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Effect of Windbreaks on Wind Speed Reduction and Soil Protection against Wind Erosion

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Abstract

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Windbreaks form efficient soil protection against wind erosion particularly at the time when soil cover is not protected by the cultivated plant vegetation cover. The objective of this research was to evaluate windbreaks efficiency in terms of wind speed reduction. Wind speed along the windbreaks was measured in the cadastral areas of Dobrovíz and Středokluky (Czech Republic, Central Europe). The measurement was carried out by 4 stations placed at windward side (1 station at the distance of 3 times the height of the windbreak) and at leeward side of the windbreak (3 stations at the distance of 3, 6, and 9 times the height of the windbreak). Each station contained 2 anemometers situated 0.5 and 1 m above surface. The character of windbreak was described by terrestrial photogrammetry method as the value of optical porosity from the photo documentation of the windbreak at the time of field measurement. A significant dependence between the value of optical porosity and efficiency of windbreak emerged from the results. The correlation coefficient between optical porosity and wind speed reduction was in the range of 0.842 to 0.936 (statistical significance more than 95%). A significant effect of windbreak on airflow reduction was proven on the leeward side of windbreak in a belt corresponding to approximately six times the height of the windbreaks depending on the optical porosity and it was expressed by a polynomial equation.

Keywords: airflow; anemometer; field measurement; optical porosity; soil conservation

Wind erosion is a dynamic process when soil particles are detached and relocated by erosive forces of wind. Wind erosion starts at the time when wind forces exceed the threshold value of soil resistance to erosion. The speed and extent of this type of erosion are influenced by geological, climatic, and anthropogenic factors (van Pelt *et al.* 2010). This process is the result of the whole complex of interactions of wind speed, rainfall, surface roughness, soil texture, soil aggregation, soil moisture, agricultural activities, vegetation cover, the plot area (Janeček *et al.* 2012) as well as freezing and thawing cycles or freeze drying during winter seasons (Středová *et al.* 2015).

One of the ways how to permanently prevent soil loss removal is to reduce wind speed and the intensity of wind erosion by windbreaks (Santiago *et al.* 2007). In dry areas, suitably distributed windbreaks on 5% of the area can reduce wind speed by 30–50% and soil losses even by 80% (Bird *et al.* 1992). However, optimal distribution and composition of windbreaks is a very complicated process not clearly described so far (Středa *et al.* 2008).

As a windbreak we consider any woody vegetation of linear character, which protects soil against erosion and affects not only erosion processes, but also micro climate of the close surroundings – temperature, soil moisture, evapotranspiration, soil temperature, etc. (Vigiak *et al.* 2003). The ability of windbreak to fulfill its function in landscape is given by its external and internal structure. The external structure is defined by width, height, shape, and orientation. The internal structure is given by the amount and arrangement of branches, leaves, and trees or shrubs trunks (Brandle *et al.* 2004).

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Permeability of windbreaks is generally defined based on their porosity. Windbreaks are classified into: wind porous (porosity ca. 60%), medium-porous, and non-porous (porosity ca. 20%) (Abel *et al.* 1997; Janeček *et al.* 2012). Windbreak structure is affected by the number of tree rows, distance between woody plants, foliage density, and structure of branching, which is established by the woody plants used when creating the windbreak and their management (Kuhns 2012). The parameters of height and porosity of windbreak can be used to define the windbreak structure (Podhrázská & Novotný 2007). The porosity of windbreaks 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 windbreak and the average speed in open space (Guan *et al.* 2003). Optical porosity (*OP*) is considered to be the ratio of the background which is visible from the vertical direction to the windbreak (Burke 1998). Due to the fact that aerodynamic porosity is very difficult to define, the parameter of *OP* is mostly used (Vigiak *et al.* 2003). For the evaluation of windbreak efficiency, *OP* is determined by using the photogrammetry method (Kenney 1987; Tamang *et al.* 2012; Lampartová *et al.* 2015).

According to Heisler and DeWalle (1988), windbreaks of low and medium porosity have significantly higher efficiency in comparison with windbreaks of higher porosity. Windbreaks of low porosity have more frequent occurrences of turbulent flow with higher wind speed on the leeward side than windbreaks with medium porosity (Cornelis *et al.* 2000). Brandle *et al.* (2004) found out that if windbreak reduces wind speed to one half, drag force of the wind is one eighth of the original value. According to Cornelis and Gabriels (2005), optimal *OP* value is 20–35%, similarly Santiago *et al.* (2007) set the optimal value at 35%.

Many authors relate the reduction of windbreak efficiency to the value of *OP*. The effect of windbreaks on wind speed reduction is stated in the range of 20 to 35 H (H – height of the windbreak) on the leeward side (Heisler & DeWalle 1988; Abel *et al.* 1997; Vigiak *et al.* 2003; Brandle *et al.* 2004; Janeček *et al.* 2012). According to Wu *et al.* (2013) the effect of windbreaks is up to the distance of 10 H; at a farther distance the efficiency of windbreaks was not proven. Torita and Satou (2007) defined the shelter distance as a parameter called d70 which is within the distance $U/U_0 < 0.7$ (U_0 – windward speed, U – leeward speed). According to field measurements the d70 distance was ascertained up to 20 H. Thuyet *et al.* (2014) found out the d70 distance of 8–16.5 H depending on windbreaks structures. However, Středa *et al.* (2008) did not confirm the dependence of optical porosity on windbreak height.

This study investigates the relation between the optical porosity of windbreaks and their efficiency of wind speed reduction on the leeward side. The purpose of the present paper is to find out a protective zone (buffer zone) against wind erosion along different types of windbreaks in various phenological phases expressed by the value of optical porosity.

MATERIAL AND METHODS

Windbreak efficiency was analyzed for windbreaks in the cadastral area of Dobrovíz (50°06'26.98"N; 014°13'47.43"E) and Středokluky (50°07'11.26"N; 014°13'48.97"E) in the Czech Republic. The windbreak at Dobrovíz consists of 3–4 rows of trees of an average height of 16 m, width 19 m, and about 2.5 m high shrubs. It is composed of *Quercus petraea* (60%), *Acer pseudoplatanus* (20%), *Acer campestre* (10%), *Platanus × acerifolia*. The shrub layer consists of *Sambucus nigra* and *Symphoricarpos albus.*

The windbreak at Středokluky is created by 2–3 rows of trees of an average height of 11 m, width 9 m, height of shrubs about 2 m. It is composed of the following woody plants: *Quercus petraea* (70), *Acer pseudoplatanus* (20%), *Platanus × acerifolia* (a mixture), *Tilia platyphyllos*. The shrub layer consists of *Rosa canina*, *Crataegus laevigata*, *Sambucus nigra* L., *Euonymus verrucosus*, and *Juglans regia.*

Both these windbreaks are in a good health condition. The windbreaks are located in flat agricultural lands. The land management is under standard tillage and the main plants are cereal species.

The field measurement of the windbreak efficiency was carried out by stationary anemometric stations. Currently optical porosity was evaluated from the photographs taken during the measurement.

The field measurement of the windbreak efficiency was performed during favourable meteorological conditions, i.e. at vertical direction of wind to the windbreak. Wind speed was measured by anemometers Vantage Pro 2 (Davis Instruments Corp., Hayward, USA). The extent of measurement stated by the producer is from 0.5 to 89 m/s with the accuracy of ± 1 m/s or ± 5%. The anemometers were interconnected with a device WIND DATALOGER (AP-EL

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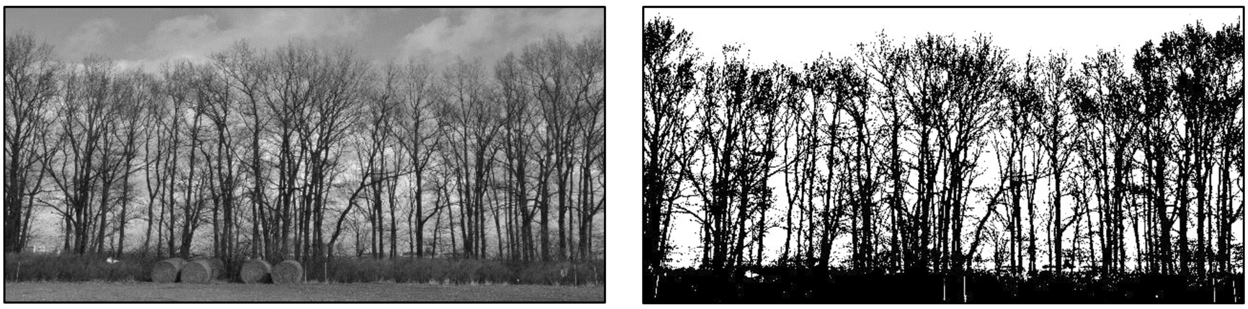
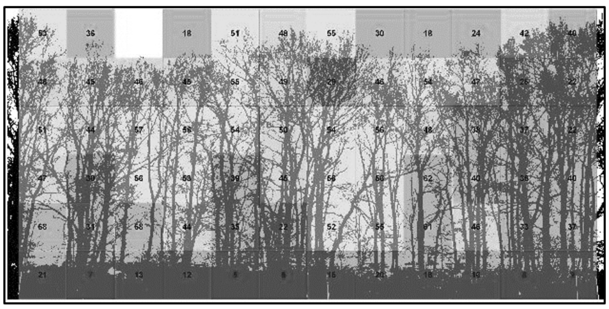
Applied Electronics, Český Brod, Czech Republic), which serves the purpose of data collection and communication with the computer. The anemometers were attached to a steel rod 0.5 m and 1 m above the soil surface, alternatively above the plant cover. On the windward side, one measuring station was placed at the distance of 3 H and on the leeward side three measuring stations were placed at the distance of 3, 6, and 9 H.

Optical porosity was determined on the basis of photographs taken by a digital camera Nikon D5100 (Nikon Corporation, Tokyo, Japan). A 30-meter-long representative section was depicted in the windbreak by stakes. The photos of the marked out part were taken during the measurement both on the windward and the leeward side of the windbreak, always in the vertical axis to it. The photos were taken from the tripod at the height of 1.6 m. The following programs were used to evaluate optical porosity: GIMP (Version 2.8.2), ArcGIS for Desktop (ArcMap 10.2), and MS Excel 2013. Firstly, the photos were processed in the graphical software GIMP. Depending on accessible tools, a graphical modification of the photography (highlighting of the vegetation cover from the background) was carried out in order to create a binary picture. This conversion was very important for the cover determination and the background of the windbreak (black grid = cover, white grid = background). These modified photographs were analyzed in the ArcGIS. A square grid of 6–7 rows and 12 columns was used for the analysis of the binary picture. For the lower row of windbreaks, the dimension of one square of the grid was 2.5 × 2.5 m (Figure 1). For the analysis of the upper row of windbreaks, a more detailed grid was used – each square sizing 2.5 × 2.5 m was further divided into 16 smaller squares. A more detailed method for the upper row was used to increase the accuracy of total optical porosity determination, where the height of windbreak in each column of evaluation was taken into account. The squares in the highest row with optical porosity of 100% were not included into determination of the total optical porosity and did not affect the value of total optical porosity of windbreak.

The field measurements were recorded for a period of at least 2 h (depending on favourable wind speed and direction) at 10 s intervals. However, the data was assessed at 5-minute intervals, primarily the average wind speed was taken into consideration. Each 5-minute interval of the average wind speed on the windward side was compared with the values of average wind speed on the leeward side. Thus, it was possible to present the wind speed reduction on the leeward side. Statistical evaluation (correlation) of the relationship between wind speed and optical porosity was performed using MS Excel program as well as the correlation between the anemometers position 0.5 and 1 m above the surface. The wind speed reduction was taken into consideration as a multiple quadratic regression of optical porosity and the distance from





53	36		18	51	48	55	30	18	24	42	40	38
48	45	46	45	55	49	29	46	54	47	26	22	43
51	44	57	56	54	50	54	56	48	38	37	22	47
47	30	56	53	39	45	56	56	62	40	36	40	47
68	31	68	44	35	22	52	55	61	46	33	37	46
21	7	13	12	5	5	15	20	18	16	8	9	12
48	**32**	**48**	**38**	**40**	**36**	**44**	**44**	**43**	**35**	**30**	**29**	**39**

Figure 1. Example of photograph modification and evaluation of optical porosity (in %)

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the windbreaks. The calculation was done for the input data of both 0.5 and 1 m. The equation was calculated by STATISTICA software (Version 10.2).

Four measurements were performed at the Dobrovíz windbreak in different phenological phases of woody plants with the corresponding value of optical porosity (*OP* in %) on these dates: 9th May (23%), 22nd September (12%), 14th January (12%), and the 1st April (41%). Five measurements were realized at the Středokluky windbreak: 25th September (17%), 4th April (53%), 22nd October (18%), 9th November (25%), and 18th November (46%).

RESULTS AND DISCUSSION

The average wind speed values and wind speed standard deviations of the field measurement from the entire record are stated in Table 1.

Figures 2 and 3 show the wind speed reduction on the leeward side at Středokluky. The highest efficiency

Table 1. Field measurements data

Measurement	Optical porosity (%)	Wind speed (m/s)	Anemometer position/stand position (m above surface)							
			0.5				1			
			W	L			W	L		
			3 H	3 H	6 H	9 H	3 H	3 H	6 H	9 H
Dobrovíz										
		average	3.9	1.0	1.0	2.2	3.5	1.3	1.6	2.4
9/5/2014	23	SD	0.62	0.01	0.01	0.39	0.44	0.23	0.30	0.71
		highest*	5.1	1.1	1.1	3.0	4.4	1.8	2.1	3.7
		average	4.5	1.3	1.6	NA	3.4	1.1	1.7	NA
22/9/2014	12	SD	0.38	0.17	0.35	NA	0.28	0.07	0.38	NA
		highest*	5.5	1.7	2.6	NA	4.0	1.3	2.8	NA
		average	4.4	2.0	2.3	2.5	3.8	1.7	2.3	3.0
14/1/2015	37	SD	0.80	0.49	0.73	0.60	0.46	0.41	0.64	0.69
		highest*	6.3	2.9	3.3	3.4	4.6	2.3	3.1	3.8
		average	6.1	2.5	2.7	5.3	6.6	3.3	4.1	5.6
1/4/2015	41	SD	0.88	0.74	0.50	0.82	0.89	0.75	0.50	0.89
		highest*	9.2	4.6	3.5	7.2	9.5	4.8	4.1	7.2
Středokluky										
		average	3.3	1.1	1.2	1.4	2.5	1.0	1.1	1.6
25/9/2014	17	SD	0.42	0.15	0.12	0.21	0.28	0.03	0.09	0.33
		highest*	4.3	1.5	1.4	1.9	3.0	1.1	1.3	2.5
		average	3.9	2.5	3.2	4.2	4.4	2.8	3.7	4.7
4/3/2015	53	SD	0.38	0.37	0.50	0.52	0.59	0.35	0.46	0.60
		highest*	4.8	2.6	4.6	5.5	5.6	3.0	4.8	6.1
		average	2.8	1.0	1.0	1.2	3.0	1.0	1.0	1.2
22/10/2015	18	SD	0.33	0.00	0.01	0.16	0.30	0.00	0.26	0.15
		highest*	3.7	1.0	1.1	1.6	3.6	1.0	1.1	2.1
		average	4.0	1.1	2.2	NA	4.2	1.3	2.7	NA
9/11/2015	35	SD	0.36	0.10	0.28	NA	0.30	0.08	0.33	NA
		highest*	4.4	1.3	2.7	NA	4.6	1.5	3.4	NA
		average	5.8	3.0	4.1	6.0	6.4	3.8	5.4	6.0
18/11/2015	46	SD	0.73	0.47	0.37	0.57	0.68	0.56	0.48	0.62
		highest*	6.9	4.0	4.7	6.8	7.3	4.8	6.2	7.2

NA – data not available (complete data is not available due to failure of the sensor); SD – standard deviation; W – windward side; L – leeward side; 3 H, 6 H, 9 H – distance from the windbreak to the stand position in 3, 6, 9 times the height of the windbreak; *the highest wind speed in 5-minute intervals

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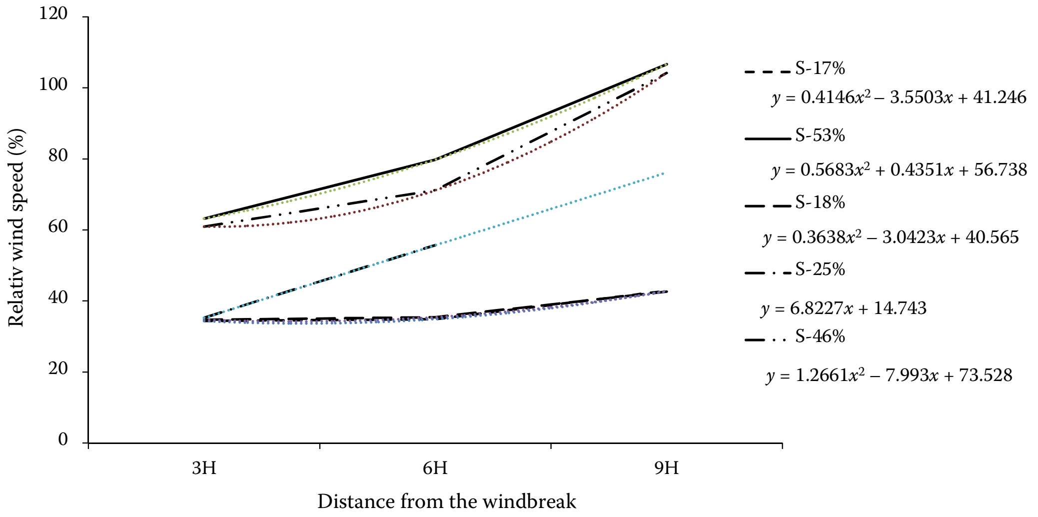

Figure 2. Wind speed reduction at Středokluky 0.5 m above the surface (in %) and the polynomial trend lines, regression equations, coefficient of determination = 1 for all values; in caption: S – Středokluky then value of optical porosity

of windbreak was manifested at the lowest values of *OP* 17 and 18%. The correspondence of measurement is evident for *OP* values of 17 and 18%, as both curves of wind speed have a practically similar progress in position 0.5 m above the surface. On the contrary, the lowest wind speed reduction was at *OP* values 46 and 53%. No evident wind speed reduction was found at *OP* 53% at the distance 9 H; by contrast wind speed was higher there than on the windward side. Středa *et al.* (2008) came to the same conclusion.

Figures 4 and 5 present a direct proportion of wind speed reduction to *OP* and distance. It is apparent for the values of *OP* 23, 37, and 41%. Thus, the highest efficiency of windbreaks was found for *OP* 23% and the lowest for *OP* 41%. The efficiency for *OP* 12% is balanced around the value of 23%. The data of *OP* 12% could not be assessed at the distance of 9 H due to failure of the sensor. Wind speed reduction was found higher for lower values of *OP* (37 and 41%), the effect could be explained by higher wind speed during measuring of *OP* 41%. The statement could not be compared with other data because there was no measurement for the same value of *OP* and a significant difference in wind speed.

The presented results show that for the *OP* values up to 25%, the wind speed reduction ranges between

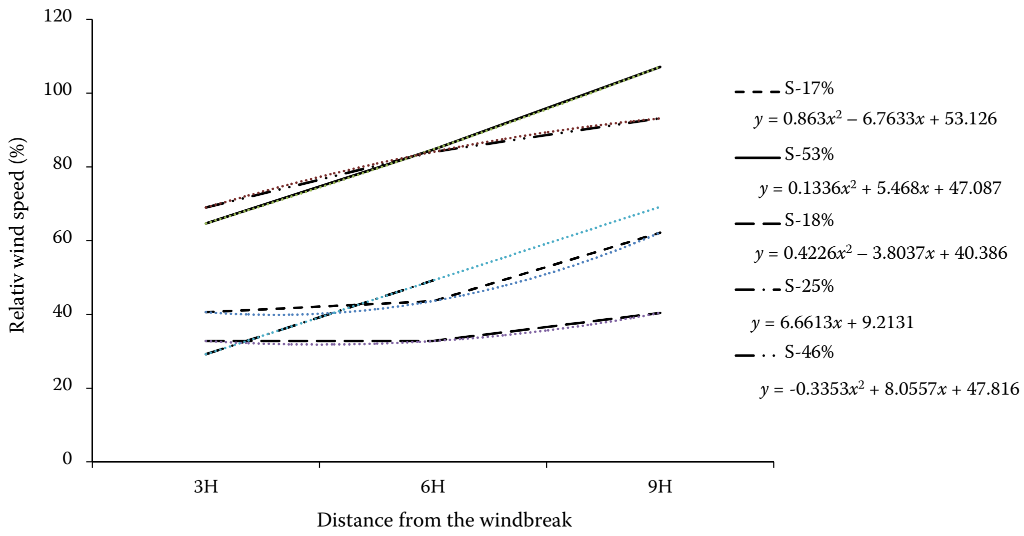

Figure 3. Wind speed reduction at Středokluky 1 m above the surface (in %) and the polynomial trend lines, regression equations, coefficient of determination = 1 for all values; in caption: S – Středokluky then value of optical porosity

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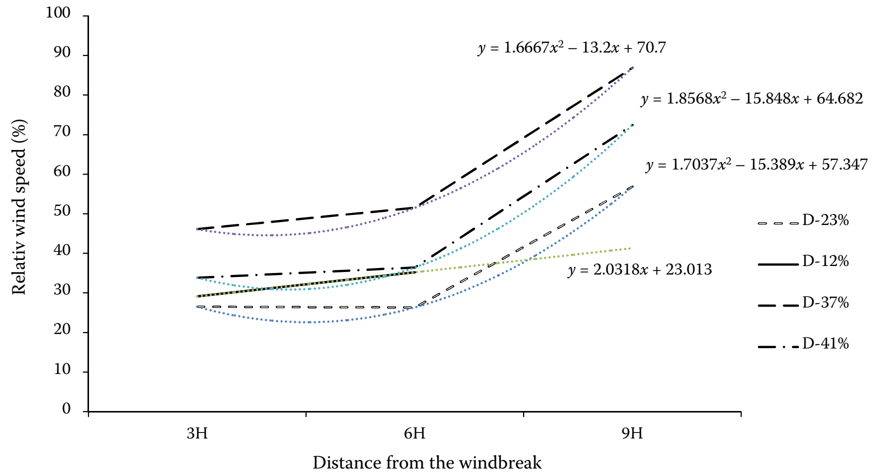

Figure 4. Wind speed reduction at Dobrovíz 0.5 above the surface (in %) and the polynomial trend lines, regression equations, coefficient of determination = 1 for all values; in caption: D – Dobrovíz then value of optical porosity

25 and 50% on the leeward side at the distance 3 H and 6 H. Cornelis and Gabriels (2005) and Santiago *et al.* (2007) stated that to reach the maximal wind speed reduction, the *OP* value should be 20–35%. Based on our measurements we may state that the values lower than 20% (18, 17, and 12%) may be considered as optimal *OP* values. On the contrary, our terrain measurements showed that the windbreak protective impact is not expressed at *OP* 53% at the distance of 9 H, which is in contrast to the findings of Vigiak *et al.* (2003) and Brandle *et al.* (2004) and starting from the value of *OP* 41% the impact has not been proven.

The measurement of wind speed at heights 0.5 and 1 m above the surface and/or vegetation cover did not show any statistically important relationship. Wind speed measurement at different heights should have shown the lowest wind speed on the ground and with the rising height the speed should have been increasing similarly to the progress of parabolic function. However, the established correlation coefficient 0.036 for the anemometers at the evaluated heights did not prove this dependence.

The correlation coefficient ranges between 0.842 and 0.936 (Table 2), which corresponds with the findings of Heisler and DeWalle (1988).

Equation (1) presents the relationship between wind speed reduction, *OP*, and distance from windbreak with the coefficient of determination R^2 = 0.8599:

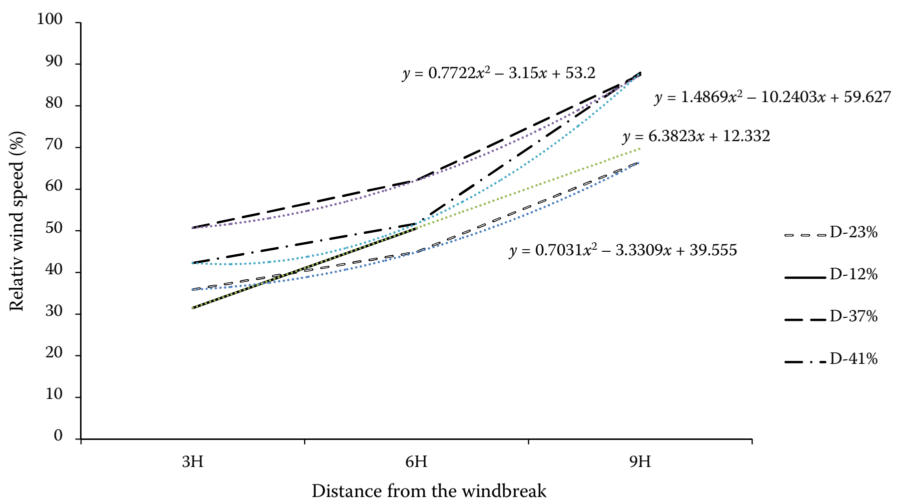

Figure 5. Wind speed reduction in Dobrovíz 1 m above the surface (in %) and their polynomial trend lines, regression equations, coefficient of determination = 1 for all value; in caption: D – Dobrovíz then value of optical porosity

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Table 2. Correlation between the optical porosity and the reduced wind speed

	Anemometer position (leeward side) (m above surface)					
	0.5			1		
	3 H	6 H	9 H	3 H	6 H	9 H
Measurements	9	9	7	9	9	7
Correlation coefficient	0.899	0.842	0.936	0.922	0.869	0.934
P-value	0.006364	0.01754	0.0006149	0.00293	0.00376	0.001403

H – height of the windbreak

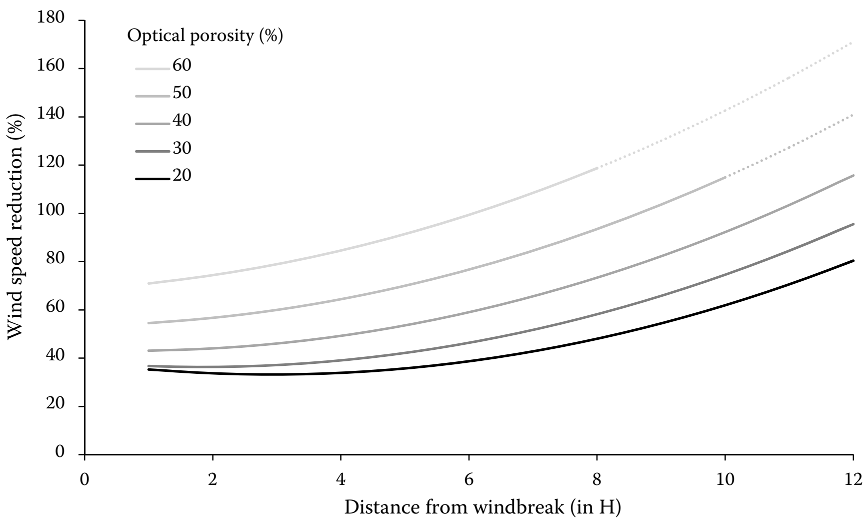

Figure 6. Wind speed reduction according to the designed equation

$$U = 52.80619 - 1.23901OP - 5.80657D + 0.12503OPD + 0.56948D^2 + 0.02507OP^2$$

U – wind speed reduction on the leeward side (%)
OP – optical porosity (%)
D – distance from windbreak in multiple of windbreak height (H)

It is to note that Středová *et al.* (2012) arrived to the same equation, however they calculated with the distance from windbreak in meters with no relation to windbreak height.

CONCLUSION

The protective zone responds to the highest wind speed reduction which was recorded at the distances up to 6 H on the leeward side. No evident wind speed reduction was found for the high value of *OP* (53%) at the distance 9 H on the leeward side. The direct correlation between the *OP* and the efficiency of windbreaks was found with the coefficient of ca. 0.9. Therefore the windbreak with four rows of trees was more effective mainly in erosion risk season. The windbreak efficiency increases with foliage, however it is during the period when the agricultural land is protected by crop.

The above equation enables us to calculate wind speed reduction at leeward side position in dependence on distance multiple heights of windbreak and optical porosity. Figure 6 shows the courses of wind speed reduction calculated from the equation for *OP* value of 20, 30, 40, 50, and 60%. It could be used to determine the protective zone of windbreak on the basis of *OP* value. The value of wind speed reduction above 100% cannot be taken into consideration because wind speed at leeward side higher than at windward side is not supposed.

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