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Windbreak Efficiency in Agricultural Landscape of the Central Europe: Multiple Approaches to Wind Erosion Control

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Abstract

Windbreak is one of the key factors for making the agriculture systems successful through reduced wind erosion, improved microclimate, increased biodiversity, and production potentiality of timber and agricultural crops. Even though windbreak occupies only a small part of agricultural landscape, its advantages on the ecological and economical perspective are quite high. This study evaluated the effects of three windbreak types on the wind erosion control in relation to their structural diversities, wind-speed reduction, and optical porosities in the central part of the Czech Republic. Diversity in the windbreak was evaluated based on its species diversity, vertical structure, spatial pattern, and complexities. Wind speed was measured at the different distances on the leeward side of the windbreak and one station placed on the windward side as a control. Windbreak characteristics were described by terrestrial photogrammetry method using the values of optical porosity. The timber volume of the windbreaks with rich biodiversity species ranged from 224 to 443 m^3 ha^{-1}height of the windbreak on the. Results of the windbreak efficiency showed significantly closer relationship between optical porosity and structural indices. The optical porosity significantly correlated with wind-speed reduction, especially in the lower part of the windbreak. A significant dependency of the windbreak efficiency on the tree dominant height was also observed for each windbreak type. The most significant effect on the wind-speed reduction in terms of structural indices had total diversity index and Arten-profile index describing vertical structures, which are recommended together with the optical porosity to evaluate the windbreak efficiency in controlling wind erosion.

Keywords Airflow · Wind-speed reduction · Optical porosity · Structural diversity · Production · Czech Republic

Introduction

The agricultural farming, which involves forming and using the landscape based on its quality, has always been a main reason of economic development in the Europe for the past few centuries (Ellis and Ramankutty 2008; Jepsen et al. 2015). The agriculture landscapes have been substantially changed through the intensification of land use and farming that has steadily been increasing over the past 150 years (Ramankutty and Foley 1999; Erb 2012). The intensification of land use includes gradual unification of the land blocks by means of the efficient agricultural machineries, which have an unstoppable advancement through time (Robinson and Sutherland 2002; Steen et al. 2012). With this mechanism, there has been a decrease in the size of biotopes, such as field boundaries, groves and woods (Robinson and Sutherland 2002; Wrzesień and Denisow 2016). Minimizing the sizes of these biotopes does not only mean a significant decrease of biodiversity (Wrzesień and Denisow 2016), but also an increased migration and transfer of soil particles from one place to other by water and wind, which could cause the landscape destruction and soil erosion as well. These problems increased significantly due to a large-scale farming and an intensification of land use in the Europe (Robinson and Sutherland 2002). The negative changes on the quality of landscape and soil had occurred mainly during 1950s in the Czech Republic, because of an increased wind erosion (Pasák 1970). This particularly

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affected the south Moravia, which is considered as one of the most wind-erosion-affected regions in the central Europe (Podhrázská et al. 2015).

The windbreak and shelterbelt are the barriers, which significantly reduce wind speed and prevent wind erosion (FAO 1989). The windbreak created through plantation of tree and shrub species is one of the effective biological measure in reducing wind speed and increasing ecological effects that are supportive to agriculture farms (Torita and Satou 2007; Chendev et al. 2015; Řeháček et al. 2017). Besides acting as soil protection against wind erosion, windbreak also improves the local environment along the windbreak through various ways (Ferreire 2011; Kuhns 2012), such as improvement in evapotranspiration, protection of crops, amelioration of microclimate, and creation of new bio-communities that are largely supportive to increasing yields of the main and subsidiary crops (Campi et al. 2009; Alemu 2016; Nerlich et al. 2013). The windbreak also provides shelter for various animal and bird species (Ferreire 2011), and thus helps increase biodiversity through improvement of a sum of both biotic and abiotic factors in the agricultural landscape (Fukamachi et al. 2011; Sreekar et al. 2013; Alemu 2016).

Since primary function of the windbreak remains the reduction of wind erosion (Bird et al. 1992; Ferreire 2011; Chendev et al. 2015; Řeháček et al. 2017), this stops transferring soil particles from one place to another. Transfer of soil particles has negative impacts on the local environment that may cause degradation of soil quality and crop damages (Burke 1998). Destructive activity of wind is significantly influenced by landscape conditions, especially by geological and soil characteristics (surface roughness, soil texture, soil aggregation, soil moisture), climate (rainfall, wind speed), and anthropogenic factors (farming activities, vegetation cover, estate size) (Brandle et al. 2004; Hupy 2004; Li et al. 2007; Du et al. 2017). Agricultural land is often prone to wind erosion, especially during the time when soil surface is not protected by planted trees or shrubs against erosion-causing factors (Wolfe and Nickling 1993). For the purposes of mitigating wind erosion on the agriculture landscapes, windbreaks are often built in several countries in the Europe and outside, e.g. China, Canada, Australia, and United States, especially in their arid and semi-arid regions (Kort 1988; Cleugh and Huhges 2002; Peri and Bloomberg 2002; Brandle et al. 2004; Alemu 2016).

The windbreak is properly characterized based on its structures, such as spatial structure (Forman and Gordon 1986; Heisler and Dewalle 1988) which is mainly described by porosity (Wan et al. 2005; Středa et al. 2008; Středová et al. 2012). Spatial structure of the windbreak influences the efficiency on controlling wind erosion (Cornelis and Gabriels 2005; Straight and Brandle 2007). External structure of the windbreak consists of width, height, shape, and orientation, and its internal structure consists of amount and arrangement of branches, leaves, and trunks of trees or shrubs (Brandle et al. 2004). The windbreak is also characterized based on its level of porosity, such as porous (porosity ca. 60%), medium porous and nonporous (porosity ca. 20%) (Abel et al. 1997). The effect of the windbreak on the wind-speed reduction can be in the range of 20−35 times the height of the windbreak 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). These studies have shown significant relationships between reduction of the windbreak efficiency and values of optical porosity. Spatial structure of the windbreak changes throughout the year based on the phonological phases of woody plants. The leafy windbreak in a vegetation period has a bigger impact on reducing wind speed compared to the windbreak without foliage during winter (Středa et al. 2008; Řeháček et al. 2017).

Vegetation diversity of the windbreak can also be described using structural indices and functions, which have frequently been used to evaluate forest stand structures (Pretzsch 2009; Vacek et al. 2014; Král et al. 2015; Bílek et al. 2016; Králíček et al. 2017). Stand structure is evaluated horizontally (Clark and Evans 1954; Mountford 1961; Geyer 1999; Bulušek et al. 2016) and vertically (Ferris-Kaan et al. 1998; Pretzsch 2006). However, only few studies have been carried out on the vertical stand structures (Vacek et al. 2015b), which more significantly influence the windbreak efficiency compared to the horizontal structures (Zhu et al. 2003). Using the complex diversity indices, which include indices describing both stand structures and functions, can be more effective means of evaluating windbreaks (Jaehne and Dohrenbusch 1997; Neumann and Starlinger 2001) than using only structural indices (McElhinny et al. 2005). The indicators of species diversity also play important roles from the structural point of view (Shannon 1948; Margalef 1958; Pielou 1975). The taxonomical structure of a windbreak is thus one of the crucial parameters predetermining its wind reduction efficiency.

The literature dealing with the impact of the windbreak on the wind erosion control is either based on the numerical models (Bitog et al. 2012; Speckart and Pardyjak 2014) or wind speed and optical porosity (Loeffler et al. 1992; Řeháček et al. 2017). However, knowledge of the multiple approaches of establishing complex indices in relation to the diversity of woody plants of the windbreak is still lacking. Thus, a general objective of this study was to determine the effects of three different windbreak types on the wind erosion in the central Bohemia region of the Czech Republic. Specific objectives were (1) quantification of structure, species and complex diversities of tree layer and shrubs of the windbreaks; (2) determining optical porosity of the

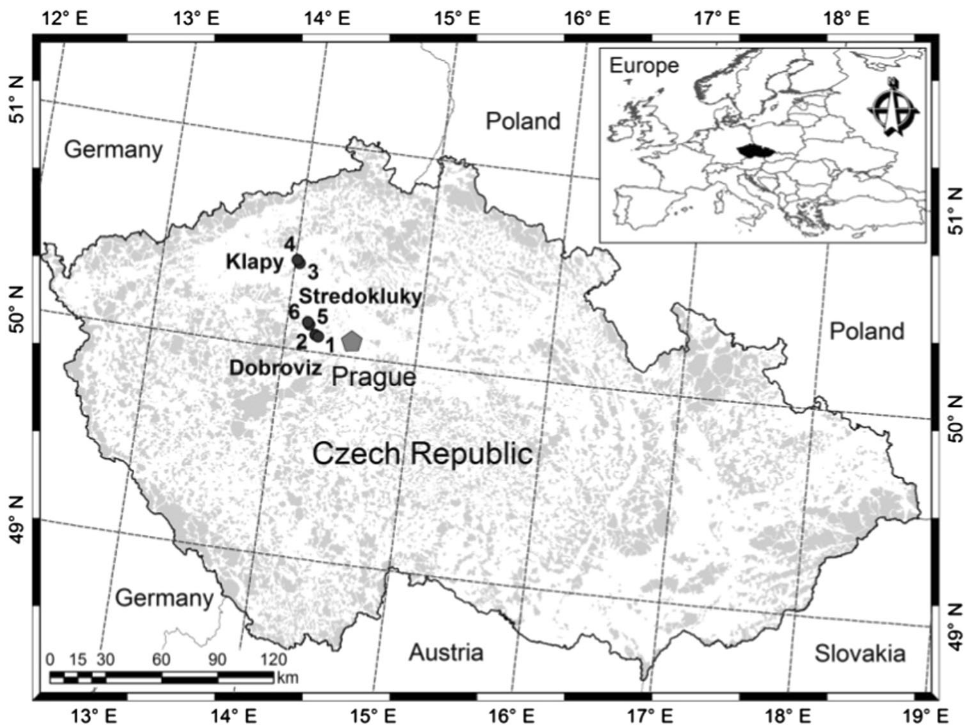

Fig. 1 Location of six permanent research plots in the windbreaks in three localities of the Czech Republic (gray color indicates forest cover)

windbreaks and wind speed at different distances on the leeward side; (3) assessing the windbreak efficiency in terms of wind-speed reduction, optical porosity, and biodiversity; (4) determining the relationships among optical porosity, wind speed, and biodiversity of the windbreaks and (5) identifying the most appropriate type of the windbreak in terms of reducing wind erosion. This study was mainly based on the hypothesis that wind-speed reduction would have the strongest correlation with total complex diversity in terms of the indices used. The results presented in the article may be useful for creation of the windbreaks and their evaluation.

Material and Methods

Study Site

The study was carried out in the windbreaks on six permanent research plots (PRP) in three localities (two repetitions) with altitude varying from 187 to 355 m above mean sea level, in the central Bohemia region of the Czech Republic. The territory has warm summer temperate climate according to Köppen climate classification (Köppen 1936), or rather by a detailed region Quitt classification (Quitt 1971)–it belongs to warm district. The mean annual precipitation varies from 350 to 590 mm and mean annual temperature fluctuates around 8.3 °C. The length of growing season lasts for 170 days with mean temperature 14.1 °C and mean amount of precipitation is 340 mm. The parent rock of this region is formed mainly by limestone, basalt, and slate. Dominant soil types are Luvisols and Cambisols for PRP Dobroviz and Stredokluky, and Chernozem for PRP Klapy. Each PRP is shown in Fig. 1 and basic characteristics of PRP are presented in Table 1.

In the locality of Dobroviz there is a three-to-four rows mixed windbreak consisting of two tree layers. The tree layer is made up from the following: 86–90% *Quercus petraea* (Matt.) Liebl., 5–10% *Acer campestre* L. and less than 3% is made up from *A. platanoides* L. and *A. pseudoplatanus* L. In the upper tree layer, the most dominant is *Q. petraea*, while maple trees form lower layer. About 16% of the tree level is made up by lower layer, 38% by middle layer, and 46% by upper tree layer. In shrub layer, more prevalent species are *Symphoricarpos albus* (L.) S. F. Blake and *Sambucus nigra* L.

In the locality of Klapy there is a nonpermeable four-to-five-rows three-tree layer windbreak. The tree layer is made up from 59 to 82% by *Acer pseudoplatanus*, from 16 to 32% by *Fraxinus excelsior*, and from 3 to 9% by *Ulmus glabra* Huds. and less than 1% is formed by *Acer platanoides*. The division of tree layer from the vertical stratification is as follows: 46% lower layer, 37% middle layer, and 17% upper layer. In the upper layer, dominant types are *A. pseudoplatanus* and *Fraxinus excelsior* L., while *Ulmus glabra* represents the trees that are suppressed and subleveled. In the shrub layer, more prevalent species are *Ligustrum vulgare* L. and *Sambucus nigra*.

Table 1 Overview of basic characteristics of permanent research plots in windbreaks

PRP[a]	Name	GPS coordinates		Altitude (m)	Exposure	Size (m)	Species[b]	Number of rows	Age (y)	Height[c] (m)
1D1	Dobroviz 1	50°6′26″N	14°13′48″E	353	N	30 × 19	QP, APl, AC	3–4	68	19.1
2D2	Dobroviz 2	50°6′37″N	14°13′46″E	355	N	30 × 19	QP, APl, AC	3–4	68	18.7
3K2	Klapy 1	50°25′33″N	14°1′52″E	194	NE	30 × 24	APs, FE, UG	4–5	66	20.0
4K2	Klapy 2	50°25′22″N	14°1′58″E	187	NE	30 × 24	FE, APs, UG	4–5	66	22.7
5S1	Stredokluky 1	50°7′10″N	14°13′49″E	352	NE	30 × 9	QP	2	59	14.9
6S2	Stredokluky 2	50°7′18″N	14°13′45″E	346	NE	30 × 9	QP, FE	2	59	16.0

[a]Permanent research plots–marks indicate: plot ID, locality abbreviation, number of couples in the same locality

[b]Main tree species: QP, *Quercus petraea* (Matt.) Liebl.; APl, *Acer platanoides* L.; AC, *Acer campestre* L.; FE, *Fraxinus excelsior* L.; APs, *Acer pseudoplatanus* L.; UG, *Ulmus glabra* Huds.

[c]Dominant height of tree layer (95% quantile)

In the locality of Stredokluky, there is a semi-permeable two-rows pure species windbreak made up by one tree layer. The tree layer is made up from 99 to 100% by *Quercus petraea* and less than 1% by *Fraxinus excelsior*. In rare shrub layer, more prevalent species are *Symphoricarpos albus* and *Sambucus nigra*.

Data Collection

Six PRP of 30 × 9–24 m (270–720 m^2) were established in 2016 using the Field-Map technology (IFER-Monitoring and Mapping Solutions Ltd; Šmelko and Merganič 2008) to determine the tree layer structures. All individuals with breast height diameter (DBH) > 4 cm and their crown projections were located using this technique. The crown radii were measured at least in four directions perpendicular to each other, from the center of the bole. DBH, height and height of live crown base were measured in all trees. Height to live crown base was measured at the point where branches formed a continuous whorl of a crown. DBH of the tree layer were measured with a caliper (accuracy mm) while tree heights and crown heights were measured with the Vertex laser hypsometer (Haglöf Sweden; accuracy 0.1 m). All trees and stand characteristics were measured following the inventory protocols prepared by Forest Management Institute (FMI 2003). Natural regeneration from height ≥ 1.5 m was measured on each PRP. The characteristics measured for recruits are position, height, height to live crown base, and crown projection area. Shrub individuals or continuous groups were recorded, but individuals with height ≥ 1.5 m and their crown projection areas were measured. Heights were measured with an altimeter rod (accuracy in cm). Field studies were carried out in accordance with the notification provision of the nature protection, and therefore not detrimental to wildlife and soil.

Measurement of wind speed was carried out during the period without foliage from November to March in 2015–2017. Wind speed was measured during favorable wind conditions, hence having sufficient wind speed and in a direction perpendicular to the windbreak ± 20°. The terrain measurement was carried out using portable anemometers Vantage Pro 2 (David Instruments Corp., Hayward, USA) with range 0.5–89 m s^{-1} and accuracy ± 1 m s^{-1} or ± 5% whichever is greater. Anemometers were placed at the height of 1 m above the surface. Four anemometers were placed on the leeward side at 3, 6, 9, and 12 multiples of the height of the windbreak (*H*), and one check anemometer was placed on the windward side at the distance of 3*H* (three times the height of the windbreak) (Fig. 2). Minimum time used for measurement was 2 h and the data were recorded at 10 s intervals. Three field measurements of wind speed were performed for each of PRP.

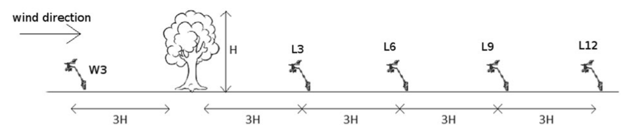

Fig. 2 Scheme of wind-speed measurement and anemometry positions (H windbreak height, W windward side, L leeward side)

The optical porosity was determined based on the photographs (with resolution 4928 × 3264; 16 M) taken by digital camera Nikon D5100 (Nikon Corporation, Tokyo, Japan). The same stretch of the windbreak delineated in the terrain by pegs and GPS coordinates was pictured and assessed. The photographs were taken in the perpendicular axis to the windbreak for both windward and leeward sides. The optical porosity was assessed on three photographs with the most contrast of the windbreak and background. Photographs were taken from the height of 1.6 m using standard tripod (Řeháček et al. 2017).

Data Analysis

Structural and growth parameters, quantity of production, horizontal and vertical structures, and total biodiversity in all individuals of the tree layer on each sample plot were

Table 2 Overview of indices describing stand structures and their interpretations

Criterion	Quantifiers	Label	Reference	Evaluation
Species diversity	Richness	D_1 (Mai)	Margalef (1958)	Minimum $D = 0$, higher $D =$ higher values
	Heterogeneity	H' (Shi)	Shannon (1948)	Minimum $H' = 0$, higher $H' =$ higher values
	Evenness	E_1 (Pii)	Pielou (1975)	Range 0−1; minimum $E = 0$, maximum $E = 1$
Vertical diversity	Arten-profile index	Ap (Pri)	Pretzsch (2006)	Range 0−1; balanced vertical structure $Ap < 0.3$; selection forest $Ap > 0.9$
Structure differentiation	Diameter dif.	TM_d (Fi)	Füldner (1995)	Range 0−1; low $TM < 0.3$, medium $TM = 0.3–0.5$, very high differentiation $TM > 0.7$
	Height dif.	TM_h (Fi)		
Horizontal structure	Index of nonrandomness	α (Pi&Mi)	Pielou (1975); Mountford (1961)	Mean value $\alpha = 1$, aggregation $\alpha > 1$, regularity $\alpha < 1$
	Aggregation index	R (C&Ei)	Clark and Evans (1954)	Mean value $R = 1$, aggregation $R < 1$, regularity $R > 1$
Complex diversity	Stand diversity	B (J&Di)	Jaehne and Dohrenbusch (1997)	Monotonous structure $B < 4$, uneven structure $B =$ 6–8, very diverse structure $B > 9$

assessed. Tree volume was calculated by volume equations (Petráš and Pajtík 1991). The indicators assessed for tree species diversity are species richness D_1 (Margalef 1958), species heterogeneity H' (Shannon 1948), and species evenness E_I (Pielou 1975). Structural and overall diversity was assessed based on these indices: Arten-profile index Ap (Pretzsch 2006), diameter TM_d and height differentiation index TM_h (Füldner 1995), index of nonrandomness α (Pielou 1975; Mountford 1961), aggregation index R (Clark and Evans 1954), and total diversity index B (Jaehne and Dohrenbusch 1997). All these indices are defined in Table 2.

Characteristics describing the horizontal structure of individuals on the sample plots were calculated using PointPro 2.2 software (Zahradnik and Pus). The test of deviation against the expected values for the random layout of points was carried out by Monte Carlo simulation. Medium values were estimated using the randomly generated 1999-point structures. Moreover, crown closure (Crookston and Stage 1999) and crown projection area for each individual were calculated. Layout maps were created in the ArcGIS 10.4 (Esri).

The optical porosity was determined applying the methodology devised by Podhrázská et al. (2011) with the use of software GIMP 2.8.2, ArcGIS 10.4 (ArcMap), and table processor MS Excel 2013 (Microsoft Office). The images were firstly processed in the graphical program GIMP and then converted to gray-tone images, and graphical adjustment to highlight and distinguish vegetation/cover from the background was subsequently made by using trim, brightness, and contrast tools. A function threshold was applied in order to create a binary image (black grid = vegetation/cover, white grid = background). The photograph adjusted in this way was subjected to analyses in the program setting of ArcMap. The adjusted image was transformed based on the delineated pegs to the square grid with 6 rows and 12 columns.

One square of the grid was of the size 2.5 × 2.5 m for lower rows of the windbreak. A more detailed grid with each square of size 2.5 × 2.5 m divided into 16 smaller squares was used for upper rows of the windbreak. The tool Zonal Histogram (Fig. 3) was used for subsequent analyses of the binary image. A detailed analysis of the upper row using smaller squares was carried out for the purposes of enhancing accuracy to determine the overall optical porosity. When there was a square with optical porosity of 100% in the highest row, the upper row was not included into establishing the overall optical porosity so as not to influence the value of the overall optical porosity in the windbreak. For statistical evaluation of the optical porosity in term of vertical structure, windbreaks were divided into six layers according to 2.5 m (12 squares in one line) from the bottom of shrub layer to the top of tree layer.

The wind-speed reduction was assessed as a ratio between wind speed on a leeward side and wind speed on a windward side using the following equation $U = (U_L/U_W) \times 100\,(\%)$, where U is the wind-speed reduction, U_L the wind speed on a leeward side, and U_W the wind speed on a windward side.

Statistical analyses were carried out using the Statistica 12 software (StatSoft). Data were log-transformed to acquire the normal distribution (tested by Kolmogorov−Smirnov test). The differences in diversity indices and optical porosity of the windbreaks among PRPs were evaluated using one-way analysis of variance (ANOVA) and consequently by post-hoc Tukey HSD test. In addition, the effectiveness of structural indices, wind speed, and optical porosity were evaluated using the Pearson correlation coefficients. Unless otherwise stated, 5% level of significance was used for all analyses. The unconstrained

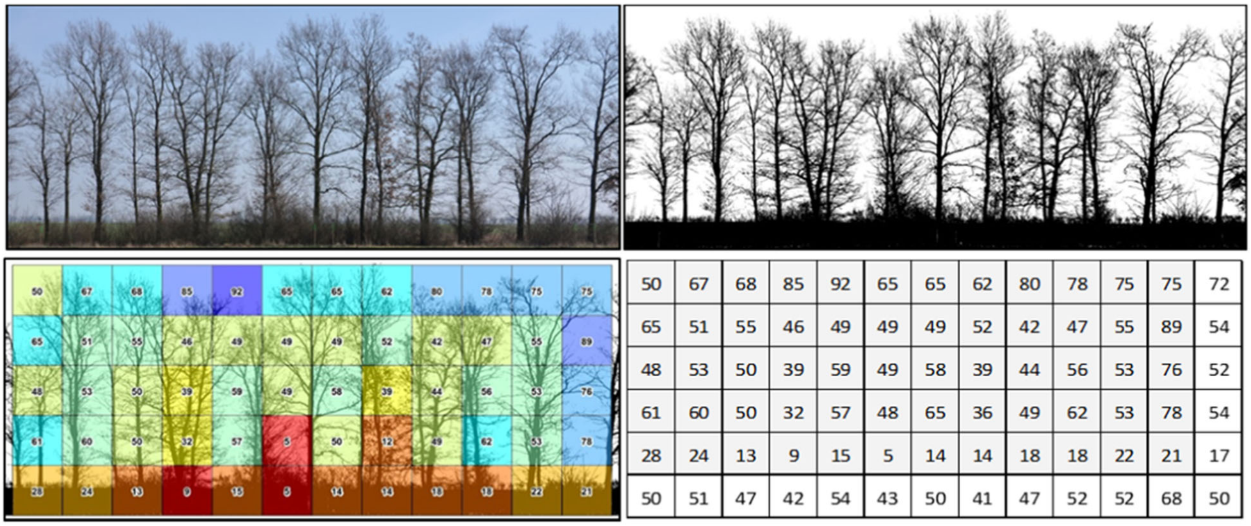

Fig. 3 Example of modification of the photography and evaluation of the optical porosity (%)

Table 3 Basic indices of the windbreak biodiversity on six permanent research plots 1–6 in 2016

PRP	D_1 (Mi)	H' (Si)	E_1 (Pii)	Ap (Pri)	R (C&Ei)	TM_d (Fi)	TM_h (Fi)	B (J&Di)
1D1	0.574 →	0.239 ↘	0.342 ↘	0.480 →	1.191^R	0.334 ↘	0.283 ↘	8.129 ↗
2D2	0.698 ↗	0.283 ↘	0.364 ↘	0.471 →	1.009^R	0.408 →	0.327 ↘	8.765 ↗
3K1	0.500 →	0.500 →	0.718 ↗	0.737 ↗	1.018^R	0.399 ↘	0.281 ↘	9.560 ↗↗
4K2	0.795 ↗	0.393 ↘	0.465 →	0.498 →	0.945 ^{A}	0.448 →	0.351 ↘	9.316 ↗↗
5S1	0.796 ↗	0.034 ↘↘	0.044 ↘↘	0.155 ↘↘	1.080 ^{R}	0.618 ↗	0.498 →	8.093 ↗
6S2	0.488 →	0.067 ↘↘	0.111 ↘↘	0.348 ↘	1.022 ^{R}	0.442 →	0.373 ↘	7.885 →

D_1 species richness index, H' species heterogeneity index (entropy), E_1 species evenness index, Ap Arten-profile index, R aggregation index for tree layer (tendency to ^{A} aggregation, ^{R} regularity), TM_d diameter differentiation index, TM_h height differentiation index, B total diversity index; arrows: ↘↘ low, ↘ low-medium, →medium, ↗ high, ↗↗ very high value

principal component analysis (PCA) in the Canoco 5 program (Microcomputer Power) was used in analyzing the relationships between stand characteristics, diversity, and porosity in order to reveal similarity of all records. Data were log-transformed, centered, and standardized before carrying out PCA. Scattered plots were divided into two parts for better interpretation and results of the PCA were visualized with an ordination diagram.

Results

Diversity and Structure of Windbreak

The indices describing biodiversity of the windbreak on PRP including the tree layer, shrub layer, and natural tree regeneration are presented in Table 3. Species richness indicated moderately rich to very rich windbreaks ($D_1 = 0.488$–0.796). The heterogeneity based on entropy H' showed low to moderate biodiversity ($H' = 0.067$–0.500). Species evenness was moderate to high ($E = 0.044$–0.718). In general, from the species diversity point of view, the highest values were found on PRP Klapy (3K1, 4K2), while PRP Stredokluky (5S1, 6S2) showed very low diversity. According to Arten-profile index, the vertical structure varied from moderately to strongly ($Ap = 0.471$–0.737) on PRP Dobroviz (1D1, 1D2) and Klapy (3K1, 4K2), respectively, and low variety on PRP Stredokluky (5S1, 6S2) ($Ap = 0.155$–0.498). Diameter differentiation of the structure was moderate to high ($TM_d =$ 0.334–0.618) and height differentiation was predominantly moderate ($TM_h = 0.281$–0.498), while on PRP 1D1 and 3K1 it was small ($TM_h = 0.281$–0.283). The tree crown differentiation (part of B index) was high ($K = 2.869$–2.916). The total diversity in PRP Dobroviz (1D1, 2D2) and Stredokluky (5S1, 6S2) denoted uneven to diverse structure ($B =$ 7.885–8.765) and in PRP Klapy (3K1, 4K2) it denoted very diverse structure ($B = 9.316$–9.560).

According to both indices determined ($R = 0.945$–1.191, $\alpha = 0.806$–1.474), horizontal structure of the tree layer was random (Fig. 4). The prevalent random distribution of tree layer individuals based on their distances (spacing) was also indicated by L-function (Fig. 5). In addition, tree stem

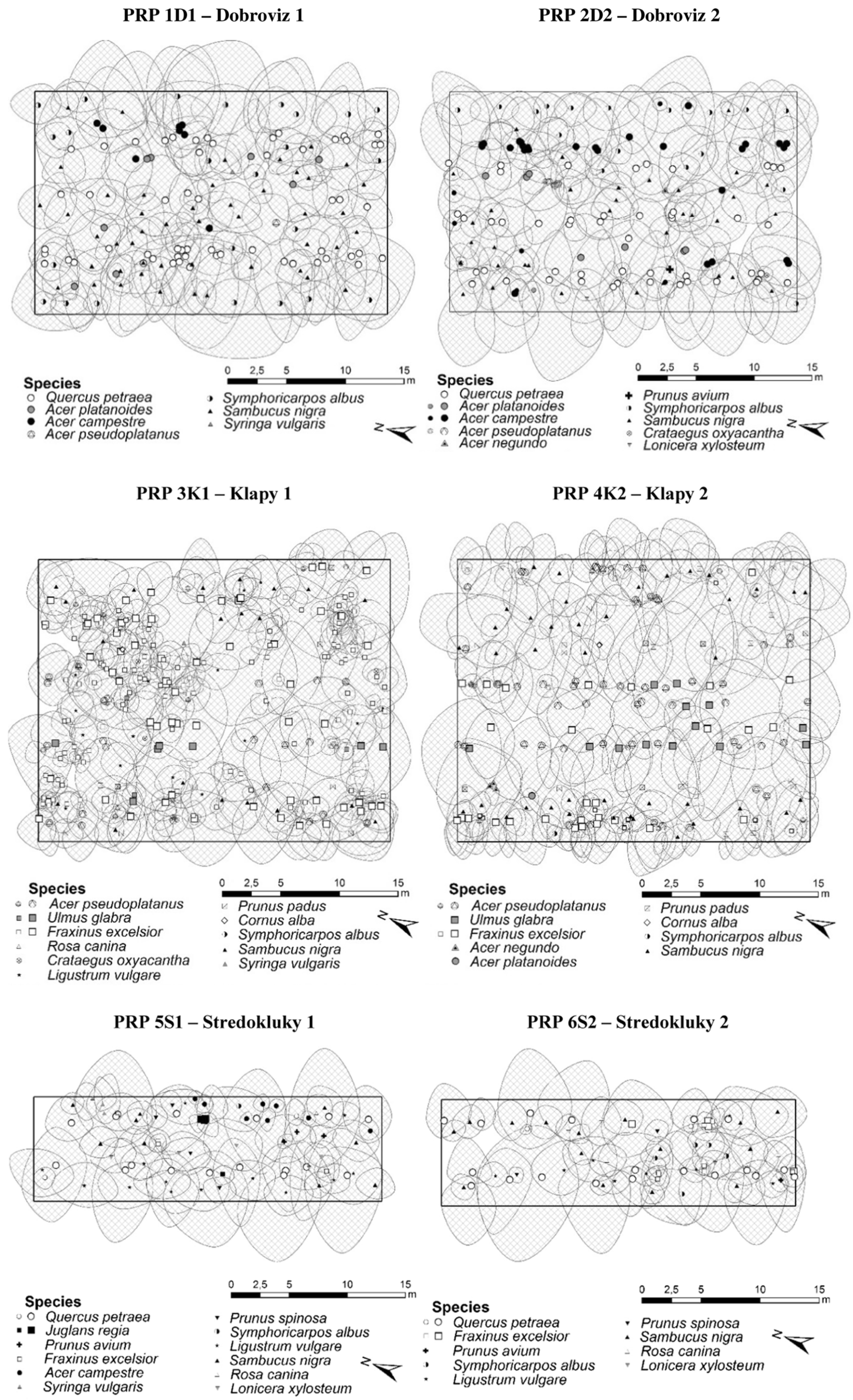

Fig. 4 Horizontal structure of tree layer (DBH ≥ 4 cm–large symbol) and understory (DBH < 4 cm, shrubs–small symbol) with displayed crown projection area of the windbreaks on the permanent research plots

layouts had the aggregated patterns according to their distances up to 1 m, and 2 m in the locality of Dobroviz (PRP 1D1, 2D2). There was a tendency to regularity at the distance from 3 to 5 m (even spacing of trees and rows) for PRP 5S1 and 6S2. The tree crown projection area (converted per hectare plot) in the tree layers ranged from 2.2 ha^{-1} (PRP 6S2) to 3.7 ha^{-1} (PRP 2D2), and crown closure ranged from 0.84 to 0.96. When comparing the absolute timber volume of the windbreaks, the lowest volume was detected on PRP 5S1–224 $m^3\,ha^{-1}$ (relative

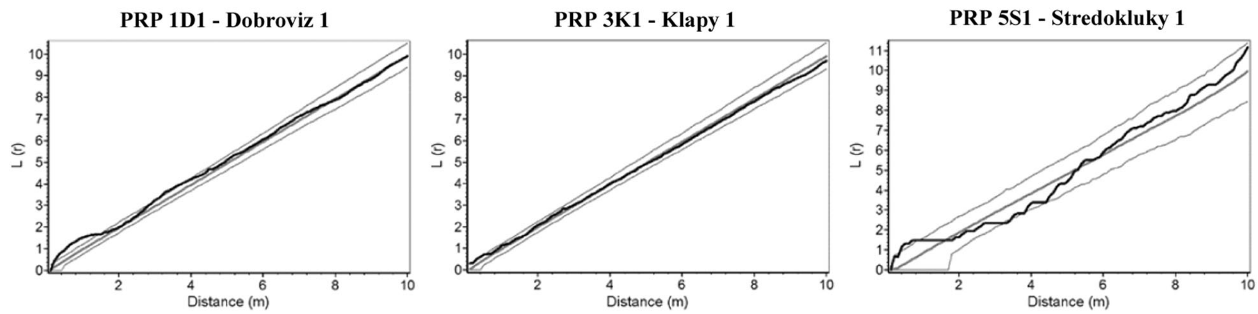

Fig. 5 Horizontal structure of selected permanent research plots from each locality expressed by the *L*-function; the black line represents the *L*-function for real distances of trees on the PRP; the bold gray line represents the mean course for random spatial distribution of trees and the two thinner central curves represent 95% interval of reliability; when the black line of tree distribution on the PRP is below, respectively above this interval, it indicates a tendency of trees toward regular distribution, respectively aggregation

volume V 83 $m^3\,ha^{-1}$ with the windbreak size being 25 × 400 m) and the highest volume on PRP 4K2–443 $m^3\,ha^{-1}$ (relative V 443 $m^3\,ha^{-1}$). The average volume in the locality of Dobroviz (PRP 1D1, 2D2) fluctuated around 303 $m^3\,ha^{-1}$ (relative V 243 $m^3\,ha^{-1}$).

While comparing individual biodiversity indices, type of the windbreak had a significant effect on its structure and diversity ($p < 0.001$–0.05). The windbreaks differed significantly among each other in terms of the species heterogeneity index H' ($F_{(2,\ 9)} = 44.1$, $p < 0.001$) and evenness index E ($F_{(2,\ 9)} = 25.1$, $p < 0.001$). Based on the Arten-profile index, vertical structure was the lowest in the two-row windbreak in the locality of Stredokluky (5S1, 6S2) ($F_{(2,\ 9)} = 12.2$, $p < 0.01$), but there was a significantly highest diameter differentiation TM_d ($F_{(2,\ 9)} = 5.9$, $p < 0.05$). The overall diversity of the windbreak was the highest in the locality of Klapy (3K1, 4K2) made up from 4 to 5 rows. On the contrary, a significant difference was not confirmed in the species richness, spatial distribution, and height differentiation among the types of windbreaks.

Optical Porosity

In terms of the optical porosity, the windbreaks in the three localities differed significantly from each other ($F_{(2,\ 9)} = 59.7$, $p < 0.001$; Table 4). In case of the windbreaks in the locality of Klapy (3K1, 4K2), a significant difference within one locality was observed ($p < 0.01$). The highest optical porosity was found for the windbreak in Stredokluky (5S1, 6S2) (51% ± 9 SD) while the lowest optical porosity was found for the windbreak in Klapy (3K1, 4K2) (27% ± 6 SD; $p < 0.01$). The optical porosity positively correlated with vertical structures (divided into six layers) of the windbreak ($r = 0.42$; $p < 0.01$). This correlation was the most significant on PRP 3K1 and 4K2 ($p < 0.001$); however, this trend was not confirmed on PRP 5S1 and 6S2 ($p > 0.05$). The lowest optical porosity was observed in the lowest shrub layer (15% ± 11 SD), and porosity was quite even in other layers (41.7−45.3%).

Table 4 Optical porosity differences by vertical layer (1–shrub layer, 6–top tree layer) of the windbreaks on six permanent research plots 1–6

Vertical layer	Optical porosity (mean % ± SD)					
	1D1	2D2	3K1	4K2	5S1	6S2
6	42 ± 12	51 ± 20	33 ± 16	45 ± 5	—	—
5	32 ± 15	57 ± 13	25 ± 8	44 ± 7	51 ± 9	49 ± 12
4	40 ± 8	48 ± 8	21 ± 8	43 ± 7	60 ± 13	51 ± 13
3	42 ± 10	42 ± 8	24 ± 9	35 ± 6	62 ± 8	67 ± 15
2	48 ± 13	38 ± 10	11 ± 5	26 ± 6	62 ± 13	65 ± 14
1	10 ± 5	18 ± 6	0 ± 0	6 ± 2	22 ± 9	32 ± 13
Total mean	36 ± 5	42 ± 4	19 ± 5	35 ± 3	51 ± 8	51 ± 10

Wind Speed Reduction

The wind speed on the leeward side significantly increased ($r = 0.83$, $p < 0.001$) with increasing relative distance (multiples of the upper height of the windbreak) from the windbreak, respectively and its efficiency decreased (Table 5). According to our measurement, the windbreak efficiency was observed more significant for the higher number of rows. The locality of Klapy (3K1, 4K2) with the highest number of rows 4–5 has the most significant efficiency in comparing with the others PRP. The differences in windbreaks' efficiency in terms of the wind-speed reduction reached between 9.7 and 15%. The smallest difference was observed in the closest distance from the windbreak (3H). Significant effect of the windbreak on reducing wind speed was observed for all distances evaluated even on the furthest location (12H).

Relationship Between Windbreak Efficiency, Optical Porosity and Stand Characteristics

Results of the PCA are presented in Fig. 6. The first ordination axis explained 66.6%, the first two 83.4% and the

Table 5 Field measurement data (from November to March in 2015–2017) of the wind-speed reduction with total optical porosity of the windbreaks without foliage

PRP	Locality	Optical porosity (%)	Wind speed (range, m s^{-1})	Anemometer position /wind-speed reduction (mean % ± SD)			
				3H	6H	9H	12H
1D1, 2D2	Dobroviz	39	4.4–9.1	44.1 ± 12.4	47.4 ± 13.1	74.3 ± 11.7	79.6 ± 10.6
3K1, 4K2	Klapy	27	4.5–7.4	41.2 ± 9.4	59.3 ± 1.9	68.0 ± 8.4	72.2 ± 9.1
5S1, 6S2	Stredokluky	51	4.5–6.3	50.9 ± 6.9	62.4 ± 10.1	79.4 ± 3.2	85.6 ± 2.3

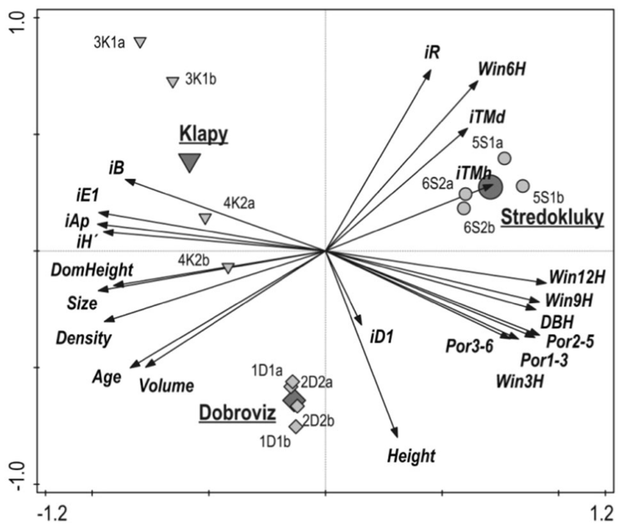

Fig. 6 Ordination diagram showing relationships among tree layer characteristics (*Density* number of tree stem, *Volume* timber volume, *DBH* diameter at breast height, *DomHeight* dominant height, *Height*, *Age*), width of windbreak (*Size*), diversity indices (*iAp* Arten-profile index, *iTMd* diameter differentiation, *iTMh* height differentiation, *iD1* species richness, *iH´* species heterogeneity, *iE1* species evenness, *iB* total diversity, *iR* aggregation), optical porosity (*Por1–3* o.p. of lower part, *Por3–6* o.p. of upper part, *Por2–5* o.p. of middle part without shrub and top layer), wind speed on the leeward side (*win3/6/9/12H* relative wind speed in the distance from the windbreak to the stand position in 3, 6, 9, 12 times the height of windbreak) and locality (*Stredokluky*, *Klapy*, *Dobroviz*); Codes: ●, ▼, ◆ indicate number of PRP (1–6) with locality (S, K, D) with number of couple in the same locality (1, 2) and half part of windbreak (a, b)

first four axes together explained 97.6% variability in the data. The first axis *X* represents width of windbreaks, vertical Arten-profile index, and species heterogeneity together with wind speed. The second axis *Y* represents the mean height of a tree layer and species richness. Wind speed in distances 3H, 9H, and 12H from the windbreak positively correlated with optical porosity, while these parameters negatively correlated with a total diversity, Arten-profile index, species evenness and heterogeneity, size of the windbreak and dominant height of the tree layer. The timber volume positively correlated with mean age and number of trees in the windbreak, while these parameters negatively correlated with height and diameter differentiation, wind speed in the distance 6H and aggregation index (tendency of aggregation with increasing number of trees). The mean height and species richness had minimum impacts on the windbreak efficiency. The contribution of species richness was relatively small. The windbreaks significantly differed for PRPs. PRP with two tree rows with higher optical porosity, wind speed on the leeward side and structural differentiation occupied a right part of the diagram while PRP with three and four tree rows was characterized by higher dominant height, total diversity, vertical structure, species diversity, and timber volume (left part of Fig. 6). Differences in one type of the windbreaks were remarkable, especially for the locality of Klapy (3K1, 4K2) as record marks were relatively distant from each other, whereas record marks for Dobroviz (1D1, 2D2) and Stredokluky (5S1, 6S2) were fairly close together in the diagram. Generally, increasing size and structural complexity of the windbreak had positive effects on the wind-speed reduction.

The structural indices, which mostly influence the windbreak permeability (relative wind speed) are index of complex diversity *B* ($r = -0.81$) and Arten-profile index describing vertical structure ($r = -0.73$). The strongest correlation was found at the distances of 3H and 6H. The indices of species diversity E_1 ($r = -0.72$) and evenness ($r = -0.69$) also significantly negatively correlated with wind speed ($p < 0.05$). Wind speed behind the windbreak was also significantly influenced by dominant height of the windbreak vegetation ($r = -0.76$, $p < 0.01$). The optical porosity was correlated with wind speed ($r = -0.80$), particularly bottom part of the windbreaks ($r = -0.84$).

Discussion

We found moderate to very rich species richness in woody parts of the windbreaks investigated in three localities. Similar results have been reported in southern Moravia of the Czech Republic (Kolibáčová 2000; Tichá 2009). However, relatively higher diversity of woody species in the windbreaks has also been reported in other studies, e.g. Mužíková and Jareš (2010). Forming a higher species diversity in the windbreak has been a long tradition in southern Moravia (Šanovec 1948), while lower species diversity can be found elsewhere in the USA (Stoeckeler 1962; Brändle et al. 2004; Singh 2010). In the latter case, the windbreaks were often created by only one species of woody plant (Lee et al. 2010). Woody leafy/deciduous plants of various species have frequently been planted to build the windbreaks in the Czech Republic (Tichá 2009; Mužíková and Jareš 2010). Significantly different stand structures and species compositions have been reported in other countries, e.g., in northern America or Canada, where windbreaks often consist of only coniferous woody plants (Brandle et al. 2004; Lin et al. 2007; Lee et al. 2010). However, no report of appropriate comparisons is available among the indices describing windbreak biodiversity in the existing literature because of a little attention paid to the issues.

Our study show different windbreak types have different significant effects on the structure and species diversity, which are influenced mainly by width of the windbreaks. The biggest influence on the wind-speed reduction was marked in the index of overall diversity B and Arten-profile index describing vertical structure of the windbreaks. It is necessary to consider this fact when building the individual windbreak types in a particular environmental condition of the forest stands (Straight and Brandle 2007). The windbreak is necessary both from ecological and economic points of view, and therefore structure and sizes of a windbreak need to be optimal for achieving desired objectives (Pasák 1970; Tichá 2009). The windbreaks provide habitat for various types of wildlife, have the potential to contribute benefits to the carbon balance equation and economic profits associated with climate change (Brandle et al. 2004; Vacek et al. 2015a; Bošela et al. 2016). A much beneficial windbreak seems to be a closed, quadrangle network with longer side, made up perpendicular to the direction of the prevalent wind and neighboring cross-windbreaks to catch the wind blown from the sides (Fekete 1961). Appropriate width of the windbreak has been reported by Cablík and Jůva (1963), which varies from 8 to 11 m, and height reaching up to 16 m, in the locations with dusty storms. When woody plants are fully grown, 5–7 rows windbreak could fulfill the desired objectives. More numbers of row of alternating trees are more effective than one- or two-row windbreaks (Bitog et al. 2012), which is in line with our results. Minimum spacing of rows should vary between 1.5 and 2 m and distance of seedlings and young plants between 0.7 and 1.5 m, depending on the type of species planted and maturity of the planting materials used (Pasák 1970; Heisler and DeWalle 1988).

In our study, the horizontal structure of tree layers was random based on the indices and L-function examined. The random to regular spacing of tree layers in the windbreaks has been reported in southern Moravia (Tichá 2009). Tree layers of the windbreaks also represent the production potential that can be higher compared to other layers. The timber volume of a 4−5-row windbreak at the age of 66 reached nearly to 450 $m^3 ha^{-1}$ (sizes approx. 25 × 400 m) in the locality of Dobroviz. Similar production potentials were also found in other studies (Brandle et al. 1992, 2004).

The highest optical porosity was found in the windbreak of Stredokluky (51%), while the lowest optical porosity was observed in the windbreak of Klapy (27%). The optical porosity, in our case, was positively correlated with vertical stand structures (divided into six layers) of the windbreak ($r = 0.42$). Similar windbreak porosities were also observed in the measurements for southeast of the Czech Republic. In this case, porosities of leafy windbreaks were found to be a little less than 30%, and it reached up to 50% after losing foliage (Mužíková and Jareš 2010). Similar porosity values (20–50%) have been also reported in the windbreaks in China (Yang et al. 2017). Frequently recommended porosity value lies between 40% and 50% (Muchová et al. 2008; Podhrázská et al. 2008) and this range can be considered to the most efficient in terms of mitigating wind surges (Brandle et al. 2004; Yang et al. 2017). This is also supported by the findings of Forman and Gordon (1986) and Cleugh and Huhges (2002), who found the windbreaks having moderate porosities as optimal ones. The windbreak porosity is significantly affected by number of rows, inter-row distance, height differentiation, amount and density of leaf and branch of tree or shrub species of the windbreaks (Bitog et al. 2012; Kuhns 2012). The porosity decreases with decreasing structural complexities of the windbreak (Thuyet et al. 2014). The porosity decreases with increased abscission (leaf falling), and therefore level of porosity may change from season to season (Heisler and Dewalle 1988; Gardiner et al. 2006; Mužíková and Jareš 2010). Coniferous trees used in the windbreaks have indisputable advantages of the windbreaks in terms of their optical porosity (Lin et al. 2007; Lee et al. 2010).

In a series of the wind-speed studies carried out so far, significant correlations have been found between the reduced wind speed around the windbreak and optical porosity ($r = 0.80$; Řeháček et al. (2017)) and correlation coefficients could increase to the maximum ($r = 0.94$). However, other literature does not describe such relationship using the correlation coefficients (Abel et al. 1997; Vigiak et al. 2003). The wind-speed reduction was observed behind the windbreak (leeward side), with the highest efficiency for 4−5-row trees and shrubs planted in the locality of Klapy. However, decreasing wind speed with the smallest effect on wind erosion was found in Stredokluky, where two-row windbreak exists, and this can be due to smaller width and height, less complex specie composition and low level of optical porosity of the windbreak. The effect of the windbreak on reducing wind speed was found in all distances, even in the distance 12H from the windbreak, which is not in line with the results by Wu et al. (2013). Brandle et al. (2004) have stated that the wind-speed reduction of multiple row windbreaks is between 40 and 55% at the distance of 12H. However, in this study the wind-speed reduction was observed in the range from 79 to 86% at the distance of 12H. Heisler and DeWalle (1988) and Vigiak et al. (2003) have published that the protective area on a windward side is up to the distance of 35H. However, the wind-speed reduction of 80% has been observed to the distance of 17H (Vigiak et al. 2003). Thuyet et al. (2014) have observed the influence of the windbreak of 80% up to the distance of 20H according to the windbreak structure.

Conclusion

This study shows that well-established and well-maintained windbreaks provide ecological benefits, such as increased production efficiency, biodiversity, amelioration of microclimate, and protection of the local environment. The windbreaks significantly contribute to a decreased wind speed, thereby protecting soil against wind erosion, increasing land productivity, protecting agricultural crops, increasing recreational values of the landscape. The optical porosity along with suitable structural indices, especially those based on the complex diversities are recommended for efficient and effective windbreak establishment. Moreover, the windbreaks even have high production functions, particularly in terms of wood production in the tree layers, which can be utilized by land owners through a gradual renewing of the windbreaks established on their field plots or parcels. However, less attention has been paid by landowners to the issues of the windbreaks, i.e. particularly for a long period until windbreaks grow up and start providing ecological and economic benefits. If the windbreaks were properly created, taken care, and kept intact or well maintained, they have long-lasting positive effects on the local environment of agricultural farms. Thus, agrarian policy should be made in favor of establishing the effective and efficient windbreaks. The windbreaks will always have increasingly bigger importance in agricultural landscapes with a minimum extent of the forest coverage for a given perspective of the global climate change.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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