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Evaluation of the Spatial Structure of Windbreaks from Digital Photography

Josef Kučera[1], Petra Fukalová[2*], Hana Středová[2], Martin Blecha[3], Roman Jakubiček[4], Jiří Chmelík[4], Jana Podhrázská[1], Tomáš Středa[2]

[1] Research Institute for Soil and Water Conservation, v.v.i., Department of Land Consolidations and Landscape Use, Lidická 25/27, 602 00 Brno, Czech Republic

[2] Faculty of AgriSciences, Mendel university in Brno, Zemědělská 1, 613 00 Brno, Czech Republic

[3] The State Land Office, Kotlářská 931/53, 602 00 Brno, Czech Republic

[4] Faculty of Electrical Engineering and Communication, Brno University of Technology, Antonínská 548/1, 602 00 Brno, Czech Republic

* Corresponding author's e-mail: petra.fukalova@mendelu.cz

ABSTRACT

The loss of fertile soil due to wind erosion has major impacts on the landscape and the environment. Its intensity and extent depend on many factors, where vegetation cover, soil moisture and wind intensity play key roles. Climatic conditions are constantly developing towards a higher extremity. Episodes of drought associated with a higher risk of wind erosion are longer and more frequent. For farmers, this results in higher demands for management in order to increase resistance against the negative effects of wind erosion. Windbreaks effectively protect the soil by reducing wind speed. This paper describes the automation of the current procedure for the evaluation of the spatial structure of windbreaks by means of advanced image signal analysis (2D) and the subsequent use of machine learning for further classification of spatial structure parameters (optical porosity). Software called Windbreak which enables the evaluation of optical porosity, including the assessment of canopy height, has been developed. The program allows working with digital photographs at the original resolution. The output from the Windbreak software can be also used as input values for determining the effectiveness of windbreaks.

Keywords: wind erosion, optical porosity, software.

INTRODUCTION

Wind erosion causes loss of fertile soil and affects not only agricultural land but the environment. Its intensity and extent depend on many factors, with vegetation cover, soil moisture and, of course, wind intensity playing a key role. In particular, climatic conditions, which are constantly evolving towards higher extremes, have a significant influence on the dynamics of wind erosion. The higher frequency of extreme weather events also adversely affect the conditions for growing agricultural crops [Trnka, 2004; Fallon and Betts, 2010]. Drought is a logical consequence of the effects of low rainfall and high temperatures. Closely related to increasing drought is the increasing risk of wind erosion, especially in areas of intensive agricultural use. This places greater demands on farmers in terms of farming practices to increase their resistance to the negative effects of wind erosion (soil loss, crop damage, air pollution, water pollution, etc.). These include measures related to soil tillage, application of organic matter to the soil, introduction of drought-tolerant varieties and changing cropping practices to respect local soil and meteorological conditions [Daryanto et al., 2016; Von Gehren et al., 2023; Vadez et al., 2024]. Damage to agricultural land caused by wind erosion is manifested not only by the transport of soil particles, fertilisers and plant protection products, but also by the stripping of plant roots and the cutting of tender stems of young plants. Wind-borne soil particles cause damage to buildings, siltation of roads, railways and ditches, and siltation of watercourses and reservoirs. Wind erosion also contributes to air pollution that threatens health [Liu et al., 2019; Katra, 2020] Health problems can arise due to fine dust particles (increase in concentration) being carried a considerable distance. At the same time, there is also air pollution due to the increase in chemical substances (from fertilizers, etc.). The increase in the frequency of wind erosion leads to an increase in dust emissions and suspended particulate pollution of the atmosphere [Xi and Sokolik, 2016; Yulevitch et al., 2020]. A suitable preventive measure to mitigate the risk of wind erosion in agricultural landscapes is the establishment and restoration of windbreaks.

In Europe, although wind erosion is not as large and severe a problem as in drier regions of the world, it can cause very significant economic and ecological damage locally [Riksen and De Graaff, 2001; Mezosi et al., 2015]. In the Czech Republic, where this study on windbreaks was carried out, approximately 25% of arable land is potentially at risk [Ministry of Agriculture, 2020]. This represents an area of more than 569 000 ha according to the LPIS database. The situation is all the more serious because the most fertile areas of the Czech Republic, which are intensively farmed and contribute significantly to food self-sufficiency and security, are particularly at risk from wind erosion. For this reason, the importance of wind erosion and the need to limit its negative impact on agricultural production will continue to grow.

Windbreaks, as the aforementioned preventive measures, have a number of other functions besides protecting agricultural land and the crops growing on it. In recent years, in addition to the soil-protective effect of windbreaks, attention has also been drawn to their influence on mitigating climate extremes, supporting the non-productive functions of the landscape and their affiliation to agroforestry systems. In addition to their ecological benefits, trees can also provide economic benefits for farmers, and specific plans for the use of wood mass should be taken into account when planning the planting itself. In the case of the Czech Republic, there is a relatively dense network of windbreaks, but they are often no longer functional because planting took place in the 1950s [Fukalová and Mašíček, 2018].

The structure of a windbreak is influenced by the number of rows in the windbreak, the spacing between trees, the density of foliage, and the branching structure, which is determined by the trees used to form the windbreak [Kuhns, 1998]. The height and porosity parameters of the windbreak can be used to define the windbreak structure. The porosity of windbrakes is usually distinguished as real (aerodynamic) and optical. Aerodynamic porosity is defined as the ratio between the average wind speed measured on the windward side of the windtree and the average speed on the open space [Litschmann et al., 2007; Guan et al., 2003; Vacek et al., 2018]. Optical porosity is taken as the fraction of the background visible from a perpendicular direction to the windbreak [Burke, 1998]. Determining the aerodynamic porosity is very difficult, so the optical porosity parameter is most commonly used [Vigiak et al., 2003]. Therefore, the optical porosity determined from photographs is more commonly used to assess the aerodynamic properties in a wind tunnel [Kenney, 1987; Guan et al., 2003; Litschmann et al., 2007].

The effect of windbreaks on reducing wind speed is reported to be in the range of 20–35 times its height on the leeward side [Heisler and Dewalle, 1988; Abel et al., 1997; Vézina, 2001; Vigiak et al., 2003; Brandle et al., 2004; Janeček et al., 2012]. The authors relate the reduction in windbreak efficiency to the value of optical porosity.

Evaluation of the effectiveness of windbreaks is essential for the establishment of protection zones. Windbreak effectiveness is defined as the ability of a particular windbreak to reduce the speed of erosion hazard winds. A windbreak protection zone is defined as a strip of land on both the windward and leeward side that is protected from the erosive effects of wind based on the effectiveness of the windbreak. The definition of the protection zones also contributes to the refinement of the potential vulnerability of the area to wind erosion. Four approaches to assessing the effectiveness of windbreaks have been published for the Czech Republic [Janeček et al., 2005; Podhrázská and Novotný, 2007; Podhrázská et al., 2008; Středová et al., 2012; Doležal et al., 2017; Řeháček et al., 2017 and Vacek et al., 2018]. Determining the optical porosity based on a thorough analysis of photographs taken in high quality is quite time consuming. Therefore, this assessment is currently already being innovated by the use of satellite images and UAVs. Using satellite images, vegetation indices (NDVI, SAVI, NDRE), biophysical parameters (Leaf Area Index, fAPAR) will be obtained and analyzed for the evaluated windbreaks. These results are not yet part of this study. This paper deals with the development of the automatic assessment of optical porosity and vitality of the structure from digital photography.

METHODOLOGY

The structure of a windbreak can be defined as the number and spatial distribution of tree parts (trunks, branches, leaves) and the free space between them. For this purpose, two parameters are very often used, which are the height of the windbreak (h) and the aerodynamic porosity. To express the aerodynamic porosity, the optical porosity (OP) is used in practical experiments and is defined as the ratio between the gaps in the windbreak to its total area [Vigiak et al., 2003] and is most often determined from photographs. In wind tunnel measurements with different wind tunnel models with optical porosity ranging from 0.016 to 0.389, it was found that the relationship between optical and aerodynamic porosity, see Equation 1, can be expressed as:

$$\alpha = \beta \times 0.4 \tag{1}$$

where: α optical porosity of windbreak, β aerodynamic porosity of windbreak.

Optical porosity can be determined in several ways. One of them is the assessment from a photograph of a representative part of the windbreak. When determining the optical porosity of individual windbreaks by the photogrammetric method, digital photographs taken perpendicular to the windbreak line are used.

In the first stage, the section to be assessed must be delineated, for which a series of photographic images will be taken. These are most often 30 – meter segments for selected windbreaks [Vacek et al., 2018; Khel et al., 2017]. In the case of uneven windbreaks (e.g., change in tree health, change in presence of shrub cover, etc.), the windbreak should be divided and the OP determined for each segment separately. The images are taken in good light visibility and care must be taken to ensure a 'clean' background of the windbreak without disturbing elements (buildings, terrain, vegetation, etc.). The focal length of the camera is set to a minimum of 35 mm, due to the distortion of the edges of the photographic image. For the acquisition of photographs, the methodological procedure from the certified methodologies of Podhrázská et al. [2011], Khel et al. [2017], Řeháček et al. [2017] and Vacek et al. [2018] was used. Current approaches [Podhrázská et al., 2011; Khel et al., 2017; Řeháček et al., 2017 and Vacek et al., 2018] offer time-consuming evaluation of spatial structure parameters. The novelty of this paper is the automation of the current procedure for the evaluation of the spatial structure of windbreaks by means of advanced image signal analysis (2D) and the subsequent use of machine learning for further classification of spatial structure parameters (optical porosity). The software for automatic evaluation of selected parameters of the spatial structure of windbreaks is developed within the project of the Technology Agency of the Czech Republic (TAČR) under the title "Advanced methods for evaluation and design of multifunctional windbreaks".

Research locality

As part of the research of the author's team, field activities related to the assessment of the spatial structure of windbreaks were focused on selected locations with an extensive network of windbreaks. For the purposes of this article, one representative location in southern Moravia near the village of Bulhary (Figure 1) was selected. The area of interest belongs to the warmest areas of South Moravia. According to the Quitt climate classification (for the period 1961–2000), the area belongs to the warm climate region. The average annual air temperature ranges from 9.1 to 10 °C and the average annual precipitation ranges from 501 to 550 mm [Voženílek and Květoň, 2011]. The average altitude is 170 m above sea level. In the location, activities were also focused on monitoring the internal spatial structure of the windbreaks in terms of leaf dynamics, from the beginning of leafing in the spring to full leafing. Four windbreaks were selected. All evaluations were carried out for segments of 30 meters in length (Figure 2). The break points of individual segments were surveyed and marked with wooden stakes. As part of the field monitoring, digital photographs of the selected segments were taken at intervals of approximately 10 to 14 days. The main goal of this thorough

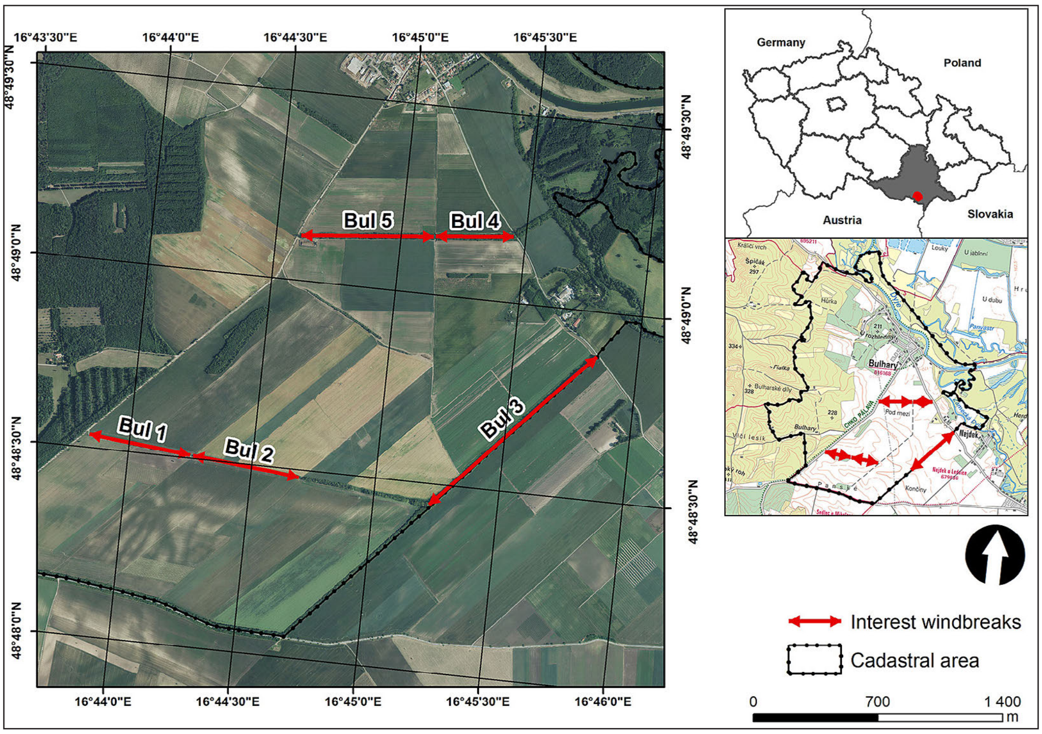


Figure 1. Overview map of the area of interest with marked windbreaks

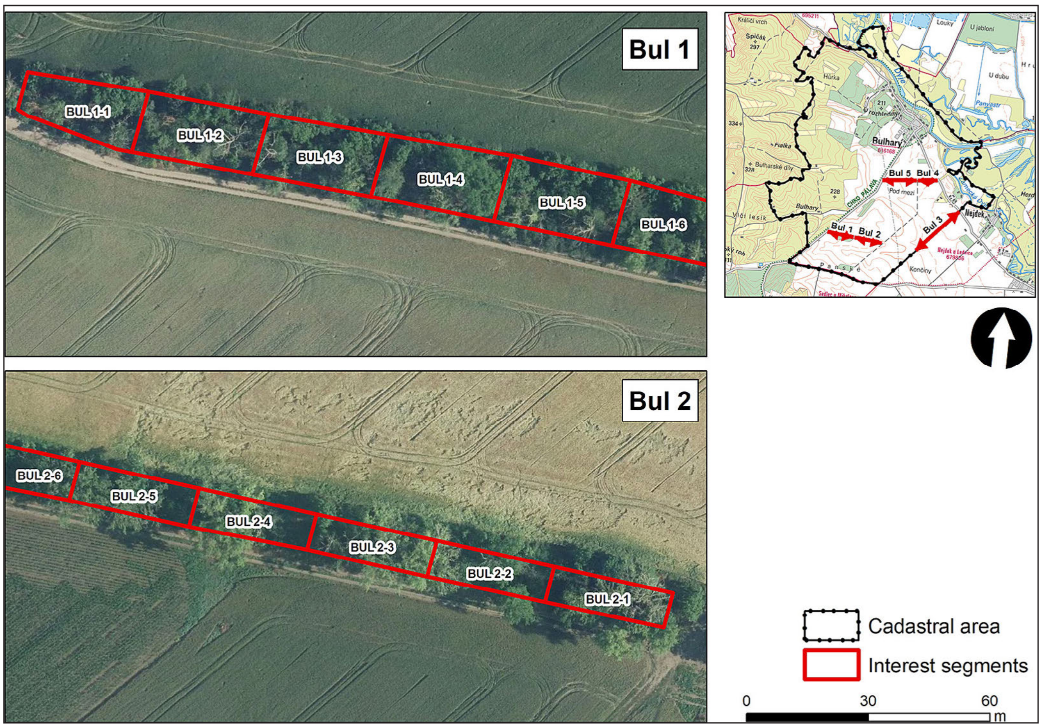


Figure 2. Example of marked segments for evaluation (individual segments are 30 meters long)

time monitoring was to obtain a wide range of data during the period of leaf growth dynamics. The outputs of this monitoring were used for the development of automated assessment of optical porosity of windbreaks. Data from the thorough monitoring were further used as validation data for a statistically more significant analysis regarding the evaluation of the spatial structure of windbreaks using satellite imagery (not the subject of this article).

RESULTS

Automated assessment of the spatial structure of windbreaks (optical porosity, height, shrub layer)

For the automatic evaluation of the spatial structure of windbreaks, software called Windbreak (beta version) has been developed. The software was created using the Matlab 2022b programming environment. Windbreak software enables the evaluation of optical porosity, including the assessment of canopy height (maximum, average, and contour-based). For the automatic evaluation of the spatial structure parameters of windbreaks, data from photographs of the selected windbreaks was collected and analyzed during the project. As mentioned, the basic input to the Windbreak program is digital photographs (RGB) of windbreak segments in.png or.tiff format. Each photograph contains information about the boundary and segment number in its name. This information is then used for segment identification/focus in the program. Since each segment has a clearly defined width of 30 meters, the height of the windbreak can also be derived. Advanced image processing methods, including adaptation, are used for image analysis. This leads to a significant improvement, refinement, and acceleration of the automated assessment of windbreak spatial structure (optical porosity, height, shrub layer) from 2D photographs using machine learning. Deep learning methods (convolutional neural networks of the image-to-image type, such as U-Net, for image segmentation and prediction of the desired windbreak parameters) have been utilized for automated assessment, providing very good results in various image processing applications.

The first part of the program allows for the management of all images contained in the selected folder, in which it is necessary to outline the boundaries of the evaluated segment and, if present, enter the height of the shrub layer using a second line. Figure 3 shows the program environment for delineating the area of interest and determining the height of the shrub layer. The program allows for the continuous saving of marked lines. Based on these lines, the image is cropped and rotated to a horizontal position according to the boundary line (green). The program allows for working with photographs at the original resolution, which is very computationally demanding. It is therefore possible to reduce the resolution to one of three levels, significantly reducing computational complexity and increasing program smoothness without an observed reduction in accuracy or quality of the achieved results.

After marking the areas of interest and making subsequent adjustments, the second part of the program can be initiated, which is associated with image segmentation. The goal is to

Figure 3. Example of the beta version environment of the Windbreak program with the indication of the area of interest (green line) and the determination of the shrub layer height (yellow line)

accurately distinguish between the background and windbreak vegetation. Automatic segmentation is available, based on clustering analysis of pixels in the RGB color space using the K-means algorithm, dividing the image into two clusters - background and windbreak. Additionally, interactive manual segmentation tools are available for further adjustments to the automatic segmentation. These segmentation tools allow for both global adjustments for the entire image and local adjustments focusing on specific parts of the image**.** Figure 5 shows a part of the program dedicated to segmentation. Furthermore, this part of the program enables fully automatic calculation and export of the resulting measured optical porosities and also offers local OP analysis. This includes displaying the profiles of local and cumulative values of optical porosities depending on the specific measured height of the windbreak (see Figure 4). These values are now also exported to an Excel file along with other results.

Sample outputs from the windbreak program

In Figure 6, an example of the input image (original photo) representing one of the segments

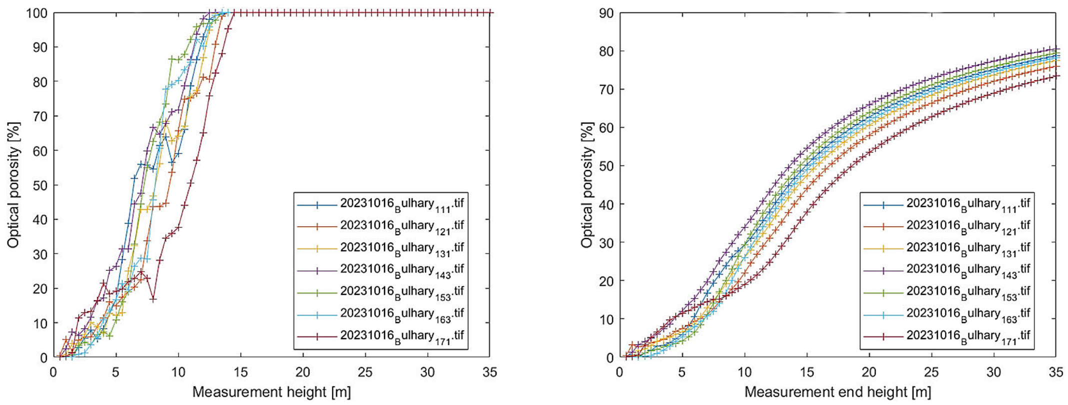
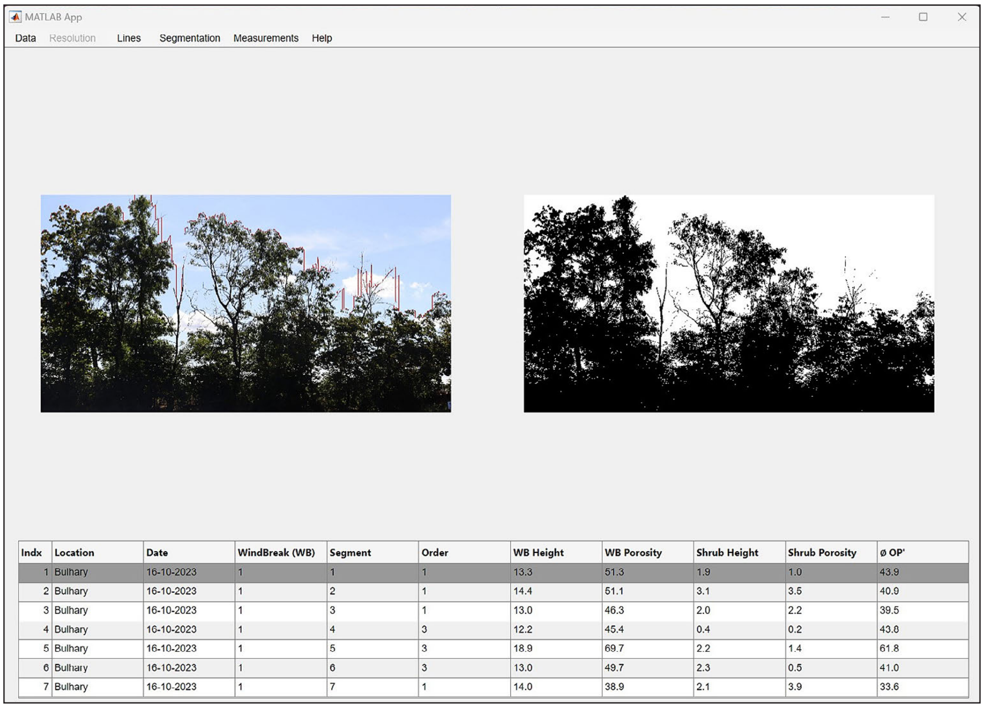


Figure 4. Example of the depiction of local (left) and cumulative (right) optical porosities as a function of the specific measured height of the windbreak



Indx	Location	Date	WindBreak (WB)	Segment	Order	WB Height	WB Porosity	Shrub Height	Shrub Porosity	ø OP'
1	Bulhary	16-10-2023	1	1	1	13.3	51.3	1.9	1.0	43.9
2	Bulhary	16-10-2023	1	2	1	14.4	51.1	3.1	3.5	40.9
3	Bulhary	16-10-2023	1	3	1	13.0	46.3	2.0	2.2	39.5
4	Bulhary	16-10-2023	1	4	3	12.2	45.4	0.4	0.2	43.8
5	Bulhary	16-10-2023	1	5	3	18.9	69.7	2.2	1.4	61.8
6	Bulhary	16-10-2023	1	6	3	13.0	49.7	2.3	0.5	41.0
7	Bulhary	16-10-2023	1	7	1	14.0	38.9	2.1	3.9	33.6

Figure 5. Example of the environment of the beta version of the Windbreak program with use of segmentation and measurement tools

Figure 6. Original photo of the evaluated section of the windbreak without foliage (input image into the program)

of the windbreak of interest (without foliage) with the designation Bul2 in the area of Bulhary was presented. Another, Figure 7, represents the output image after the segmentation of the input image. This is a black and white image, where white represents the background and black represents the windbreak itself. Based on the ratio of background vegetation, only OP was further determined. An example of the output file after evaluation using the Windbreak program is represented by Figure 8. The evaluation includes information on the location name, date of image acquisition, windbreak designation (WD), segment designation (seg), photograph order number, OP values, shrub layer height (porosity2), and OP and height of the vegetation with the shrub layer (porosity) and average OP (⌀OP), according to the methodology of Khel et al. [2017]. For each segment, the values of the opening height can be obtained for three windbreak heights: maximum height (OP max), average height (OP avg), and contour height (OP cont). The following, Figure 9, shows the values of OP cont for segments of the windbreak of interest, Bul2.

Figure 7. Original photo of the evaluated section of the windbreak after image segmentation without foliage (black colour = vegetation; white colour = background)

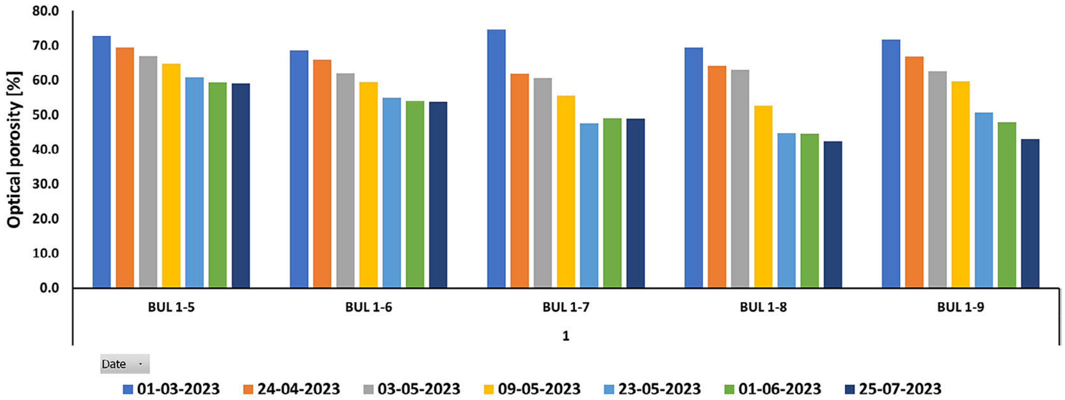


Figure 8. Example of the output table of the Windbreak program for the interest segment of the windbreak Bul 1 in terms of capturing the dynamics of leaf onset

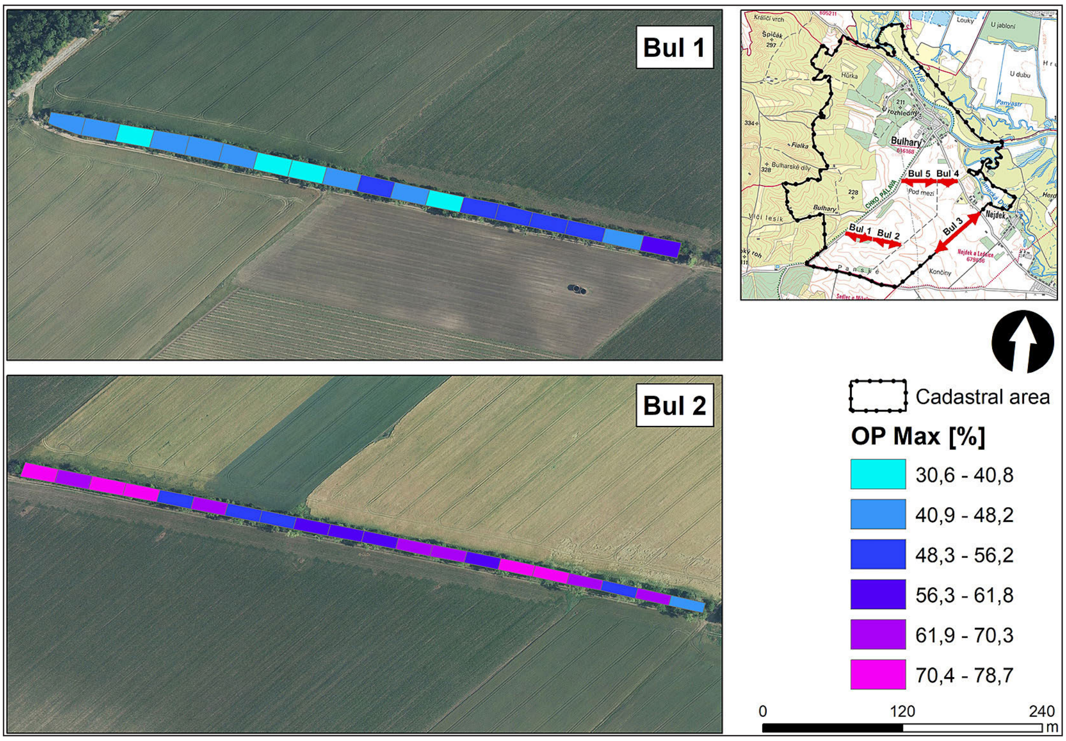


Figure 9. Example of an interest element in the area of Bulhary (Bul 2) with a marked evaluation of optical porosity, related to the height of vegetation, according to the maximum height of the evaluated element

Assessment of the effectiveness of windbreaks

The output from the Windbreak software can be further used as input values for determining the effectiveness of windbreaks in the form of protective zones. Evaluating the effectiveness of windbreaks is significant for a more precise determination of the potential risk of wind erosion in an area. The relationship between optical porosity (OP) and wind speed reduction on the leeward side shows a relatively strong correlation. This relationship is tightest at a distance of 50 meters behind the windbreak. With increasing distance, this relationship decreases as other influences on air flow prevail. With full foliage in the summer months (OP 10%), wind speeds at a distance of 50 meters can decrease to 40% of the value before the windbreak, and at a distance of 150 meters, it is around 70%. For non-foliaged windbreaks, these numbers increase to approximately 80% and 90%. The reduction effects of the windbreak on the windward side are significantly lower. Regardless of OP, the distance within which the windbreak effectively reduces wind speed on the leeward side was a maximum of 250 meters (i.e. approximately 10–17 times the average height of the windbreak). This approach is based on a combined regression equation incorporated into the methodology of Doležal et al. [2017], which derives the protective zones of the windbreak based on the relationship between optical porosity and wind speed reduction on the leeward and windward sides. The parameter of windbreak height is not an input parameter for the equation, as, similar to the previous case, it is assumed to be an optimal windbreak with spatial and species composition and an average height of 15 meters.

To determine the effectiveness of windbreaks and their protective zones, an equation can be used that combines the value of optical porosity and the height of the windbreak [Řeháček et al., 2017]. The equation, derived from data from ambulatory wind speed measurements, gives the ratio of wind speed reduction on the leeward side of the windbreak compared to the wind speed on the windward side. Approaches to determining the protective zones of windbreaks are compared by Kučera et al. [2020]. The methods of Podhrázská et al. [2008] and Středová et al. [2012] yielded similar values for protective zones, while the method of Řeháček et al. [2017] identified their extent as up to 40% lower.

CONCLUSIONS

This paper deals with the newly developed Windbreak Software, which enables the evaluation of the optical porosity of windbreaks, including assessment of canopy height (maximum, average, and contour-based). Data from photographs of selected windbreaks was analyzed for the automatic evaluation of the parameters of the spatial structure of the windbreaks. The basic input to this software is digital photographs of windbreaks segments in.png or.tiff format. The program enables fully automatic calculation and export of the resulting measured optical porosities and offers local OP analysis. This includes displaying profiles of local and cumulative values of optical porosities depending on the specific measured height of the windbreak. The output from the software can further be used as input values to determine the effectiveness of windbreaks in the form of protective zones. The evaluation of the effectiveness of windbreaks is important for a more accurate determination of the potential risk of wind erosion in the area. The relationship between optical porosity (OP) and wind speed reduction on the leeward side shows a fairly strong correlation. This relationship is closest at a distance of 50 meters behind the windbreak. With increasing distance, this relationship decreases because other influences on air flow prevail. With full foliage in the summer months (OP 10%), the wind speed at a distance of 50 meters can drop to 40% of the value in front of the windbreak, and at a distance of 150 meters, it is around 70%. For unfoliated windbreaks, these numbers increase to 90%. The developed software will be further automated using machine learning tools. It will include fully automatic windbreak segmentation focusing on distinguishing complex structures, particularly differentiating vegetation and ground in the background from the windbreak itself. Furthermore, it will be possible to process input photos in batches, where the input will be a selected folder of photos and the output will be automatically analyzed data.

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