Aerodynamic parameters of windbreak based on its optical porosity

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Abstract: The paper summarizes the results of wind velocity measurement in different distances from windbreak in combination with optical porosity (OP) determination in different periods. Experimental data were obtained by direct measurement of wind speed and OP analyses of images of four windbreaks in Southern Moravia (part of Czech Republic). Wind speed at 2 m above the soil surface in a defined distance from windbreak had been measured since 2006. Thirty images of different phenological stages of selected windbreaks from 2006 to 2010 were analyzed. Windward or leeward images were converted into black and white spectrum. All available measurements were used for a map creation. The highest values of OP (up to 50%) are achieved in non-vegetation period. Due to the high OP variability in height of terminal tree branches "OP reduced" was also assessed (just squares to 2/3 height of windbreaks were evaluated). The wind speed reduction on the leeward side relatively strongly correlated with OP value. The highest correlation was found out when the wind speed measurement at 50 m on leeward side was used. The dependence decreases with increasing distance. Full foliage in summer (10% OP) reduces a wind speed about 60% at 50 m and about 30% at 150 m on the leeward. These values for non-foliaged windbreaks decrease to 80 and 90%. Maximum distance of windbreak effect on wind speed reduction was found out by the extrapolation of the curves constructed using the regression equation of wind speed reduction in dependence on OP and different distances from the windbreak. Regardless of OP value, the reduction effect disappears at a distance of 250 m. The quietest zone of evaluated windbreak with an average height of windbreaks 15–18 m was detected in the area about four times the height (4H). The effect of windbreaks decreases with increasing porosity.

Key words: optical porosity, windbreak, wind speed

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1. Introduction

Windbreaks have been used for many years to reduce wind speed as a wind–erosion control measure. However, it is still not clear what should be an optimal design for windbreaks. Aerodynamics and erosion control parameters of windbreaks are variable regarding to wood species, density and rows number. On the basis of windbreak testing (each with different stem and canopy porosity and number of rows) on their efficiency in wind–speed reduction, conclusions given below were found out. Evenly distributed porosity of stem and canopy resulted in the longest protected area. Dense lower parts were more efficient than more porous lower parts. Erosion was almost not observed in the case of a barrier with evenly distributed porosity. The absence of a dense lower part resulted in an excessive zone of erosion behind the barrier (*Cornelis et al., 2000*). In term of permeability and efficiency windbreaks are classified into wind porous, wind medium porous and non–porous (*Abel et al., 1997*). Windbreaks alter horizontal wind speed, turbulence and vortex airflow. Height and porosity of windbreaks are two major controls on these airflows and both are amenable to design and management (*Forman, 1995*).

Actual shape of wind speed curve depends mainly on height and porosity of windbreak and additionally on other important characteristics of airflow × windbreak system (i.e. on characteristics of incoming flow such as wind speed, wind direction, turbulence intensity and atmospheric stability and on external characteristics of the windbreaks, such as windbreaks shape, width and length (*Vigiak et al., 2003*). Significantly variable aerodynamic properties of deciduous trees during the year must be taken into account.

The aerodynamic porosity of the windbreak determines the ratio between airflow that passes through the barrier pores ("through–flow") and airflow that diverges over the barrier ("diverged–flow"). It is impractical, at least throughout the landscape, to physically measure the aerodynamic porosity of natural tree windbreaks (*Loeffler et al., 1992*).

The impact of individual windbreaks on air flow in its vicinity (in the vertical and horizontal profiles) can be described by the methods that allow simple expression of windbreak aerodynamic properties during the year. An analysis of optical porosity (OP) of the windbreak allows assessing its effect in different phenological phases.

The method is based on computer analysis of digital images and windbreaks. OP is defined as the ratio between the gaps in windbreaks to its total area (*Guan et al., 2003*). OP is expressed as a remainder to value 1 or in percents as a remainder to 100 percent. Decreasing OP means increased windbreak efficiency and its protective function. An impact of OP in different contexts was quantified by *Fu et al. (1992), Loeffler et al. (1992), Groß (1993), Jiang et al. (1994), Zhu et al. (2003).*

Most papers referring to OP method do not contain its exact description but just a general information. For example according to *Sudmeyer and Scott (2002)* the OP is a ratio of the windbreak area trough which the sky is visible in frontal view to the total windbreak area. The individual sections were assessed by planimeter from contrasting black and white photographs. The main disadvantage of this method is a conversion and reduction of 3D space to 2D space (*Loeffler et al., 1992*).

Procedure for OP determination applicable to our conditions was published by *Litschmann and Rožnovský (2005)*. They described the detailed assessments of OP for each vertical layer of windbreaks to define OP changes with height. *Litschmann et al. (2007)* described OP assessment in vertical and horizontal direction. In this case, the windbreak area was covered by grid-network and OP was determined for each square. This concept was then used with some modifications by *Mužíková and Jareš (2010)* and *Mužíková et al. (2010).*

Wan et al. (2005) found out a significant correlation between windbreak porosity, number of rows and row spacing. *Forman (1995)* presents that highly porous windbreak, such as a row of planted poplars (*Populus*) decreases wind speed only minimally, but it has the advantage of also minimizing turbulence. Furthermore a highly porous windbreak provides a relatively long distance of reduced airflow downwind, although wind speed is only slightly slower than wind in the open. Low-porosity windbreak produces a short downwind zone of highly diminished wind speed and high levels of turbulence. Medium-porous windbreak has the wind speed reduction nearly as great as the impenetrable barrier.

In frame of field measurements *Grant and Nickling (1998)* evaluated a vegetation drag coefficient to optimal management of windbreak and its function modeling. They found out the highest vegetation drag coefficient when optical porosity was about 20% and volume porosity about 50%.

Decreasing porosity below 20% does not further increase the extent of shelter. Several wind tunnel trials indicate that the optimal extent of shelter is provided by windbreaks with 20% porosity (*Burke, 1998*). *Ian et al. (2009)* determined for practical uses that porosity did determine wind speed and the degree of shelter is roughly similar to windbreak density i.e. a windbreak with 30% porosity would reduce wind speed to 70% of the open-field speed at the most sheltered location.

The paper summarizes the results of wind velocity measurement in different distances from windbreak in combination with OP determination in different periods. The procedure is suitable for relatively rapid assessment of the windbreak efficiency. It can be applied in erosion control measures realization in frame of land adjustment or for revitalizing of existing windbreaks. The obtained results could be successfully used in landscape and urban planning.

2. Materials and methods

Experimental windbreaks:

Experimental data were obtained by direct measurement of wind speed and OP analyses of images of four windbreaks in southern Moravia: municipalities of Micmanice (MC), Suchá Loz (SL), Dolní Dunajovice (DD) and the Blatnice pod Svatým Antonínkem (BS). Windbreaks in Moravian countryside were planted in the fifties to sixties in 20th century with subsequent insufficient maintenance and management. Main woods are mostly *Populus × euroamericana* and *Fraxinus excelsior* L. Additional trees are mostly *Tilia cordata* Mill. and *Acer negundo* L. Height of individual windbreaks varies from 12 to 25 meters, width from 12 to 20 m. Surrounding of windbreaks is used for intensive agricultural cultivation. The windbreaks are described in detail by *Litschmann et al. (2007)*.

Measurement of wind speed:

Wind speed at 2 m above the soil surface in a defined distance from windbreak has been measured since 2006. The wind speed and direction were measured by anemometers type W1 (TM Prague) and W2 (TM Prague). Anemometers were regularly calibrated in the Czech Hydrometeorological

Institute (CHMI) laboratory. Six anemometer sets measured at the distances of 150 and 50 meters from the windbreaks on the windward side and at 50, 100, 150 and 200 m on leeward side. The measurements were realized when wind was blowing perpendicular to the windbreaks and average wind speed exceeded 2 m.s^{-1}. Measurements were carried out before and after the main crop growing season or during the growing season to a maximum plant height of 10 cm. The duration of measurement was about 2 hours. Instantaneous wind speed from each anemometer was recorded in a separate data logger in 5 second step.

Optical porosity:

Thirty images of different phenological stages of selected windbreaks from 2006 to 2010 were analyzed. Windward or leeward images were always taken from the same point at a distance of 30 m. The images were converted into black and white spectrum, divided into 9 to 11 vertical columns and 7 to 9 horizontal lines. The precision and spatial distribution of OP determination increases with the number of squares. OP of each square was assessed by ImageTool analyses. The resulting OP for each image was then determined as the arithmetic average of all squares.

Graphic and statistical expression:

Reduction of air velocity at different distances from the windbreaks and at different optical porosity was expressed by 2D contour map. The input data and mapping output were carried out by program Surfer ver.8.03, local polynomial interpolation method, polynomial order 2nd. All available measurements (from all selected windbreaks) were used for a map creation.

Reduction of wind speed in dependence on OP and the distance from the windbreaks were expressed by multiple linear regression method in STATISTICA ver.7 software. The relationship between two independent variables (OP and the distance from the windbreaks) and the dependent variable (reduction of wind speed) was quantified by quadratic regression equations.

3. Results and discussion

Optical porosity, relative wind speed at distance of 50, 100 and 150 m on the leeward side and at 150 m on the windward side (100%) in terms of

individual measurements are given in Table 1.

The OP was assessed as "OP total" (for the whole height of the wind-
breaks) and due to the high OP variability in height of terminal tree branches
as well as "OP reduced" (just squares to 2/3 height of windbreaks were eval-
uated).

Table 1. OP values and reduction of relative wind speed on the leeward side compared
with wind speed at 150 m on the windward side

Term of the measurement	OP total (%)	OP reduced (%)	Speed at the distance of 50 m (%)	Speed at the distance of 100 m (%)	Speed at the distance of 150 m (%)
Suchá Loz					
18.4.2007	52	50	83	87	99
24.4.2009	32	31	61	59	68
11.11.2007	43	37	55	67	83
Dolní Dunajovice					
19.4.2006	32	30	68	79	90
5.5.2008	18	13	40	58	75
Micmanice					
4.5.2006	20	19	36	46	74
11.10.2006	21	15	45	56	59
Blatnice					
31.10.2010	31	27	52	58	73

Overview of the analyzed image and OP value in individual terms are
given in Fig. 1. The highest values of OP (up to 50%) are logically achieved
in non-vegetation period. Almost full foliage of windbreaks occurs in ap-
proximately 10 days in the spring. The OP is changing analogically (from
values typical for the winter to values of full foliage). Autumn leaf fall
lasts longer and a gradual change of OP is longer. Although two values of
OP (vegetation and non-vegetation) for each windbreak can be considered.
Transitional periods are very short and their timing is given by weather
conditions of the particular year.

The combination of wind speed reduction and OP total and OP reduced
for all evaluated windbreaks and measurements is shown in Fig. 2 and Fig. 3.
The wind speed reduction on the leeward side is relatively strongly corre-
lated with OP value (especially when using OP reduced value). The highest
correlation was found when the wind speed measurement at 50 m on lee-
ward side was used. The dependence decreases with increasing distance and
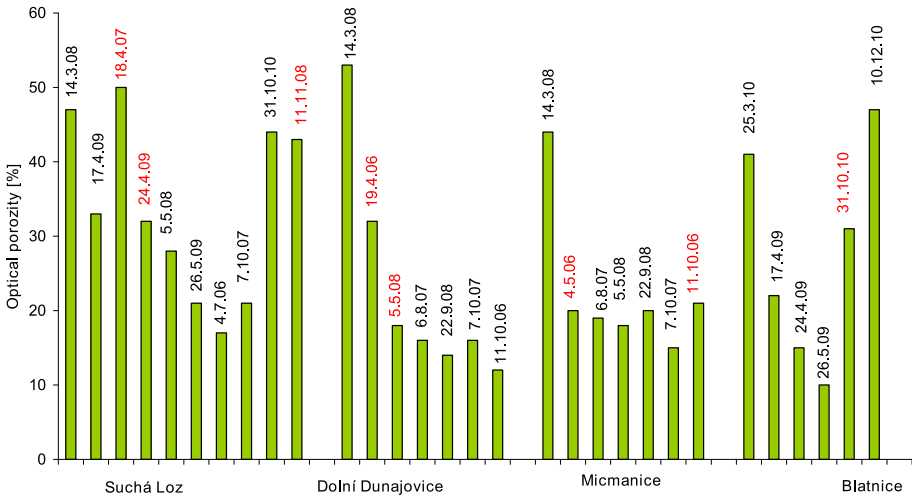influence of other factors on the air flow is more significant. Full foliage in

Fig. 1. Comparison of OP values during the vegetation (wind speed profile was simultaneously measured as shown by red).

summer (10% OP) reduces a wind speed about 60% at 50 m and about 30% at 150 m on the leeward side in comparison with speed at 150 m on the windward side. These values for non-foliaged windbreaks decrease to 80 and 90%.

The curves shown in Fig. 4 were constructed using the regression equation of wind speed reduction in dependence on OP and different distances from the windbreaks. The wind speed reduction on the leeward side for individual OP values can be derived from the curves. Maximum distance of windbreak effect on wind speed reduction was determined by the curves extrapolation. Regardless of OP value the reduction effect disappears at a distance of 250 m. *Marshall (1967)* defined the maximum wind speed reduction about 60% approximately at a distance of four times height of windbreak. An average altitude of windbreaks in the SL, DD, MC and BS 15 to 20 m means this distance from 60 to 80 m. *Caborn (1957)* observed minor speed reduction on the leeward side even at a distance of 30 multiple of its height (30H). Practical effect (reduction of wind speed at least about 20%) is achieved at a maximum distance of 15 to 20H.

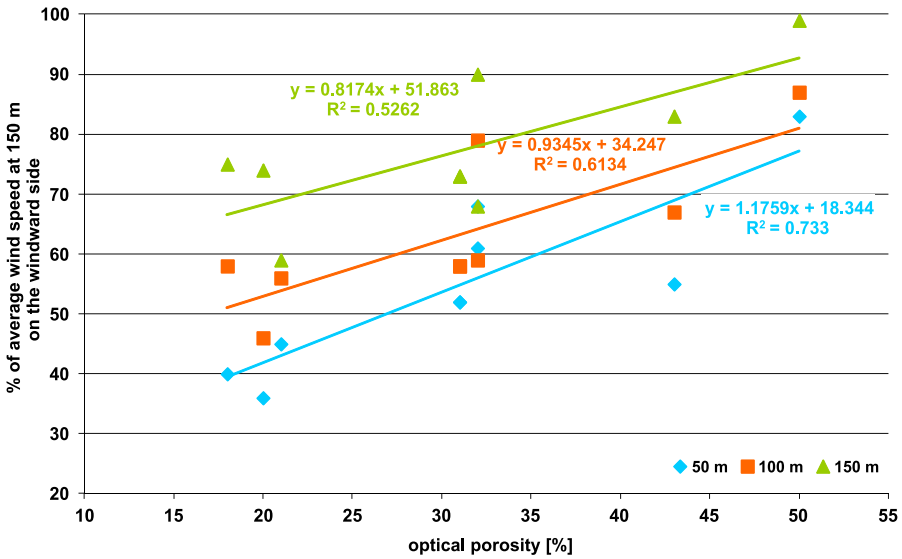The main task of analyzed windbreaks is a protection against wind ero-

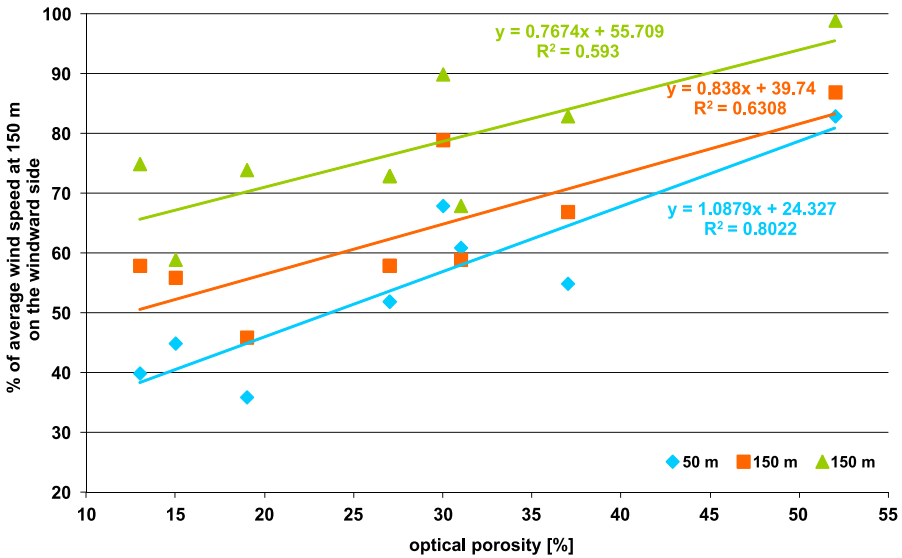Fig. 2. Influence of OP on wind speed reduction on the leeward side – OP total.

Fig. 3. Influence of OP on wind speed reduction on the leeward side – OP reduced.
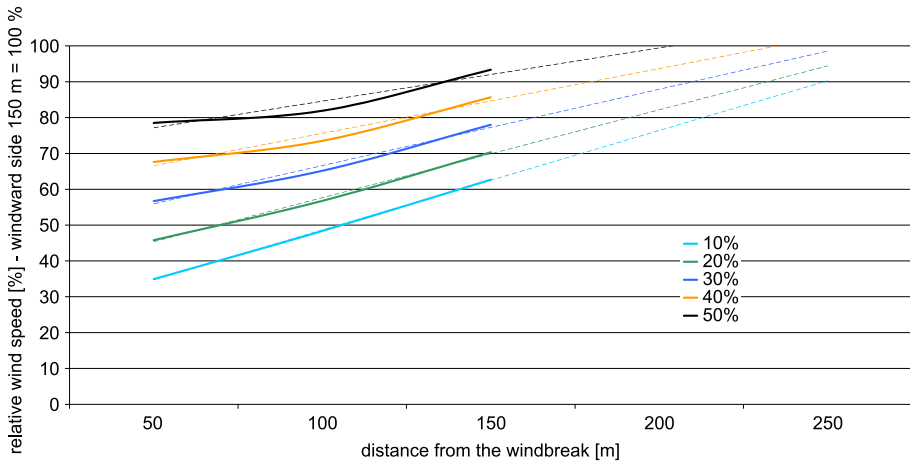
Fig. 4. Wind speeds reduction at different distances on the leeward side of windbreaks depending on OP.

sion. Therefore their effect in the autumn and spring seasons (i.e. when higher OP values) is the most significant. Effectiveness of windbreaks in this critical period can be particularly enhanced by evergreen trees planting. Windbreaks with conifers are able to not only protect the area against erosion, but also from cold winds in winter, i.e. when deciduous windbreaks show reduced efficiency (*Straigh and Brandle, 2007*).

Wind speed reduction by windbreak of different OP is expressed in Fig. 5 by 2D maps created in Surfer program. The application provides a user-friendly output with a simple determination of the wind speed reduction based on the OP and the distance from the windbreaks. Surfer is primarily mapping software, which provides only graphical output. A regression equation of used interpolation method is therefore not provided. Figure 5 indicates the highest wind speed reduction at a distance of about 50–60 meters on the leeward side.

According to *De Sy (2009)* a quiet zone forms in the lee of the windbreak. It has a triangular shape with the boundaries formed by the windbreak, the ground surface, and a line sloping downwards from the top of the windbreak. This line intersects the ground between 3 and 8H downwind of the windbreak. In the quiet zone the minimum wind speed occurs, and turbu-

lent eddies are smaller and less energetic than in the approach airflow.

The quietest zone of evaluated windbreak with an average height of windbreaks 15–18 m was detected in the area about 4H. The effect of windbreaks decreases with increasing porosity. The results therefore fully correspond with other authors – maximum wind speed reduction between 2H and 8H (depending on porosity) and 80% recovery of the upwind wind speed around 20H (*Cleugh, 2003; Cleugh, 1998; Hagen, 1991* and *Hagen, 1995* in *Vigiak et al., 2003; Bird et al., 2007; Ian et al., 2009).*

Relationship between OP and the distance from windbreak as well as their effect on the wind speed reduction was defined by multiple regression with a quadratic polynomial interlaying of fifth grade with usage of software STATISTICA:

$$Z = 46.1894 + 0.1709\,X - 0.4606\,Y - 0.0008\,X^2 - 0.0004\,XY - 0.000094226\,Y^2,$$

where:
Z – wind speed reduction (%)
X – distance from the windbreak (m)
Y – optical porosity (%)

Figure 6 presents a verification of model quality compared with real measured data. Determination Index of 0.664 and low values dispersion outside the 99% confidence interval indicate a relatively good agreement between modeled and real data. 67 data sets (distance from windbreak and OP versus the wind speed reduction) obtained from measurement of four structurally different windbreaks were used for the validation.

4. Conclusion

The paper evaluates the wind speed reduction by windbreak on the basis of OP assessment. The method allows quantifying the influence of windbreaks of different structures in different phenological stages without the need of direct terrain measurements. Computer analysis of digital photographs of the two pheno-phases is sufficient for the evaluation (in the case of larger or heterogeneous windbreaks more images might be needed).

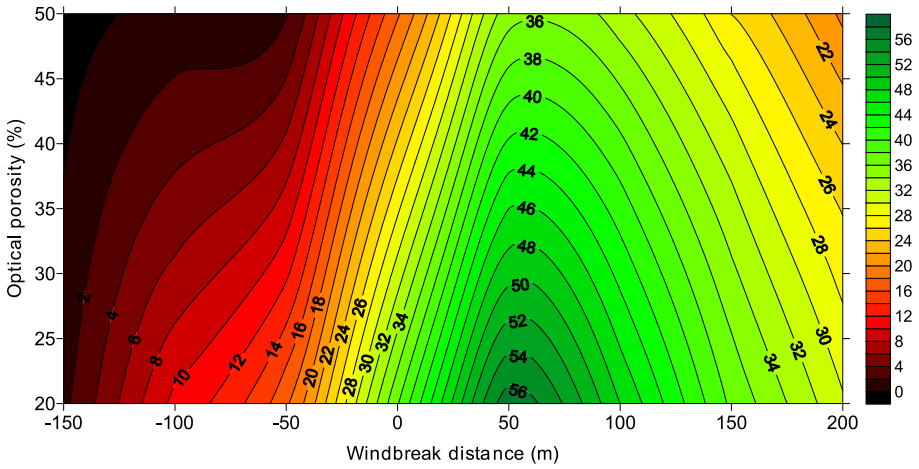The described method is applicable for the line windbreaks (up to tens

Fig. 5. Wind speed reduction (in %) at different distances from the windbreak depending on the OP.
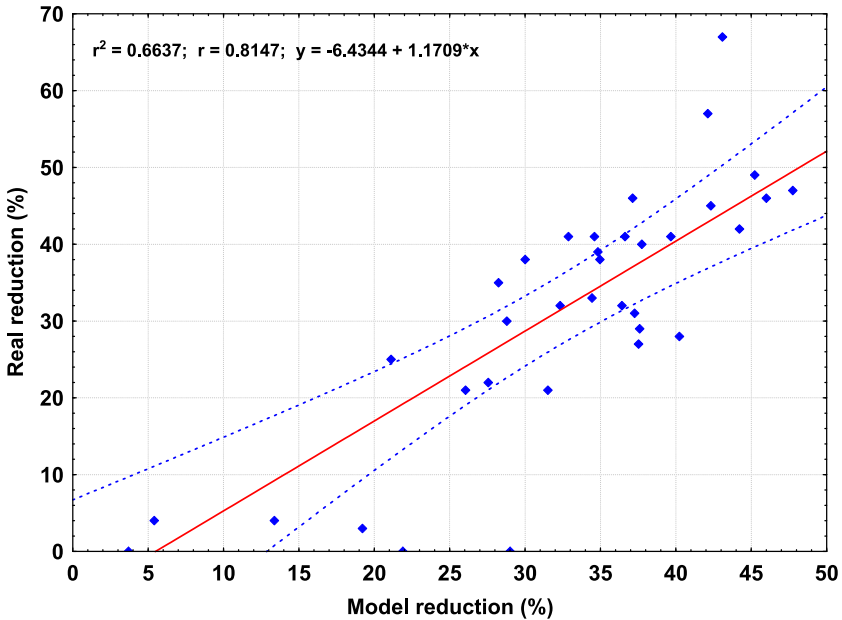

Fig. 6. Comparison of wind speed reduction based on the model output compared with measured values.

meters wide) and requires high-resolution images (*Kenney, 1987* and *Jiang et al., 1989*). In the case of wider windbreaks the relationship between spaces of possible air circulation (aerodynamic porosity) and spaces permeable for the light (optical porosity) is no longer valid. The optical porosity is less than the real porosity and the difference is the highest for the wide shelterbelt *(Lindholm et al., 1988).* Mutual occultation of individual plant parts on two-dimensional images causes almost near-zero optical porosity, despite the actual existence of three-dimensional air circulation spaces (among others *Torita and Satou, 2007*). Aerodynamic porosity of windbreaks wide 12 to 20 meters can still be successfully evaluated by the optical porosity method.

The relationship between OP and the wind speed reduction is the strongest at the distance of the first measurement (i.e. at 50 m). The relationship is reduced with increasing distance due to other factors. The relationship between OP and the wind speed reduction is higher when just lower 2/3 of windbreak is used for OP assessment (OP reduced). When evaluating the entire height of windbreaks (OP total) some errors caused by complicated pixel resolution of sparse crown and sky can occur. The relationship between OP and wind speed reduction at different distances on the leeward side proved the full foliage windbreak influence even at a distance of 200 to 250 m. For the bare windbreaks this distance is only about 50 m. When increasing the number of rows a positive effect could only be observed close to the windbreak. From a distance of about 10H single-row windbreaks with evenly distributed porosity were most effective in reducing wind speed *(Cornelis et al., 1999).*

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