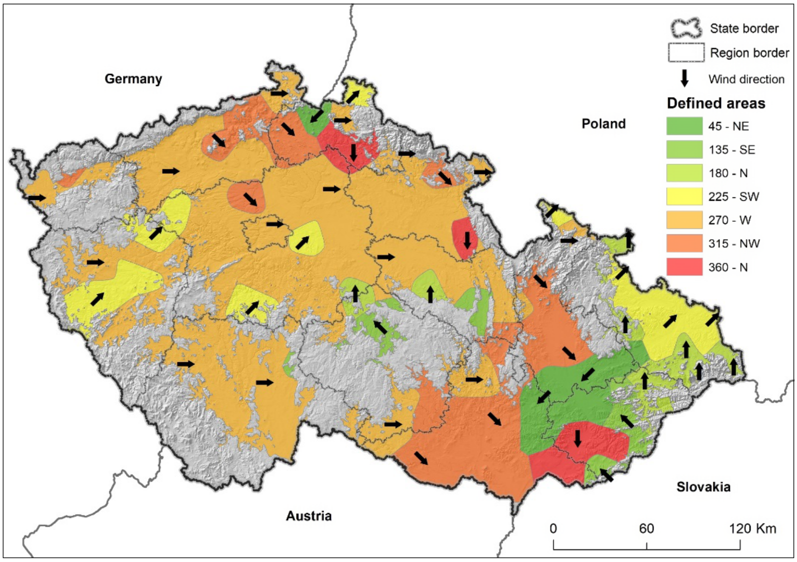

Fig. 2. Map of prevailing erosive winds directions in the Czech Republic (*Kučera et al., 2023*).

2.2. Comprehensive wind erosion risk assessment taking into account an effect of windbreaks (revised PWE map – RPWE)

1st step: Merging layer A and B:

The map of PWE risk is combined with the map of protective zones of windbreaks. Only barriers with higher efficiency are selected. Protective zones are generated on their windward and leeward sides according to Table 1. The land covered by the zone is protected and its PWE risk category becomes "subtle exposed", i.e. the area is no longer in risk. The effect of the protective zone is reflected in the resulting map by two-digit codes (see Table 2) when value 0 is added to the original category 1 to 6. This creates a code designation in which information from both layers is preserved.

Table 2. Divergence code pattern of revised PWE risk category merging PWE risk categories and protective zones.

PWE risk category	PWE risk category within protective zone	PWE risk category outside of protective zone
1	10	10
2	10	20
3	10	30
4	10	40
5	10	50
6	10	**60**

2nd step: Assessment of landscape resilience to wind erosion in terms of its structure, specifically according to tolerated length of plots

The susceptibility of agricultural land to wind erosion is expressed by so called tolerated lengths of plot in the direction of the prevailing erosive winds. Methodological protocol designed by *Podhrázská et al. (2008)* set the tolerated lengths with respect to PWE risk categories (Table 3) following a recommendation of *Podhrázská and Novotný (2007)* and *Janeček et al. (2007)*. This approach is based on the assumption: the longer the area in the direction of the erosive wind, the more soil particles are loosened from the surface. If the tolerated length is exceeded, the plot is claimed to have more risk to wind erosion, which is again reflected in the resulting digit code. Plots exceeding limit get value 1 to the last digit of the code (i.e. 0

Table 3. Tolerated plot lengths for revised PWE risk category.

PWE risk category	Tolerated length – L_{max}
10 – 40	850
50	600
60	350

from previous step is replaced by 1) – see Table 3. Such a code pattern makes it possible to identify which factors are responsible for the final risk (Tables 4 and 5).

Table 4. Divergence code pattern of revised PWE (RPWE) risk category distinguishing whether tolerated length was exceeded.

PWE risk category	RPWE risk category taking account protective zones	
	plot with tolerated length	plot exceeding tolerated length
1	10	11
2	20	21
3	30	31
4	40	41
5	50	51
6	60	61

Table 5. Comprehensive two digits code description of revised PWE (RPWE) risk category.

RPWE risk category code	Plot description
10	subtle exposed or protected by a windbreak
20	slightly exposed, unprotected, with tolerated length
30	moderately exposed, unprotected, with tolerated length
40	highly exposed, unprotected, with tolerated length
50	very highly exposed, unprotected, with tolerated length
60	the highest exposed, unprotected, with tolerated length
11	subtly exposed, unprotected and with exceeded tolerated length limit
21	slightly exposed, unprotected and with exceeded toleratedlength limit
31	moderately exposed, unprotected and with exceeded tolerated length limit
41	highly exposed, unprotected and with exceeded tolerated length limit
51	very highly exposed, unprotected and with exceeded tolerated length limit
61	the highest exposed, unprotected and with exceeded tolerated length limit

3. Results and discussion

According to the above-mentioned methodical procedure, a map of RPWE was prepared including the protected zones of existing vegetation barriers and their influence on the tolerated length of land on a national scale, see Fig. 5. The map is available online in the form of an interactive web application: `https://vetrnaeroze.vumop.cz`. This application allows the user to work with the map in detail of the land plot of interest (LPIS-ESE). The whole methodological procedure has been illustrated using the example of the model land plot (see Fig. 3):

1) Classification of PWE risk category for selected plot of land according to PWE map (input layer A). The plot belongs to PWE risk category 5 (Fig. 3 – see brown) and is separated from neighbouring plots by fully developed windbreaks (Fig. 3 – see orange). Evaluation of tolerated length (L_t) for risk category according to Table 3 is 600 m.
   Category 5 (Fig. 3: section 1-a and 1-b on the left);

2) Reclassification of the PWE risk category reflecting the protective zones of the windbreak (input layer B) according to Table 2. For a fully developed windbreak, it is 300 and 100 m in the direction of prevailing wind (Fig. 2, see grey). According to Table 3, the part of the plot covered by the protective zones automatically falls into category 10, while the remaining part retains the original risk category supplemented by 0 (i.e. 50). The resulting RPWE risk category of the plot is given by the prevailing PWE risk category within the plot (10 in this case).
   Reclassified category 10 (plot protected by windbreak) (Fig. 3: section 2-a, 2-b and 2-c);

3) Evaluation of tolerated length (L_t) for revised risk category according to Table 3.
   $L_{t\_10} = 850$ m

   Determination of maximal length (L_{max}) of the plot in the direction of prevailing wind according to Fig. 3 (Fig. 3, see black arrows).
   $L_{max} = 686$ m

   Comparison L_{max} and L_{t_10}: if $L_{max} \geq T_{t\_10}$ then plot falls into RPWE risk category coded 10, if $L_{t\_10} \geq L_{max}$ then it falls into RPWE risk category with code 11

$L_{t\_10} = 850 \geq L_{max} = 686$

Final category 10 (plot protected by windbreak) (Fig. 3: section 3).

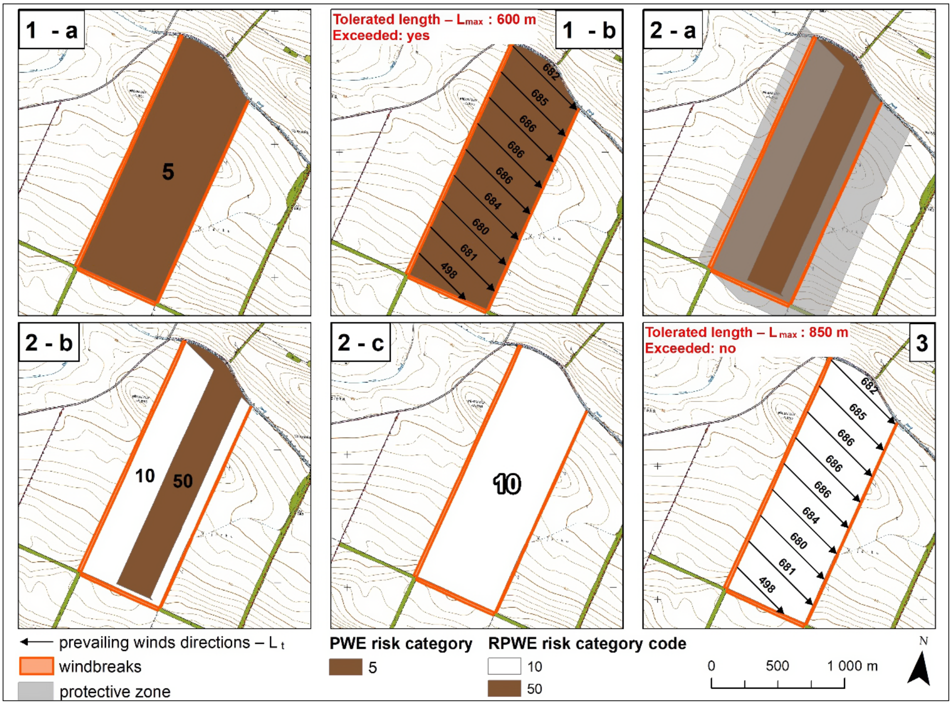

Fig. 3. Example of protective zone effect on RPWE risk category (the maximum length of the plot in the direction of the prevailing wind is 686 m).

The main goal of the paper was to update and extend methodological protocol of PWE identification and classification presented as a "road map" by *Středová et al. (2021)*. The main novelty lies in incorporating a protecting effect of the windbreaks and its reflection in RPWE risk category. Figure 4 graphically summarizes all inputs and whole methodological process. Based on this, a map of the RPWE risk assessment with respect to the effect of the windbreak is shown in Fig. 5. Bottom part of the figure focuses on the selected area with high RPWE risk in order to show the map resolution (5 × 5 m).

The published procedure assumes a method for evaluating vegetation barriers that have a defined fixed protected zone. A limitation is that the

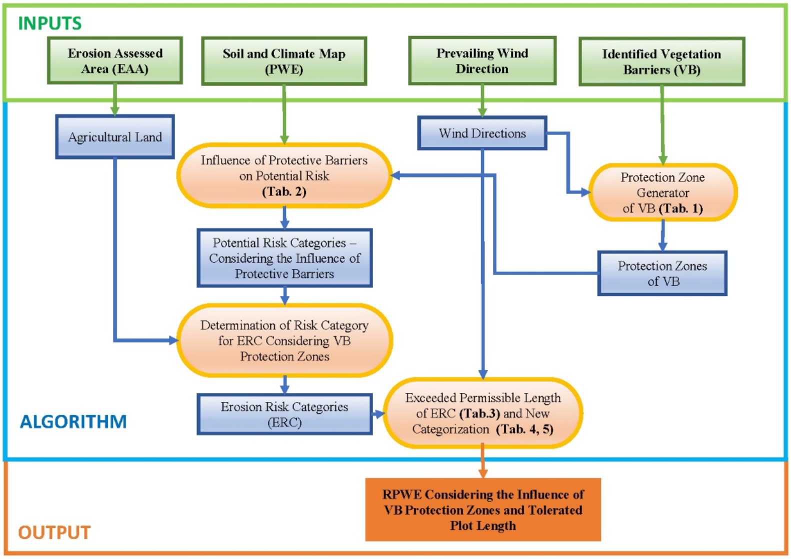

Fig. 4. Implementation scheme of RPWE risk respecting windbreaks' effect.

existence of the vegetation barrier is assessed, but the current state of the vegetation barrier is not taken into account. However, in published assessments, other methods of defining protected zones based on the use of the so-called optical porosity can be included (*Středová et al., 2012* and *Řeháček et al., 2017*). These methods better characterize vegetation barriers in relation to the current state of vegetation. A certain disadvantage of these methods is the need to obtain data (digital photographs) directly from the field. The published interactive web application already has integrated tools for using protected zone assessment for methods using optical porosity.

When using the method on a local scale (e.g. on the scale of a cadastral area), it is always recommended to prepare a new wind rose to determine the current prevailing wind direction. This recommendation has been established to ensure that the data is representative of the area of interest. Furthermore, the timeliness of the data (soil and climate) is ensured by the continuous updating of these data by the Ministry of Agriculture of the Czech Republic. Soil data are updated continuously, according to the activities related to the updating of the soil database. This database is managed by the state authorities. For climatic data, regular updates are planned every 5 years.

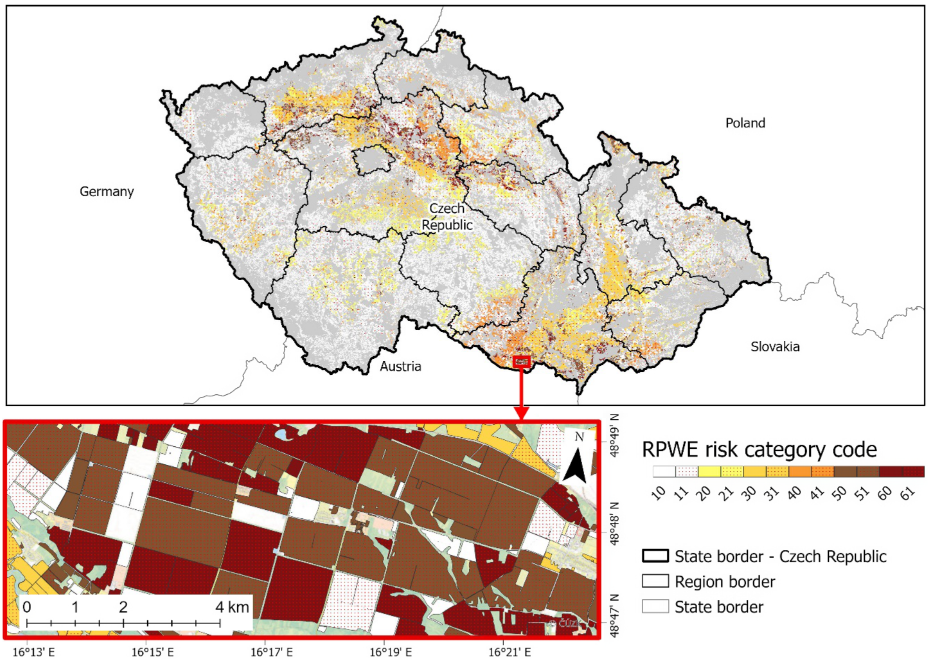

Fig. 5. Map of RPWE risk respecting windbreaks' effect.

Methods for assessing the effectiveness of windbreaks have been widely discussed in Europe, Asia and Nothern America, for example, by *Brandle et al. (2004), Liu et al. (2014), Řeháček et al. (2017), Gonzales et al. (2018), Zhou et al. (2018), Li et al. (2022)* and others. Our newly created map (Fig. 4) for the Czech Republic is a valuable input for reasonable and well-elaborated fight against erosion including planting of windbreaks. Similar attitude introduce *Scheper et al. (2022)* who used a wind erosion risk map as the main input and developed the TASOW model (Tool for Automated selection of Windbreaks) for the design of potential locations for new windbreaks. Their model parameters are adjustable, transferable to other regions and can be changed according to the user's needs. As a result, potential windbreak localities are ranked in order of suitability. Well-designed and managed introducing of woods into agricultural land as powerful measure reducing wind erosion advocates also *van Ramshorst et al. (2022)*. As reported by *Kestel et al. (2023)*, effective land management practices for controlling wind erosion vary locally and may include shelterbelts, revegetation, and similar sustainable measures to increase soil cover, biological diversity, and minimum soil disturbance. In order to do so, they call for detailed field-based studies which are required for high-resolution mapping of target areas to develop individual adaptation strategies. Our method, revealing wind erosion risk at the plot resolution, represents a valuable contribution to the field in this regard. In the context of evolving digital technologies, the results of our study were incorporated into a web application "Wind Erosion Risk Management", employing automated and interactive smart tools.

4. Conclusions

- ✓ This paper brings a new methodological procedure for potential wind erosion risk assessment.
- ✓ The novelty of this method lies in taking into account the protective effect of windbreaks (i.e. merging soil and climate based RPWE category with windbreaks database).
- ✓ The identification of vulnerable areas enables the prioritization of protection measures and their deliberate implementation and planning (i.e. optimization of plot size, removal of redundant or ineffective windbreaks, maintenance of well-functioning ones and planning of new ones with suitable parameters and location).
- ✓ Our results are crucial for wide range of stakeholders and end-users engaged in practical landscape management. As they rarely seek for information in scientific papers, we transformed our results into practically usable interactive web application, which provides all outputs on-line. The web application is available from: `https://vetrnaeroze.vumop.cz`.
- ✓ The web application enables virtual modelling of the effect of above mentioned protection measures, which helps to find tailored solutions for specific conditions.

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References

Ballesteros-Possú W., Brandle J. R., Ordóñez H. R., 2019: Carbon storage potential of windbreaks in the United States. Revista de Ciencias Agrícolas, **36**, E, 108–123, doi: 10.22267/rcia.1936E.111.

Bitog J. P., Lee I.-B., Hwang H.-S., Shin M.-H., Hong S.-W., Seo I.-H., Kwon K.-S., Mostafa E., Pang Z., 2012: Numerical simulation study of a tree windbreak. Biosyst. Eng., **111**, 1, 40–48, doi: 10.1016/j.biosystemseng.2011.10.006.

Borelli P., Ballabio C., Panagos P., Montanarella L., 2014: Wind erosion susceptibility of European soils. Geoderma, **232–234**, 471–478, doi: 10.1016/j.geoderma.2014.06.008.

Borrelli P., Panagos P., Ballabio C., Lugato E., Weynants M., Montanarella L., 2016: Towards a pan-European assessment of land susceptibility to wind erosion. Land Degrad. Dev., **27**, 4, 1093–1105, doi: 10.1002/ldr.2318.

Borelli P., Lugato E., Montanarella L., Panagos P., 2017: A new assessment of soil loss due to wind erosion in European agricultural soils using a quantitative spatially distributed modelling approach. Land Degrad. Dev., **28**, 1, 335–344, doi: 10.1002/ldr.2588.

Brandle J. R., Hodges L., Zhou X. H., 2004: Windbreaks in North American agricultural systems. Agrofor. Syst., **61**, 1-3, 65–78, doi: 10.1023/B:AGFO.0000028990.31801.62.

Bullock M. S. Larney F. J., Izaurralde R. C., Feng Y., 2001: Overwinter changes in wind erodibility of clay loam soils in Southern Alberta. Soil Sci. Soc. Am. J., **65**, 2, 423–430, doi: 10.2136/sssaj2001.652423x.

Chang H.-H., Meyerhoefer C. D., Yang F.-A., 2021: COVID-19 prevention, air pollution and transportation patterns in the absence of a lockdown. J. Environ. Manag., **298**, 113522, doi: 10.1016/j.jenvman.2021.113522.

Chen Y. C., Bundy D., Hoff S., 1998: Modeling the variation of wind speed with height for agricultural source pollution control. ASHRAE Tran., **104**, 1685–1691.

Chen S., Chen J., Zhang Y., Lin J., Bi H., Song H., Chen Y., Lian L., Liu C., Zhang R., 2023: Anthropogenic dust: sources, characteristics and emissions. Environ. Res. Lett., **18**, 10, 103002, doi: 10.1088/1748-9326/acf479.

Chepil W. S., 1953: Factors that influence clod structure and erodibility of soil by wind: I. Soil structure. Soil Sci., **75**, 6, 473–484.

Chepil W. S., 1954: Seasonal fluctuations in soil structure and erodibility of soil by wind. Proc. Soil Sci. Soc. Am. J., **18**, 1, 13–16, doi: 10.2136/sssaj1954.03615995001800010004x.

CHMI, 2024: Informative Inventory Report Czech Republic. Submission under the UN-ECE Convention on Long-range Transboundary Air Pollution Reported inventories 1990–2022. Czech Hydrometeorological Institute, Prague, available online at: https://www.chmi.cz/files/portal/docs/uoco/oez/embil/CZ-informativni-zprava-emisni-inventury-2024.pdf.

Doležal P., Podhrázská J., Kučera J., Středová H., Středa T., Doubrava D., 2017: Řízení rizika větrné eroze; Certifikovaná metodika (Wind erosion risk management; Certified methodology). Brno, VÚMOP, v.v.i. (in Czech).

Fryrear D. W., Bilbro J. D., Saleh A., Schomberg H., Stout J. E., Zobeck T. M., 2000: RWEQ: Improved wind erosion technology. J. Soil Water Conserv., **55**, 2, 183–189.

Gonzales H. B., Casada M. E., Hagen L. J., Tatarko J., Maghirang R. G., Barden C. J., 2018: Porosity and drag determination of a single-row vegetative barrier (*Maclura pomifera*). Trans. ASABE, **61**, 2, 641–652, doi: 10.13031/trans.12338.

Hinman W. C., Bisal F., 1968: Alterations of soil structure upon freezing and thawing and subsequent drying. Can. J. Soil Sci., **48**, 2, 193–197, doi: 10.4141/cjss68-023.

Janeček M. et al., 2007: Ochrana zemědělské půdy před erozí – metodika (Protection of agricultural soils against erosion – methodology). VÚMOP, Praha, 76 p. (in Czech).

Kestel F., Wulf M., Funk R., 2023: Spatiotemporal variability of the potential wind erosion risk in Southern Africa between 2005 and 2019. Land Degrad. Dev., **34**, 10, 2945–2960, doi: 10.1002/ldr.4659.

Kučera J., Podhrazska J., 2020: Identification of vegetation barriers to model their influence on the effects of wind erosion in the Czech Republic. In: Proc. MendelNet, November 11–12, 2020, Mendel University in Brno, Brno, 43–248, https://mendelnet.cz/pdfs/mnt/2020/01/45.pdf.

Kučera J., Podhrázská J., Středa T., Středová H., Papaj V., 2021a: Mapa účelové kategorizace trvalých vegetačních prvků v územích ohrožených větrnou erozí; Certifikovaná mapa (Map of purposeful categorization of permanent vegetation elements in areas threatened by wind erosion; Certified map). Brno, VÚMOP (in Czech).

Kučera J., Podhrázská J., Papaj V., Středa T., Středová H., Chuchma F.; Lang J., Janoušek M., Novotný I., 2021b: Ohroženost zemědělské půdy větrnou erozí se zohledněním vlivu trvalých vegetačních prvků; Certifikovaná mapa (Vulnerability of agricultural land to wind erosion, taking into account the influence of permanent vegetation elements; Certified map). Brno, VÚMOP (in Czech).

Kučera J., Podhrázská J., Chuchma F., Středa T., Středová H., Papaj V., Novotný I., 2023: Mapa oblastí vymezující převládající směry větrů pro potřeby hodnocení rizika větrné eroze; Certifikovaná mapa (Map of areas defining prevailing wind directions for the purpose of wind erosion risk assessment; Certified map). Brno, VÚMOP (in Czech).

Lackóová L., Lieskovský J., Nikseresht F., Halabuk A., Hilbert H., Halászová K., Bahreini F., 2023: Unlocking the potential of remote sensing in wind erosion studies: A review and outlook for future directions. Remote Sens., **15**, 13, 3316, doi: 10.3390/rs15133316.

Li H., Wang Y., Li S., Askar A., Wang H., 2022: Shelter efficiency of various shelterbelt configurations: A wind tunnel study. Atmosphere, **13**, 7, 1022, doi: 10.3390/atmos13071022.

Liu B., Qu J., Zhang W., Tan L., Gao Y., 2014: Numerical evaluation of the scale problem on the wind flow of a windbreak. Sci. Rep., **4**, 6619, doi: 10.1038/srep06619.

Loeffler A. E., Gordon A. M., Gillespie T. J., 1992: Optical porosity and windspeed reduction by coniferous windbreaks in Southern Ontario. Agrofor. Syst., **17**, 2, 119–133, doi: 10.1007/BF00053117.

Lukasová V., Vido J., Škvareninová J., Bičárová S., Hlavatá H., Borsányi P., Škvarenina J., 2020: Autumn phenological response of European beech to summer drought and heat. Water, **12**, 9, 2610, doi: 10.3390/w12092610.

Ministry of Agriculture of the Czech Republic, 2020: Zpráva o stavu zemědělství ČR za rok 2020 „Zelená zpráva 2020" (State of Agriculture Report 2020 "Green Report 2020"). Available online at: https://mze.gov.cz/public/portal/mze/-q264717---hl9MEIXb/zelena-zprava-2020 (in Czech).

Mrekaj I., Lukasová V., Rozkošný J., Onderka M., 2024: Significant phenological response of forest tree species to climate change in the Western Carpathians. Cent. Eur. For. J., **70**, 2, 107–121, doi: 10.2478/forj-2024-0009.

Pasák V. [et al.], 1984: Ochrana půdy před erozí (Soil protection against erosion). Státní Zemědělské Nakladatelství (SZN), Praha, Czech Republic (in Czech).

Pénzes J., Hegedűs L. D, Makhanov K., Túri Z., 2023: Changes in the patterns of population distribution and built-up areas of the rural–urban fringe in post-socialist context—A Central European case study. Land, **12**, 9, 1682, doi: 10.3390/land12091682.

Pi H., Huggins D. R., Webb N. P., Sharratt B., 2020: Comparison of soil-aggregate crushing-energy meters. Aeolian Res., **42**, 100559, doi: 10.1016/j.aeolia.2019.100559.

Podhrázská J., Novotný I., 2007: Evaluation of the wind erosion risks in GIS. Soil Water Res., **2**, 1, 10–14, doi: 10.17221/2101-SWR.

Podhrázská J., Novotný I., Rožnovský J., Hradil M., Toman F., Dufková J., Macků J., Krejčíř J., Pokladníková H., Středa T., 2008: Optimalizace funkcí větrolamů v zemědělské krajině: metodika (Optimizing the functions of windbreaks in agricultural landscapes: a methodology). Praha, Výzkumný ústav meliorací a ochrany půdy (in Czech).

Podhrázská J., Kučera J., Středová H., 2015: The methods of locating areas exposed to wind erosion in the south Moravia region. Acta Univ. Agric. Silvic. Mendelianae Brun., **63**, 1, 113–121, doi: 10.11118/actaun201563010113.

Podhrázská J., Kučera J., Doubrava D., Doležal P., 2021: Functions of windbreaks in the landscape ecological network and methods of their evaluation. Forests, **12**, 1, 67, doi: 10.3390/f12010067.

Řeháček D., Khel T., Kučera J., Vopravil J., Petera M., 2017: Effect of windbreaks on wind speed reduction and soil protection against wind erosion. Soil Water Res., **12**, 2, 128–135, doi: 10.17221/45/2016-SWR.

Riksen M. J. P. M., de Graaff J., 2001: On-site and off-site effects of wind erosion on European light soils. Land Degrad. Dev., **12**, 1, 1–11, doi: 10.1002/ldr.423.

Scheper S., Kitzler B., Weninger T., Strauss P. Michel K., 2022: TASOW – A tool for the automated selection of potential windbreaks. MethodsX, **9**, 101826, doi: 10.1016/j.mex.2022.101826.

Schoeneberger M. M., 2009: Agroforestry: working trees for sequestering carbon on agricultural lands. Agrofor. Syst., **75**, 1, 27–37, doi: 10.1007/s10457-008-9123-8.

Stout J. E., Zobeck T. M., 1996: The Wolfforth field experiment: A wind erosion study. Soil Sci., **161**, 9, 616–632, doi: 10.1097/00010694-199609000-00006.

Stout J. E., 2007: Simultaneous observations of the critical aeolian threshold of two surfaces. Geomorphology, **85**, 1-2, 3–16, doi: 10.1016/j.geomorph.2006.03.034.

Středová H., Podhrázská J., Litschmann T., Středa T., Rožnovský J., 2012: Aerodynamic parameters of windbreak based on its optical porosity. Contrib. Geophys. Geod., **42**, 3, 213–226, doi: 10.2478/v10126-012-0008-5.

Středová H., Podhrázská J., Chuchma F., Středa T., Kučera J., Fukalová P., Blecha M., 2021: The road map to classify the potential risk of wind erosion. ISPRS Int. J. Geo-Inf., **10**, 4, 269, doi: 10.3390/ijgi10040269.

Středová H., Rožnovský J., Středa T., 2013: Predisposition of drought occurrence in selected arid areas of the Czech Republic. Contrib. Geophys. Geod., **43**, 3, 237–252, doi: 10.2478/congeo-2013-0015.

Tyndall J., Colletti J., 2007: Mitigating swine odor with strategically designed shelterbelt systems: a review. Agrofor. Syst., **69**, 1, 45–65, doi: 10.1007/s10457-006-9017-6.

Vacek Z., Řeháček D., Cukor J., Vacek S., Khel T., Sharma R. P, Kučera J., Král J., Papaj V., 2018: Windbreak efficiency in agricultural landscape of the Central Europe: multiple approaches to wind erosion control. Environ. Manag., **62**, 5, 942–954, doi: 10.1007/s00267-018-1090-x.

van Ramshorst J. G. V., Siebicke L., Baumeister M., Moyano F. E., Knohl A., Markwitz Ch., 2022: Reducing wind erosion through agroforestry: A case study using large eddy simulations. Sustainability, **14**, 20, 13372, doi: 10.3390/su142013372.

Weninger T., Scheper S., Lackóová L., Kitzler B., Gartner K., King N. W., Cornelis W., Strauss P., Michel K., 2021: Ecosystem services of tree windbreaks in rural landscapes—a systematic review. Environ. Res. Lett., **16**, 10, 103002, doi: 10.1088/1748-9326/ac1d0d.

Xi X., Sokolik I. N., 2016: Quantifying the anthropogenic dust emission from agricultural land use and desiccation of the Aral Sea in Central Asia. J. Geophys. Res. Atmos., **121**, 20, 12270–12281, doi: 10.1002/2016JD025556.

Yang F., Liu T., Shi Z., Xia Y., Jiang Z., Han T., 2021: Influence of height of earth embankment type windbreak wall on flow field characteristics and catenary wind-induced displacement. Eng. Appl. Comput. Fluid Mech., **15**, 1, 672–691, doi: 10.1080/19942060.2021.1910573.

Yulevitch G., Danon M., Krasovitov B., Fominykh A., Swet N., Tsesarsky M., Katra I., 2020: Evaluation of wind-induced dust-PM emission from unpaved roads varying in silt content by experimental results. Atmos. Pollut. Res., **11**, 2, 261–268, doi: 10.1016/j.apr.2019.10.010.

Zhou Q. Z., Zhao Y., Gao G. L., Zhang Y., Cheng Y. X., 2018: Wind tunnel simulation experiment of windbreak effects of shelterbelt along Xining-Golmud section of Qinghai-Tibet Railway. Ningxia Agric. For. Sci. Technol., **59**, 4.