



Aerodynamic properties of windbreaks of various designs formed by thinning in central Ukraine

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Abstract In this article, we investigate the regulation of wind regime by windbreaks of different designs formed by thinning. In particular, we look at the effects of thinning in 52–67 years old oak stands. Based on our results, different windbreaks designs of foliage and aphyllous states influence wind regime of adjacent fields. This research shows that windbreaks of sieve-looking and blown designs with an average optical porosity of 20–25% between the trunks and 5–10% in the crowns have better aerodynamic properties than windbreaks of dense design. The

uniformity coefficient of reduction in the airflow ranged between 0.42 and 0.76. There is a clear tendency to decrease wind velocity at a distance of 15H in the leeward side, which has a beneficial effect on agronomic productivity of the surrounding areas. With the transition of windbreaks from full foliage to aphyllous state the optical trunk porosity of plantations increases 1.8–3.0 times, and in crowns—2.5–4.0 times. The windbreaks of blown and sieve-looking designs in the aphyllous state with an average porosity between trunks of 40–50% and in the crowns of 20–30%, regulate more effectively the wind regime in comparison with windbreaks of dense design. According to our findings, the windbreaks of blown design with porosity 40–50% between the trunks and 0–10% in crowns and sieve-looking design have the best ameliorative properties in the region.

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Introduction

Windbreaks fulfil an important function among available measures aiming to increase the productivity of agricultural crops. They are effective in preventing droughts, dry winds, water and wind erosion in natural areas. In particular, windbreaks of optimal structures provide a favourable effect on the microclimate of

adjacent fields (Alemu 2016; Pylypenko et al. 2019). Windbreaks also constitute an important element of agroforestry systems (Pylypenko et al. 2004) and as a climate change mitigation and adaptation tool for agriculture (Schoeneberger et al. 2012).

Ukraine has more than 200 years of history of protective afforestation and windbreak systems. Since the early 1930s, field protective afforestation was carried out regularly by the state, regional and local projects (Pylypenko et al. 2019). According to the official 2016 statistics, agricultural lands in Ukraine cover 70.8% of land area, including 53.9% of arable lands, while forestlands occupy about 15.9% of the area (State Agency 2017). The most common landscapes are the agricultural ones, meaning landscapes which are based on farmland and protective forest stands (Yukhnovskiy 2003). In general, more than 85% of the land base in Ukraine is sustainably managed in forestry or agriculture. Based on the National Standard of Ukraine, “Agricultural afforestation” defines the term of “forest agricultural landscape” as an agricultural landscape with a complete system of protective forest stands (ISO 48-74: 2007). According to the Standard, forest-agricultural landscape is an agricultural landscape with a system of protective forest plantations that includes windbreaks. Optimal placement of windbreaks in forest-agricultural landscapes is one of the determining factors of a positive impact on surrounding areas. If chosen correctly, the direction of and distance between windbreaks ensure maximum protection from negative natural phenomena such as dry winds and ensure sustainable use of agricultural land.

Over the years, many scientists researched wind regime of windbreaks (Pylypenko et al. 2004) and reported a wide range of windbreak influences on reducing wind velocity. In many instances, a simulation was used to determine the effect of windbreaks on airflow (Guan et al. 2003; Santiago et al. 2007; Stredova et al. 2012; Hradil 2014). The predictive equations to describe wind speed reductions by windbreak fences were developed by Hong et al. (2015) using non-linear regression analysis. The modelling procedures and accuracy were validated in advance by wind tunnel experiments. The worldwide literature on windbreaks and the response, both positive and negative, to wind protection are given in the book of the First Symposium on Windbreak

Technology (Brandle et al. 2012). State-of-the-art information is presented on general design criteria and principles of planting and establishment for a wide range of conditions and objectives. On the other hand, the regulation of wind and the effectiveness of the windbreaks depends on their width. Osorio et al. (2018) studies have shown that the efficiency of narrow 11-m windbreaks is almost twice as high as 24-m windbreaks.

The effect of windbreaks on the microclimate of surrounding areas depends on their designs (constructions), causing different wind transmission (Bradley and Mulhearn 1983; Wilson 1987; Heisler and DeWalle 1988; Cornelis and Gabrieis 2005; Řeháček et al. 2017). Abel et al. (1997) classify windbreaks in terms of permeability and efficiency into three groups: wind porous, wind medium porous and not porous. Jan et al. (2009) determined that the degree of shelter design correlates with windbreak density. It means that a windbreak with 30% porosity would reduce wind velocity by 70% of open-field speed at the most sheltered location.

The conceptual design of windbreaks is defined by the structure of its longitudinal vertical profile in a leafed state that determines its aerodynamic properties. According to ISO 48-74: 2007, there are four primary windbreak designs (Fig. 1) a. Dense (not-blown) design with almost no gaps (up to 10%) around the longitudinal vertical profile; b. Blown design with optical porosity 30–60% and 10% in the bottom and top of the vertical longitudinal profile, respectively; c. Sieve-looking design with evenly spaced lumen area from 15 to 35% for all vertical longitudinal profile; and d. Sieve-blown design with optical porosity more 30–60% and 15–35% in the bottom and top of the vertical longitudinal profile, respectively.

The maximum reduction in wind velocity differs among windbreaks of different design. Windbreaks of dense design are often characterized by zero wind velocity on the leeward side. Windbreaks of sieve-looking design reduce wind velocity by 20–40% in the initial stage and blown design by up to 40–60%. The windbreaks of blown and sieve-looking designs provide greater wind velocity reduction further down the field in comparison to dense windbreaks.

The objective of this research was to perform a comparative analysis of aerodynamic properties of windbreaks of different structures after thinning and to

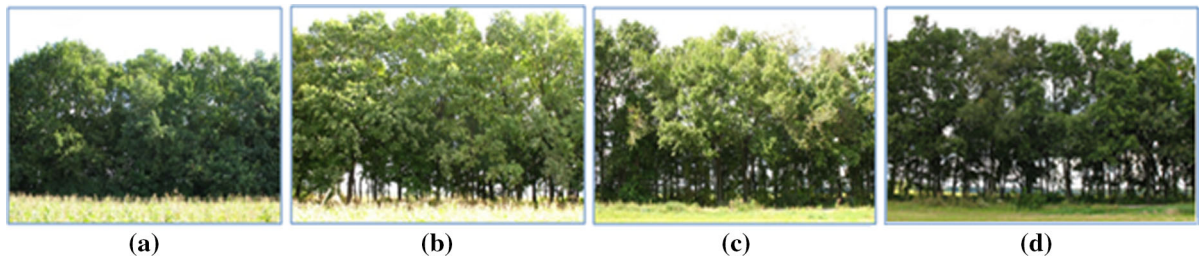


Fig. 1 Different types of windbreak designs: **a** dense (not-blown) design; **b** blown design; **c** sieve-looking design; **d** sieve-blown design

determine the optimal design of windbreaks in the central part of Ukraine. To achieve this objective, we identified the structural features of windbreaks, generated various variants of windbreak designs and determined their forestry and biometric indices on experimental objects, and analysed the aerodynamic properties of windbreaks of various designs taking into account their phenological phase.

Materials and methods

This research of aerodynamic properties of windbreaks of various designs formed by thinning was carried out in agricultural complex “Sovky” in Pushcha-Vodytsa agro-industrial complex in Kyiv region. The spatial placement of windbreaks is presented in Fig. 2.

The system of windbreaks was planted during the 1960s and middle 1970s. Over the past decades, a large part of the windbreaks was in poor condition due to lack of proper forestry management. The primary indicators of their unsatisfactory condition are their poor original design that resulted in the formation of dense edges, poor health condition and the spread of windbreaks on arable land which leads to a sharp increase of their width and alienation into arable land.

The analyzed windbreaks system has reached the third age period (55–65 years), which requires forestry measures to maintain optimal windbreak designs. Among these measures, it is necessary to perform thinnings in the main species and remove dead trees as well as those damaged by natural disasters, pests and diseases.

The formation of a blown windbreak design required removing parts of the second tier, understory vegetation including woody species. All windbreaks

of this system had a dense design with porosity in the full-foliage state of about 5% for oak-maple windbreaks and 5–10% for oak-ash plantations. The existing windbreak design was ineffective under existing forest-ameliorative indicators and did not fully provide adequate protective functions.

For this research, we established 12 permanent sample plots to capture the windbreaks of different thinning intensity. The different windbreaks thinning intensities formed the blown, sieve-looking and sieve-blown designs. The length of each windbreak sample plot was 100 m long. It allowed, to some extent, to avoid the influence of adjacent samples with different thinning intensities. The width of the samples varied from 24 to 30 meters (for an average of 27 m). Crown projections were taken into account when measuring the widths of windbreaks. Thinning intensities and other windbreak attributes are shown in Table 1.

The primary tree species that made up windbreak canopy were common oak (*Quercus robur* L.) and ash (*Fraxinus excelsior* L.). Adjoining trees that formed the second tier were sycamore maple (*Acer pseudo-platanus* L.), Norway maple (*Acer platanoides* L.), silver maple (*Acer saccharinum* L.) and rough elm (*Ulmus scabra* L.). Fruit trees were commonly found in the windbreaks such as cherries (*Cerasus avium* (L.) Moench.), sour cherry (*Prunus cerasus* L.), forest apple (*Malus sylvestris* Mill.). The understory was formed by elderberry (*Sambucus nigra* L.), hazel (*Corylus avellana* L.), dogwood (*Cornus sanguinea* L.), blackthorn (*Prunus spinosa* L.), cherries (*Cerasus avium* (L.) Moench.) and yellow acacia (*Caragana arborescens* Lam.).

The main indicators that characterize windbreaks effectiveness are the length of the zone of reduced wind velocity (range of influence) and the degree of maximum decrease in wind velocity and total wind



Fig. 2 Spatial placement of the windbreaks system (samples numbers are in the circles)

protection. A quantitative indicator of windbreaks' protective effect is an average percentage of wind velocity reduction to 30 H (heights), known as “total wind protection”. According to Pylypenko et al. (2004), the total wind protection in the foliated state of windbreaks of blown design is 45%, sieve-looking—42% and dense—36%. The uniformity of windbreak influence on adjoining agricultural lands in the zone 0–25 (30) H, is characterized by a “uniformity factor” (K). This indicator is defined as the ratio of difference between the maximum and minimum effects in the named part to its average. The smaller K (closer to zero), a windbreak more evenly affects the adjacent fields (Pylypenko and Yukhnovskiy 2000).

We established sample plots in the longitudinal windbreaks, which had a meridian direction of placement and were part of the windbreak system. The field experiments were conducted during two seasonal periods, spring–summer of 2014 and autumn–winter of 2014 and 2015.

The angle of wind flows to research plantations was $90^\circ (\pm 10\text{--}30^\circ)$. Wind velocity was measured at 1 m height from the ground in windbreaks of full-foliage and aphyllous state. The hand-cup anemometers with

counting mechanism MC-13 were calibrated in an aerodynamic tube by State Enterprise “All-Ukrainian State Scientific and Production Center for Standardization, Metrology, Certification and Consumer Protection”. The range of calibrated sensors was $1\text{--}20 \text{ m s}^{-1}$. The measurements were conducted from 11 am to 3 pm.

The method of aerodynamic research included the determination of windbreak wind permeability and wind velocity reduction under the protection of windbreaks in adjacent fields. We carried out aerodynamic research in all variants of windbreak designs for the anticyclonic type of weather conditions with the stable dry winds of the eastern directions (N–E; E; S–E). The air temperature was higher than $20\text{--}25^\circ \text{C}$, the relative humidity of air was less than 40–50%, and wind velocity in an open field at the height of 1 m was more than $3\text{--}4 \text{ m s}^{-1}$.

To record the wind velocity in the adjacent fields under the protection of windbreaks, the anemometric transect was laid perpendicular to the windbreak through its centre on the windward and leeward sides. The anemometers were installed at points selected based on the distances from the windbreak multiplied

Table 1 Parameters of thinning of windbreaks (numerator—overstore, denominator—mid and understory)

Sample numbers	Composition of stand*		Stock, m ³ ha ⁻¹			Closeness (1,0)	
	Before thinning	After thinning	Before thinning	Cut Out	Selected wood, %	Before thinning	After thinning
1	<u>10Qr + Apc</u>	<u>10Qr + Apc</u>	<u>336</u>	–	–	<u>0,8</u>	<u>0,8</u>
	6Apc4Qr	6Apc4Qr	39	–	–	1,3	1,3
2	<u>10Qr + Apc</u>	<u>10Qr + Apc</u>	<u>417</u>	<u>25</u>	<u>6</u>	<u>0,9</u>	<u>0,9</u>
	5Qr5Apc	6Apc4Qr	34	12	35	1,2	0,9
3	<u>9Qr1Apc</u>	<u>9Qr1Apc</u>	<u>365</u>	<u>20</u>	<u>5</u>	<u>1,0</u>	<u>0,9</u>
	6Qr4Apc	5Qr5Apc	35	12	34	0,9	0,8
4	<u>9Qr1Apc</u>	<u>9Qr1Apc</u>	<u>315</u>	<u>32</u>	<u>10</u>	<u>1,0</u>	<u>0,9</u>
	8Apc2Qr	8Apc2Qr	65	41	64	1,0	0,6
5	<u>9Qr1Apc</u>	<u>9Qr1Apc</u>	<u>357</u>	–	–	<u>1,0</u>	<u>1,0</u>
	8Apc2Qr	8Apc2Qr	32	–	–	1,0	1,0
6	<u>8Qr2As</u>	<u>8Qr2As</u>	<u>299</u>	<u>17</u>	<u>6</u>	<u>0,9</u>	<u>0,9</u>
	6As2Qr2Apl	7As2Apl1Qr	52	14	27	1,0	0,8
7	<u>10Qr + Apc</u>	<u>10Qr + Apc</u>	<u>272</u>	<u>2</u>	<u>1</u>	<u>0,9</u>	<u>0,9</u>
	5As3Qr2Apl	6As2Qr2Apl	44	7	16	0,9	0,8
8	<u>10Qr</u>	<u>10Qr</u>	<u>266</u>	<u>1</u>	<u>1</u>	<u>0,9</u>	<u>0,9</u>
	7As3Qr + Apl	7As3Qr + Apl	33	20	61	1,0	0,5
9	<u>8Qr2Fe + Us</u>	<u>8Qr2Fe + Us</u>	<u>270</u>	–	–	<u>0,8</u>	<u>0,8</u>
	8Pc2Fe + Qr	8Pc2Fe + Qr	36	–	–	0,7	0,7
10	<u>7Qr2Pc1Fe</u>	<u>7Qr2Pc1Fe</u>	<u>224</u>	–	–	<u>0,8</u>	<u>0,8</u>
	7Pc2Qr1Fe	7Pc2Qr1Fe	38	4	11	0,7	0,6
11	<u>7Qr2Pc1Fe</u>	<u>7Qr2Pc1Fe</u>	<u>227</u>	<u>6</u>	<u>3</u>	<u>0,8</u>	<u>0,7</u>
	5Us4Qr1Fe	5Us4Qr1Fe	48	4	8	0,8	0,6
12	<u>6Qr3Fe1Pc</u>	<u>6Qr3Fe1Pc</u>	<u>260</u>	–	–	<u>0,8</u>	<u>0,8</u>
	7Pc2Fe1Qr	6Pc2Fe2Qr	40	17	42	0,8	0,5

*Qr—*Quercus robur* L., Apc—*Acer pseudoplatanus* L., Apl—*Acer platanoides* L., As—*Acer saccharinum* L., Fe—*Fraxinus excelsior* L., Us—*Ulmus scabra* L., Pc—*Prunus cerasus* L

by its height (H), and in specific: (a) windward (eastern) side: 1st point—5H, 2nd—1H, 3rd—windbreak edge; (b) the leeward (western) side: the 4th—the leeward edge (0H), 5th—1H, 6th—5H, 7th—10H, 8th—15H, 9th—control. As control was defined as a point of wind measurement located in an open field at a distance not closer than 40–50H from the windward side.

A total of 9 points were installed. The height of anemometer installation was 1 m above the ground and in the cases where agricultural vegetation was present, at a height not less than 0.5 meters above the vegetation cover. The anemometers were screwed into wooden racks and oriented by a dial toward the wind.

A total of 3–5 measurements were collected with a duration of 10 min for each anemometer. During steady wind that blew at 90-degree angle to a windbreak, 1–3 measurement were collected at a time interval of 30 min.

The wind permeability was determined by the ratio of wind velocity to the distance of the windbreak height (H) at the leeward edge to the wind velocity of the control.

The anemometric transects were installed in the treated windbreaks with the design of different porosity formed by thinnings, and on the control plots (where thinning were not conducted). Specifically, in dense (control)—variant I (samples 1, 5 and 9), in

blown—option II (samples 2, 6 and 10), in sieve-looking—option III (samples 3, 7 and 11), in sieve-blown—variant IV (samples 4, 8 and 12). Optical porosity is defined as the ratio between spaces in windbreak to its total area and measured using a digitalized photograph of the windbreak. A digital camera was used for taking pictures. Digital photographs were taken in two phenological phases to evaluate optical porosity of windbreaks of various designs. Optical porosity was estimated for the same location where the measurement of wind velocity was carried out.

The porosity of windbreaks in the foliage state (Table 2) after the thinning varied from 0 to 45% between the trunks and from 3 to 20% in crowns. Prior to the thinning, the porosity along the whole vertical profile varied from 0 to 5%.

To study the reduction of wind velocity on adjacent fields under the protection of windbreaks in aphyllous state, the anemometric transects were installed in the following designs of windbreaks formed by thinning: blown design—variant VI (samples 2, 6), sieve-looking one—option VII (samples 3, 7), sieve-blown design – option VIII (samples 4, 8). Determination of wind velocity for comparative analysis (control) was also carried out in plantations with dense design—option V (samples 1, 5).

Data in Table 3 shows that after thinning porosity of experimental variants of windbreaks in the aphyllous state reaches 20–65% between the trees and 20–45% in crowns.

The design of the windbreak was determined by the openness between the trunks (up to a height of 1.5–2 m) and in crowns. The optical porosity was measured visually from a distance of 50 meters from the plantation and using photographs.

Table 2 The porosity of windbreaks in full-foliage state

Variant	Design of windbreak	Optical porosity, %	
		between trunks	in crowns
I	Dense	0–5(10*)	0–5(10*)
II	Blown	25–35	3–5
III	Sieve-looking	10–20	10–15
IV	Sieve-blown	35–45	10–15(20*)

*Porosity in the oak-ash windbreaks

Table 3 Porosity of windbreaks in aphyllous state

Variant	Windbreak design	Optical porosity, %	
		between trunks	in crowns
V	Dense	20–30	25–35
VI	Blown	40–50	20–25
VII	Sieve-looking	35–45	25–35
VIII	Sieve-blown	55–65	35–45

Comparative methods of direct field studies (Pylypenko et al. 2004) were also used to assess forestry and meliorative indicators of the windbreaks. Four variants of windbreaks of various designs were laid in accordance with a comprehensive methodology developed by the Agroforestry Department of NULES (Pylypenko et al. 2004) to make a methodological comparison of wind regimes.

The main methodological requirements to the analysis of forestry features of windbreaks include reconnaissance survey and familiarization with the general state of plantations for the purpose of selecting the most typical windbreaks and sites to establish plot samples. The plot size sample determined the number of trees of primary species measured at DBH (diameter at breast height). The upper canopy ranged from 100 to 200 trees, which ensured 2–5% accuracy within 68% confidence interval.

Lower tier (midstory and undergrowth) was analysed separately. The lower tier included trees whose height reached the middle of windbreak crown or differed from the upper canopy trees by at least 20–25%. Growth of trees in the lower canopy was measured on ten uniformly spaced plots in each sample. The dimensions of the latter, with 5-year old undergrowth, were 1 × 1 m and the older age groups were 2 × 2 m. The average height was measured for each plot. The density of growth was set on the following scale: (a) thick with the design coverage 71–100% of the total area, (b) average density of 31–70% and (c) low density up to 30%.

Results and discussion

The mean wind velocity in the open field (50H as control) was 5.0–5.5 m s⁻¹. The data in Table 4

Table 4 Reduction of wind velocity under the protection of windbreaks of various designs in the leafed state

Option	Samples numbers	Wind velocity at the control, m·s ⁻¹ (100%)	Wind velocity at the height 1 m at the different distances of the windbreak H*, % of the control								Kr* (1.0)
			Windward side		Windbreak		Leeward side				
			5H	1H	0H	0H	1H	5H	10H	15H	
I	1	5.5	70	45	33	9	15	27	33	70	–
	5	5.3	79	59	38	15	18	44	53	62	–
	9	5.0	93	48	37	22	25	43	48	63	–
	<i>Average value</i>	5.3	81	51	36	15	19	38	45	65	1.39
II	2	5.5	88	70	83	84	73	59	54	46	–
	6	5.3	89	84	79	81	69	56	55	34	–
	10	5.0	94	91	88	89	65	53	53	39	–
	<i>Average value</i>	5.3	90	82	83	85	69	56	54	39	0.76
III	3	5.5	81	67	63	57	53	53	46	37	–
	7	5.3	85	63	62	56	52	50	44	36	–
	11	5.0	93	75	64	58	53	48	41	36	–
	<i>Average value</i>	5.3	86	68	63	56	53	51	44	36	0.42
IV	4	5.5	88	84	85	86	86	70	57	56	–
	8	5.3	91	87	88	88	84	76	63	59	–
	12	5.0	98	94	96	98	91	65	52	40	–
	<i>Average value</i>	5.3	92	88	90	91	87	70	57	52	0.54

*H—height of windbreak; Kr—coefficient of uniformity

indicate that different designs of windbreaks (options I–IV) have different effects on wind velocity within the research area (0–15H). We found that dense windbreak in the zone 0–1H reduces wind velocity the most (by 85% of the control) and at times a relative calm may be observed (option I). Our findings recorded a slight increase in wind velocity at the windward side of windbreaks of blown and sieve-blown designs (variants II and IV) by 1–3%. However, at a distance of 1H on the leeward side, wind velocity sharply decreased, and at a distance of 15H in windbreaks of blown design it was 39% less than the control (option II) and 52% less in sieve-blown windbreaks.

The maximum wind velocity was recorded on the leeward side in dense windbreaks at a distance of 15H (option I) that was 65% more than the velocity at the control. The leeward side of dense windbreaks appears to have formed a negative forest-ameliorative effect. Compared to the control, a decrease tendency of 36–39% was observed in wind velocity at the leeward

side of blown and sieve-looking designs (variants II and III), at the distance of 15H. The alignment of the latter was due to the sieve-looking design of the windbreak (variant IV), where the wind velocity practically reached the minimum speed (52% of control velocity). Wind velocity was reduced most uniformly by the sieve-looking design of windbreak (variant III), where the coefficient of uniformity was 0.42. In the windbreaks of a dense design (variant I) wind velocity was reduced less uniformly (Kr = 1.39). Thus, the windbreaks of sieve-looking and blown design (variants III and II) with medium porosity between trees of 20–5% and between crowns of 5–10% have the most influence on wind regime. The coefficient of uniformity is within the range of 0.42–0.76.

Changes in wind velocity in each windbreak design on the windward and leeward sides were carried out by simulation. During the simulation equations of different forms were analyzed and selected by best fit criteria (highest coefficient of determination, R²).

Table 5 Models of wind velocity change depending on distance to windbreak at windward and leeward sides

Option	Model	Coefficient of determination R^2
<i>Windward side of windbreak</i>		
I	$y = 39.08 \exp (0.1478 x)$ (1)	0.861
II	$y = 81.63 \exp (0.0192 x)$ (2)	0.246
III	$y = 63.48 \exp (0.0616 x)$ (3)	0.858
IV	$y = 88.67 \exp (0.0074 x)$ (4)	0.697
<i>Leeward side of windbreak</i>		
I	$y = -0.0043x^2 + 3.110x + 18.03$ (5)	0.883
II	$y = 71.24 x^{-0.1730}$ (6)	0.709
III	$y = 55.79 \exp (-0.0270 x)$ (7)	0.918
IV	$y = 0.1585x^2 - 5.050x + 91,82$ (8)	0.862

*y—the wind velocity, % of the control; x—distance, H

Table 5 provides the equation for each model and corresponding R^2 .

A graphical representation of the wind velocity reduction (aerodynamic curves) by models 1–8, is shown in Fig. 3.

Figure 3 demonstrates a sharp reduction wind flow at the leeward side in windbreaks of dense design and its increase for the distance of 15H reaching the initial value while the other designs of windbreaks smoothly reduce the wind velocity. Thus, windbreaks of blown and sieve-looking designs have the best influence on adjacent field microclimate indicators. Středa et al. (2008) investigated the wind regime of two-rows windbreaks created mainly by *Acer* sp. and *Fraxinus*

excelsior. According to the data of Středa et al. (2008) the average optical porosity of two-row windbreaks in foliage phase was 20% (May), and the reduction of average wind speed on the leeward side of windbreak in the distance of 100 m from windbreak was about 54% in this stage. Such porosity is inherent in our windbreak of blown design. With the same porosity, the windbreak reduces the speed in the zone up to 7 heights (100 m) to 51%. The changes in the phenological phase (leaf fall) result in increases in the porosity of windbreaks. The analysis of the effectiveness of windbreaks in the aphyllous state was carried out on the same variants of the windbreaks as a full

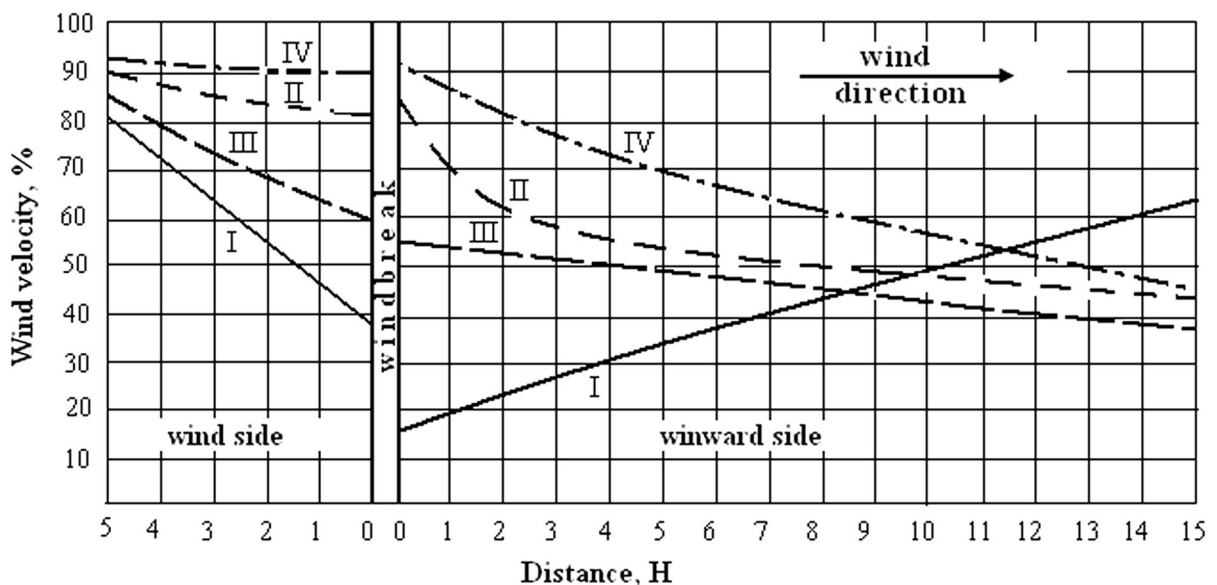


Fig. 3 Change of wind velocity by windbreaks of various designs in the foliage phase: I – dense; II—blown; III—sieve-looking; IV—sieve-blown design

foliage one. During aerodynamic studies, wind velocity averaged 3.0–3.2 m·s⁻¹.

Wind velocity flow characteristics in inter-windbreak fields in the zone 0-15H, depending on the design of a windbreak in the aphyllous state, are given in Table 6. At the same time, Fig. 4 illustrates these phenomena.

Changes in the phenological state of windbreaks (by transitioning from foliage state to aphyllous one), result in rising in the porosity of plantations of different designs between trunks in 1.8–3.0 and between crowns in 2.5–4.0 times.

Koh et al. (2014) researched the seasonal effectiveness of a Korean traditional deciduous windbreak in reducing wind speed. They determined that the relative wind speed reduction at 2H significantly decreased from 83% to 48% with the loss of foliage. However, the relative wind speed reduction at 6H significantly increased from 26% to 43%. Our data show that in the 2H zone, the defoliated windbreaks reduce wind speed from 85% (sieve-blown design of windbreak) to 64% (dense design). Korean windbreaks had the best wind protection (up to 43%) as their width reached 40 m, which is three times higher than the windbreaks we studied.

Sřreda et al. (2008) mentioned during the second measurement (October) the optical porosity of 20% and maximal wind speed reduction of 37% were assessed. According to our data (Fig. 4), the windbreak in the aphyllous state reduces wind velocity on the leeward side of windbreak in the distance of 100 m to 75%. The more effective reduction of wind is explained by the greater width of the windbreak consisting of five rows of trees.

Loeffler et al. (1992) found out the minimum wind speeds behind the windbreaks ranged from 29 to 71% of open wind speed, and these values were located 2 to 6 multiples of windbreak height away from the windbreak. The lower border of optical porosities in the windbreaks located at southern Ontario ranged from 0 to 31% which corresponds to the blown design of the windbreaks in the full-foliage state. So, data of speed reduction is consistent with our data, where the wind speed in the 5H zone on the leeward side decreases from 38 to 70% in the windbreaks of various designs.

Japanese scientists Guan et al. (2003), as well as Yusaiyin and Tanaka (2009) analyzed wind regime in laboratory condition using Eiffel-type non-circulating wind tunnel. They concluded that wind velocity could

Table 6 Reduction of wind velocity under the protection of windbreaks of various designs in the aphyllous state

Option	Samples numbers	Wind velocity at the control, m s ⁻¹ (100%)	Wind velocity at the height 1 m at the different distances of the windbreak H, % of the control								Kr (1,0)
			Windward side		Windbreak		Leeward side				
			5H	1H	0H	0H	1H	5H	10H	15H	
V	1	3.2	89	74	68	69	60	62	68	73	–
	5	3.0	96	81	73	69	67	71	74	79	–
<i>Average value</i>		<i>3.1</i>	<i>92</i>	<i>77</i>	<i>70</i>	<i>69</i>	<i>64</i>	<i>66</i>	<i>72</i>	<i>75</i>	<i>0.16</i>
VI	2	3.2	87	79	75	78	72	69	65	69	–
	6	3.0	96	87	80	83	78	75	72	75	–
<i>Average value</i>		<i>3.1</i>	<i>91</i>	<i>83</i>	<i>77</i>	<i>80</i>	<i>75</i>	<i>72</i>	<i>69</i>	<i>72</i>	<i>0.15</i>
VII	3	3.2	89	78	71	70	68	69	68	73	–
	7	3.0	96	88	80	78	75	73	77	79	–
<i>Average value</i>		<i>3.1</i>	<i>93</i>	<i>82</i>	<i>75</i>	<i>74</i>	<i>72</i>	<i>71</i>	<i>72</i>	<i>76</i>	<i>0.07</i>
VIII	4	3.2	91	81	88	89	82	69	68	70	–
	8	3.0	98	90	96	96	89	82	77	79	–
<i>Average value</i>		<i>3.1</i>	<i>94</i>	<i>85</i>	<i>92</i>	<i>93</i>	<i>85</i>	<i>75</i>	<i>74</i>	<i>74</i>	<i>0.24</i>

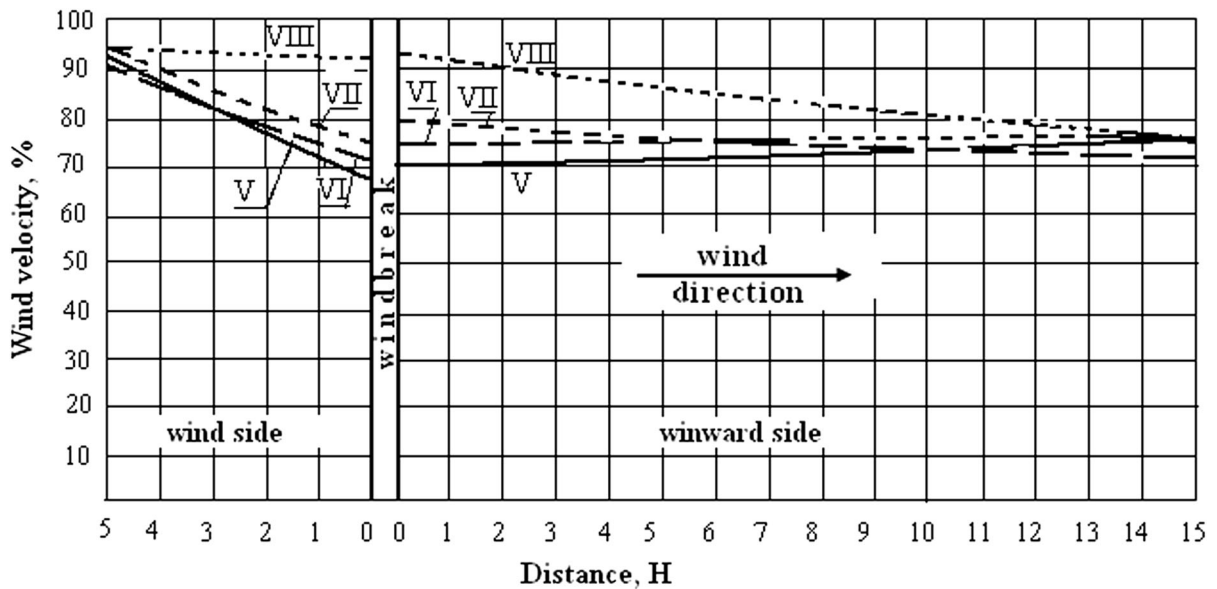


Fig. 4 Change of wind velocity by windbreaks of various designs in the aphyllous state: V—dense; VI—blown; VII—sieve-looking; VIII—sieve-blown design

be decreased by 15–22% with increasing width of windbreaks.

Studies of Řeháček et al. (2017) have shown that 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.

Our research found that the minimum wind velocity is observed the most in designs formed by thinning (variants VI, VII and VIII) at a distance of 5–10H (10–15H for sieve-blown design) and is 69% for blown, 71%—sieve-looking and 74% for the sieve-blown design of the wind velocity in the open field. At the same time in a foliage state, a minimum is observed in the zone of 15H. At the control (dense structure—variant V), the minimum wind velocity in the aphyllous state of windbreaks (64–66%) was recorded at a distance of 1–5H, and in the full foliage state, the minimum (15–19%) was shifted to a leeward edge (0–1H).

The aerodynamic effect created by thinning in the lower part of windbreaks of blown designs (variants VI and III) has led to an increase in wind velocity both in the middle of plantations and in close proximity to them. This phenomenon is clearly reflected by aerodynamic curves illustrated in Fig. 4.

Based on our results, the average decrease in wind velocity in windbreaks of different designs in the aphyllous state in comparison with the foliage one decreased by 1.5–2.0 times, and in dense plantations by 4 times.

Conclusions

Windbreaks are the primary biological elements of typical Ukrainian agroforestry systems and have multifunctional uses that provide multiple economic and ecological benefits. The economic impact of windbreaks is captured by their positive effect on the microclimate of agricultural fields, an increase in the yield of agricultural crops and firewood products from thinning activities. In central Ukraine, windbreaks tend to have dense design and on unsatisfactory tree-health conditions. In this regard, it is important to form optimal windbreaks design of high protective properties by improving tree health and vigour. This research established that windbreaks of sieve-looking and blown designs with average optical porosity between the trunks of 20–25% and in crowns of 5–10%, retained most of their aerodynamic properties. The coefficient of uniformity of wind flow reduction is within the range of 0.42–0.76. Wind velocity tends to

decrease at a distance of 15–20H, which has a beneficial effect to agronomic productivity of the surrounding areas. Phenological state of windbreaks changes (the transition of growing to dormant season) the porosity of plantations between the trunks increases by 1.8–3.0 times and in crowns—2.5–4.0 times. The windbreaks of blown and sieve-looking designs in the aphyllous state with an average porosity between the trunks of 40–50% and in crowns of 20–30% are more capable to effectively regulate the wind regime when comparing to windbreaks of dense design. Our research further found that the windbreaks of blown design with porosity 40–50% between the trunks and 0–10% in crowns have the best ameliorative properties in the region.

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