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Research Paper

The Effect of Trees with Irregular Canopy on Windbreak Function in Urban Areas

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Abstract
Wind as an atmospheric element has some annoying aspects, therefore, controlling it and reducing its speed is one of the most important matters, which should be examined in landscape engineering. Natural windbreaks such as rows of trees with different gap distances between them are used to decrease wind velocity. The current study numerically investigates the effect of trees with irregular canopy form on wind speed reduction in urban open spaces and green belts. The computational fluid dynamics (CFD) is used to simulate airflow through the trees as 3D forms. Quercus sp. is chosen as a typical tree with irregular crown shape. The influence of some criteria such as; 1. Number of tree rows, 2. Gaps between trees, 3. Trees arrangement patterns, and 4. Height levels on wind speed reduction are examined at this study. According to the results, the best reduction is observed for the heights above 5 meters with 0.50 m gap distance between trees. The results also reveal that rectangular two-row arrangement of trees with irregular forms is more effective than the other arrangements in reducing wind velocity.

Keywords: *Wind barriers, Wind velocity, Tree canopy, Numerical simulation.*

1. INTRODUCTION

One of the harmful factors which is effective on urban facilities or agricultural activities are the severe winds in each geographic region. Therefore, it is necessary to use the species with sufficient strength and environmental aesthetics values and also appropriate economic values to confront with these conditions. Lee et al. (2010) showed windbreak forests have been used for various purposes including reduction of wind speed, pollutant diffusion, improvement of environment, or increase of crop yields. These functional effects of windbreaks are directly related to the reduction of oncoming wind speed. Shelterbelt effectiveness is commonly measured by its sheltering efficiency downwind of the barrier via reduced wind speed (Kozmar et al., 2012).

The main objective of the current research is to investigate the effect of planting patterns on wind speed reduction on urban open space such as parks and green belts. Planting patterns consist of the number of tree rows, the gap distance between trees and crown shape, which are considered as important factors in controlling the wind speed. In this study, the Quercus was chosen as a case study tree with an irregular crown. The wind speed reduction was measured at different distances along the windward and leeward directions from the windbreak. CFD was applied for Numerical simulations in this study. Also, there is no more research regarding the windbreak performance based on tree crown shape.

In ecosystem services, there are several factors that can be limiting the efficiency of trees such as climate changes, plant nutrition needs and the number of water resources (McClure et al., 2017). Recently, trees have been used as windbreaks to reduce environmental issues such as wind speed. Furthermore, human used shelterbelts as techniques to improve the climatic condition and there have been studies more than earlier to find the best way to reduce stiff winds effects in a methodical way (Plate, 1971). The main role of natural elements is saving human life and his micro-environment. Since Shelter belts are capable of decreasing wind annoyance, they have been used all around the world (Basnet, 2015). Therefore, the significant function of windbreaks is preventing the wind flow and changing flow patterns on the windward and leeward of the barrier (Brandle et al., 2009). As mentioned by Plate,

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barriers have been studied to discover the best pattern of fence design in order to provide maximum reduction in wind speed (Plate, 1971).

2. LITERATURE REVIEW

Climate is the factor with the greatest impact on urban areas and open space parks. Almost all land plants have to balance five major requirements: first they need to photosynthesis, second they need to transport water, third they need to grow, four they need to reproduce, and last but not least, they need to have mechanical support under static and dynamic loading throughout their lifetime. One of the major sources of mechanical loading on plants is the wind, which, in turn, has a major impact on plant growth, morphology, physiology and ecology (Gardiner et al., 2016). Wind in the open and urban space can be controlled by a fence whose primary benefit is the reduction of wind velocity (Speckart and Pardyjak, 2014). Barriers are made using materials such as wood, concrete, metal, sod, plastic, stone or vegetation (Pickard, 2005; VerCAUTEREN et al., 2006). Therefore, artificial barriers are often made of rigid materials and are thin and 2-D structures (Khalil, 2008), although plants are three-dimensional structures and the formation of windbreaks is by planting one row or more than one row of trees and shrubs (Cornelis and Gabriels, 2005). Tree windbreaks can be applied to protect extent areas behind windbreaks to deal with extreme winds as recommended by Zhou et al (Zhou et al., 2005). In recent decades, windbreaks have been

Used to protect structures such as houses, outbuildings, roads, etc. from noises (Slusher et al., 1983) and to prevent air pollutants from diffusion (Heisler and Dewalle, 1988).

The most efficient factors that can be effective on aerodynamic features of windbreaks are height of trees (H), crown shape, width, arrangement (number of rows and ordering), density, and porosity, etc. (Li and Sherman, 2015), as well as the main external factors which are wind speed and wind direction. However, several studies have shown that porosity of tree has important effect on windbreak efficiency (Cornelis and Gabriels, 2005). However, there is no actual measurement method to define porosity of trees. However, drag coefficient (C_D) can be used to know tree resistance against wind pressure. The resistance to wind flow or the drag coefficient of the windbreak can provide information on its effectiveness and efficiency in reducing high velocity winds mentioned by (Jacobs, 1985).

Computer simulations have been conducted to study the effect of natural and artificial windbreaks to investigate the factors which are related to the air flow mechanism around obstacles. Dong et al studied the natural windbreaks experimentally in the wind tunnel (Dong et al., 2008). The effect of Black pine trees has been studied as shelter belts by Bitog et al (Bitog et al., 2009). Also, this tree was chosen by them for numerical simulation. Other numerical simulations have been used to survey the wind flow characteristic around natural and artificial windbreaks as done previous researchers (Sanz, 2003; Gromke and Ruck, 2008; Rosenfeld et al., 2010). Furthermore, (Bitog et al., 2012) used experimental results in numerical simulations to design effective windbreak systems with the aim of dust control in Korea. These studies illustrate that CFD is an appropriate numerical method to investigate flow characteristics such as wind. Also, Raine and Stevenson offered the measurements of wind speed on the leeward side of fences (Raine and Stevenson, 1977). Other researchers developed a numerical model to simulate wind flow around single and multi-array windbreaks (Wilson, 1985; Wilson, 1987; Wilson and Yee, 2003). There are also two valuable reviews presented by Caborn (1957) providing a general understanding of a windbreak classification and also the microclimatic factors affected by windbreaks (Caborn, 1957). Heisler and Dewalle (1988) explained a review work on the effect of windbreak structures on wind flow, as well as some secondary effects related to wind speed reduction (Heisler and Dewalle, 1988).

Windbreaks lead to change in wind flow patterns and are capable of protecting extent areas behind shelterbelts. Therefore, structural features of windbreaks can be effective on the total extent of the protected area and are able to decrease wind velocity and improve microclimate conditions (Zhou et al., 2005). Furthermore, as mentioned by Bitog et al. (2011) the application of shelterbelts reduces wind velocity and changes aerodynamics characteristic (Bitog et al., 2011). Consequently, since high-speed winds are the critical problem all around the world, finding the appropriate planting pattern for windbreaks is one of the most essential needs in landscape engineering.

Windbreaks are a long-term investment. They need to be carefully designed to ensure that the desired benefits are obtained. Homes, livestock, and fields are the most common areas needing protection. Windbreaks lead to change in wind flow patterns and are capable of protecting extent areas behind shelterbelts. Therefore, structural features of windbreaks can be effective on the total extent of the protected area and are able to decrease wind velocity and improve microclimate conditions (Zhou et al., 2005).

Arid and windy regions of Iran, urban areas, regional parks, and high urban buildings are susceptible to wind damage. Methods such as vegetative barriers have been implemented to minimize wind unpleasant effects. Landscape engineers and planners often use vegetative barriers (also called windbreaks or shelterbelts) because they are perceived to improve aesthetics of urban areas and shelter downwind urban areas from unfavorable wind effects. Other benefits of shelterbelts include changing microclimate of soils (Campi et al., 2009), increased crop yield crop protection (Bird et al., 1993), restoration of soil fertility (Sudhishri et al., 2008), and aesthetic benefits (Grala et al., 2010). In order to reduce the wind velocity by windbreakers in the urban areas, it is expected that the best planting pattern is obtained by taking into gap distance between trees, arrangement of trees and appropriate height from the ground.

Although the current study is conducted for a specific crown shape (irregular form), the results acquired in this study can be used to compare the capability of trees with other crown shapes in reducing wind speed in the future studies.

3. MATERIALS AND METHODS

The main purpose of this study is recognition of efficiency of trees with an irregular crown shape in reducing wind velocity. Computational fluid dynamics (CFD) has been vastly used as a powerful tool for simulating natural phenomena. Manufacturing test setups for many studies is a rather expensive, time-consuming and even impossible while using numerical methods such as CFD approaches makes such studies possible and lowers the costs. In the current study, CFD was applied to investigate planting patterns effects on reducing wind power. Also, All the conducted procedures were accomplished in ANSYS Workbench Commercial code. By helping the numerical method, simulations were conducted to simulate the conditions in a real wind tunnel, in order to validate the results with experimental results from the former studies. The wind tunnel can be referred to as a research environment, which has been used in studies to investigate the impact of air flow around barriers. In computational modeling of turbulent flows, one common objective is to obtain a model that can predict quantities of interest, such as fluid velocity, for use in engineering designs. By dividing domain into a set of non-overlapping attached rectilineal cells, and applying the boundary conditions for boundary nodes, a linear equation is acquired, which solves algebraic equations, velocity, pressure and temperature in the computational domain. Furthermore, numerical methods were used to solve the linearized potential equations. CFD simulation utilized to solve momentum and continuity equations. The continuity equations are the basis for certain transmission equations such as the Navier-Stokes (RNAS) equation. RNG k-model is vastly used to investigate the wind flow turbulence in wind tunnels. However, k- is a rather reliable model to use in this study based on [27].The importance and efficiency of Fluent commercial code for this type of numerical simulations has been debated by other researchers (Lee and Lim, 2001;Wilson and Yee, 2003;Bitog et al., 2009;Rosenfeld et al., 2010;Bitog et al., 2011;Bitog et al., 2012). Equations for continuity and RANS are presented as follow:

$$\frac{\partial \overline{v_i}}{\partial x_i} = 0 \tag{1}$$

$$\overline{\mu}_j \frac{\partial \mu_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{P}}{\partial x_i} + v\frac{\partial^2 \overline{\mu}_i}{\partial x_j^2} - \frac{\partial}{\partial x_j}(\mu'_i \mu'_j) \tag{2}$$

where ρ, μ , v, and P are air density (kg.m-3), air viscosity (N.s.m-2), velocity (m s-1), pressure (Pa), respectively. The ongoing research utilizes the numerical methods to enhance the precision and acceleration of complicated simulations such as for turbulent flows. In this study, Quercus species are assumed to have an irregular shape, and the geometry of trees was created as a 3D model that was developed using the design modeler environment of ANSYS Workbench. The visual perception of trees geometry was chosen using the research of Muderrisoglu et al in 2006 (Müderrisoğlu et al., 2006). Trees without any specific exact shape are called an irregular crown tree shape. Irregularly shaped trees add a unique dimension to their landscape. Trees grow up in different size and dimensions in each geographic region. As the velocity contours are shown in Fig. 3, the irregular shape of the tree crown is also visible.

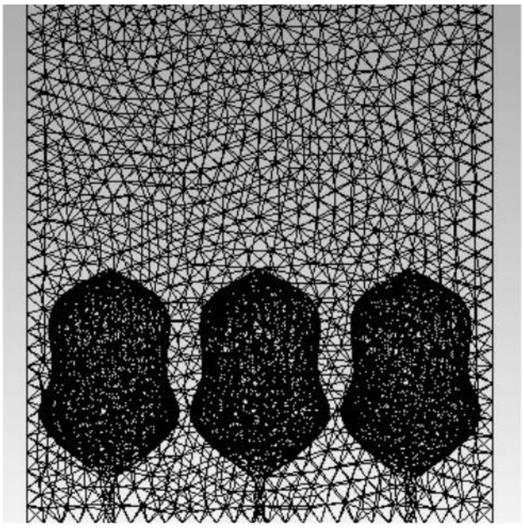


Fig 1. Quercus sp (left), the irregular tree crown shape; Gap distance= .5m, Porous= 30%, Width= 6 m, Height of tree= 11 m (right)

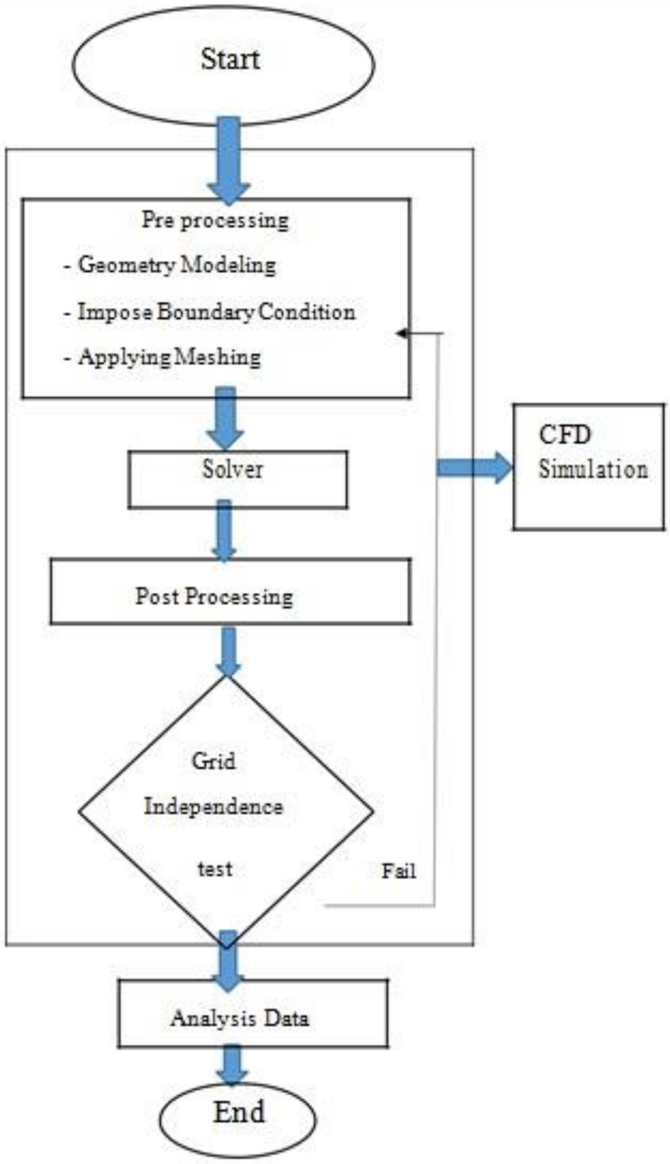


Fig 2. Modelling flowchart in ANSYS Fluent

However, Edward et al. (1993), in the Environmental Horticulture Department in Florida, revealed species characteristic due to variable environmental conditions (Sanz, 2003). The average of dimensions for Quercus species has been considered for the trees growing in Iran, which shows good agreement with real case studies existing in the country.

The most important physical characteristics of tree species are canopy width and height that are considered 6 meters and 11 meters, respectively. In this research, in order to apply the inertial resistance in the simulations, the tree canopy volume was zoned as fluid, where the porous zone was activated. The porosity for Quercus sp. was estimated 30% (70 % density). The numerical simulation is capable of determining the efficiency of the gap distance between trees, number of trees rows and also trees arrangement for reducing wind speed. The values of wind speed reduction were studied at varied heights from the surface (h=1,2,3,4 and 5 meters).

3.1. The computational domain

The total length of the computational domain was 140 meters, and the windward and leeward lengths were designed 27.5 and 112.5 meters, respectively. The total height of the domain was also designed at 5H or 55 m. The 5H has been recommended as the minimum height of the computational domain in previous simulation studies (Franke et al., 2004; Blocken et al., 2007; Tominaga et al., 2008). The width of the simulated wind tunnel domain was taken 20.00, 21.00 and 21.50 m depending on the gap distance between trees, 0.50, 0.75 and 1.00 m, respectively. The total mesh size of the whole domain was 1,371,000 cells. The minimum size of the smallest grid cells was about 0.2 m and the maximum size was 1.00 m. the small size was needed to resolve the flow around upwind and downwind faces. Both sides of the computational domain are symmetrical while the upper and lower sides of the section have been considered as surface walls. One side of the computational domain was considered having velocity inlet boundary condition, while the opposite side of the inlet boundary has pressure outlet boundary condition.

4. RESULTS AND DISCUSSION

4.1. CFD simulations

4.1.1. Validation of the simulations based on previous studies

The significant step in CFD simulations is evaluating the ability of numerical simulations to measure the airflow around barriers, which indicates the importance of validating the CFD results with previously approved results. In this research, results certification was done by comparing the obtained results with the results presented by Bitog et al. (2012) having Black Pine trees used to control dust pollution in the Coastal areas in Korea (Bitog et al., 2012). Therefore, a model using Black Pine trees was developed to compare the results with their work, before using Quercus trees as the elements applied for the current study. The given table shows the percentage of wind speed reduction for simulation study of Bitong et al. (2012) and the current research. Comparing the results shows good agreement between the two studies.

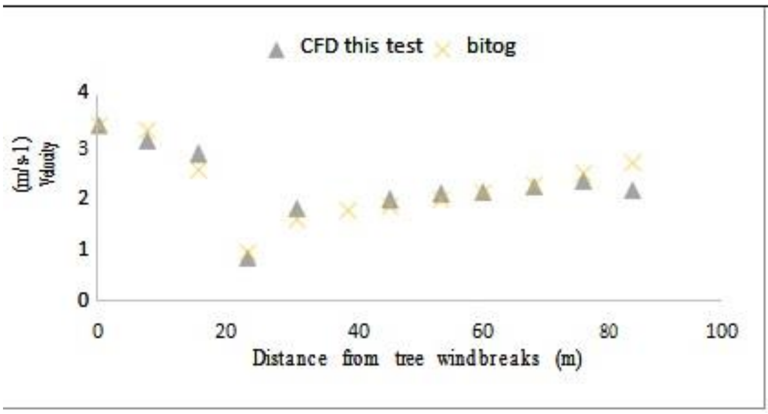
4.1.2. The airflow in the shelterbelts region behind natural windbreaks

Fig. 4 demonstrates velocity distribution in the computational domain for different arrangements with a 0.50 m gap between trees of a row. The wind initial velocity is 3.5m s-

1. As can be seen, the spaces between trees in a row act as a funnel, and the wind is trapped between these spaces. One appropriate strategy to enhance the impact of trees windbreak in reducing wind velocity is using rectangular two-row planting arrangement. However, rectangular two-row arrangement shows more effective velocity reduction at the points near to the windbreak in comparison with the triangular arrangement. It is due to the creation of high-velocity regions just after the windbreak for triangular arrangement, which deactivates the windbreak effect.

Table 1. Data and variables used in the simulation

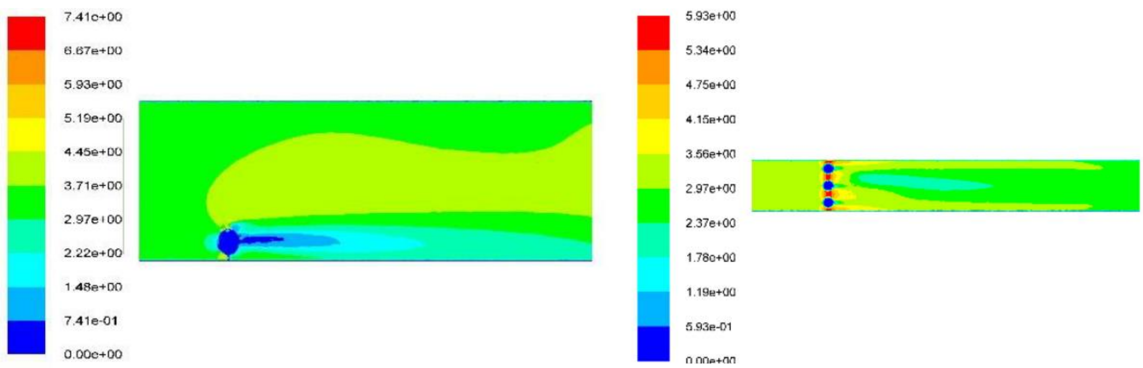
Pre- processing	Size (L ×W ×H)	Trees at 0.50 gap distance :14020.0055 m Trees at 0.75 gap distance :14021.0055 m Trees at 1.00 gap distance :14021.5055 m
	Mesh type	Tetrahedron One-rows of trees: 1258000 Two- rows of trees-rectangular arrangement: 1369000 Two- rows of trees-triangular arrangement: 1371000
	Total mesh number	turbulence mode 0.2 First order upwind Steady state
Main module	Turbulence Surface roughness Discretization Condition	Trees at 0.50 gap distance :14020.0055 m Trees at 0.75 gap distance :14021.0055 m Trees at 1.00 gap distance :14021.5055 m



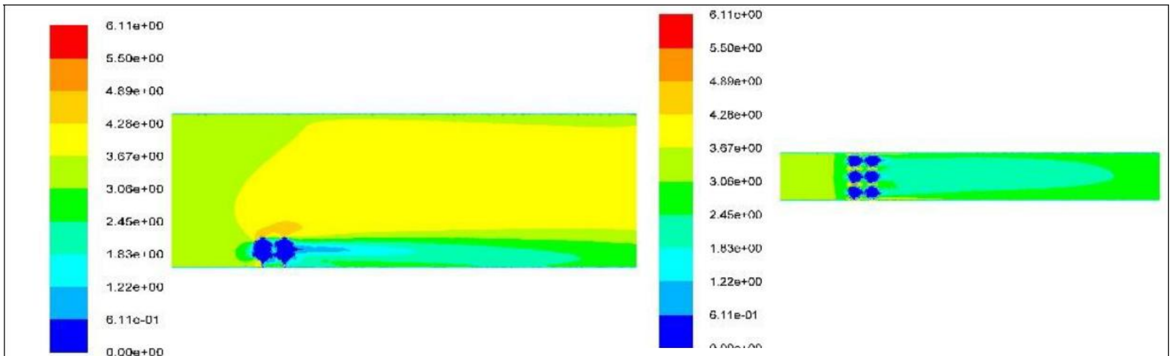
Bitog et al (2012)	this research results
2.85	7.71
24.5	16.0
70.5	73.5
52.8	46.8
46.5	41.4
45.1	57.4
37.7	34.0
32.8	35.7
27.4	31.1
20.5	35.0

Fig 3. Comparison of the results with the simulation results obtained for Black pine trees

f B 1 row



Rectangular two- row, 0.5m gap Rectangular two-row



Triangular two-row, 0.5m gap Triangular two-row

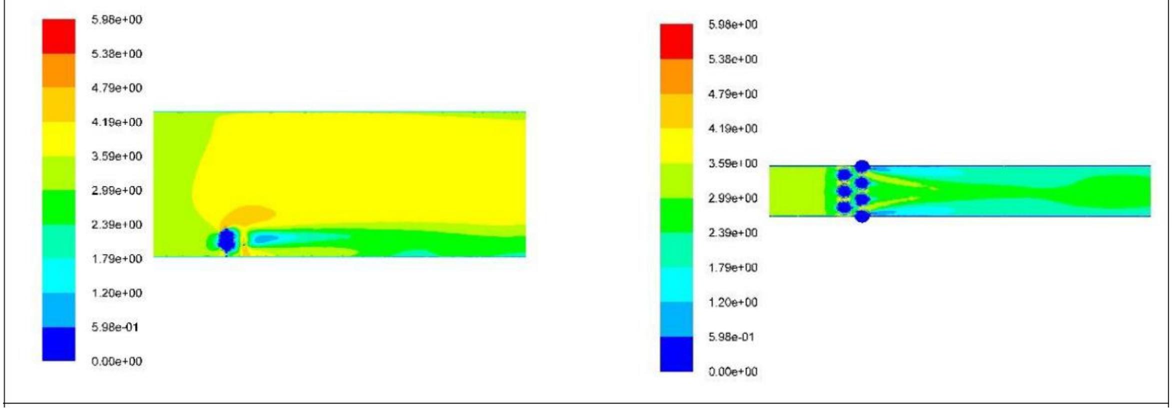


Fig 4. Velocity distribution around tree windbreak): a. side view, b. top view at 4m height

Figures 5a, 5b, and 5c show wind velocity for different arrangements at different distances and different heights from the ground. As it is seen, velocity undergoes a sudden decrease after the windbreak because of the relative stagnation condition created behind the windbreak. By getting away from the trees, velocity retrieves, while its magnitudes at different distances are not as high as the initial wind speed. For 1 row arrangement, 0.75m gap shows the most effective impact on velocity reduction, while for the 2-row arrangements 0.50m gap seems to be more effective. For 2-row arrangements, only 0.50m gap case study results are brought for the sake of abbreviation. The rectangular arrangement shows better results at closer regions, while the triangular arrangement is more effective at further distances. On the other hand, 3-meter height shows the best velocity decrease among different heights from the ground, which is due to the canopy spread at that height.

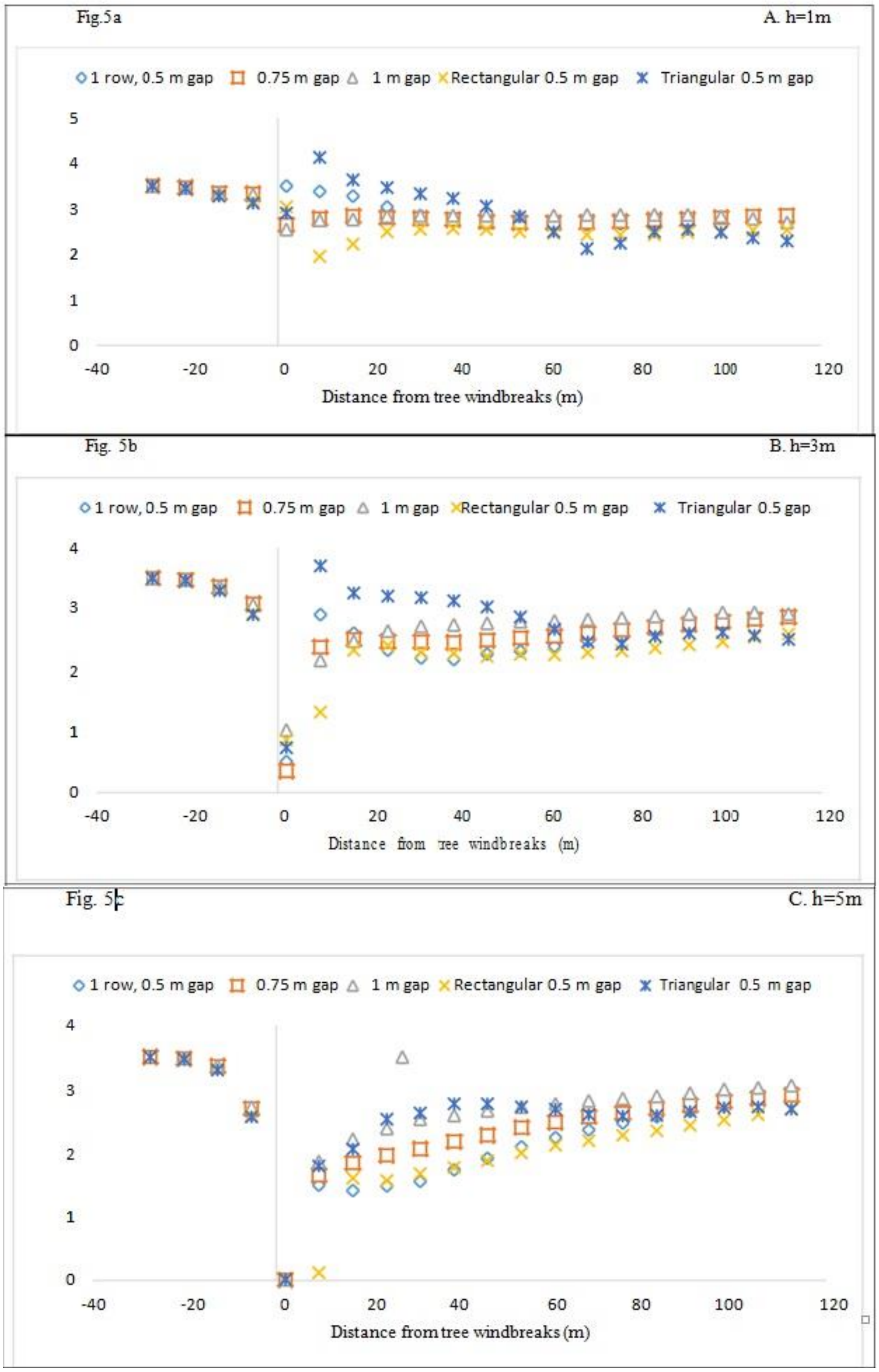


Fig 5a, 5b, 5c. Wind velocity for different arrangements at different distances and different heights (3, 4, 5m) from the ground

4.1.3. The effect of gap distance between trees, number of rows and trees arrangement on speed reduction

In this study, results illustrated that the distance between the trees, arrangement and the number of tree rows can be considered as important factors. These results are consistent with the results of previous research. According to Bitog et al. (2012), increasing distance between the trees can reduce the effectiveness of windbreak trees, which is in good agreement with the current investigation results (Bitog et al., 2012).

Tables 3,4,5,6 and 7 show wind speed reduction for different arrangements of trees at different heights from the surface, 1 until, and 5 meters. Results demonstrate that 5-meter height from the surface has the greatest effect on wind speed reduction. It is due to the maximum expansion of crown at this height level. Also, at closer regions behind the windbreaks, the maximum wind speed reduction was observed, while at further regions wind speed is retrieved. Therefore, the percentage of wind speed decrease is affected by gap distance and trees arrangements.

4.1.3.1. Single-row tree windbreak

For 0.50, 0.75 and 1.00m gaps of one-row tree planting at a 5-meter height from the surface, the percentage of wind speed decrease at 1.5H (H= tree height) distance behind the windbreak are 59.7%, 47.6 %, and 32.0%, respectively. In addition, the reduction percentage values for 4-meter height from the surface with 0.50, 0.75 and 1.00 m gap at the same distance are calculated 43.0%, 38.3%, 32.0%, respectively. As previously stated 1.5H distance, due to the proximity to windbreak has the highest wind speed decrease. On the other hand, the results show that 0.50m gap between trees in single-row arrangement provides protecting a wider area behind the windbreaks from unpleasant effects of wind. Furthermore, for 6H and 9H distances from the windbreaks with a 0. 50m gap between trees at 5-meter height, the reduction is 36.0%, 21.6%, respectively. Corresponding reduction percentages at this distances for 4m height are 34.5% and 21.8%. For 5m height from ground, 0.50m gap shows the highest wind speed reduction. This is because of crown spread reduction at a 5m height. Results from table 3, 4, and 5 illustrate that at 1, 2 and 3-meter height from surface, by increasing gap distance between trees, the wind speed reduction is increased. As an example, at 1.5H distances behind the windbreak at 0.5, 0.75, and 1-meter gap distances, wind speed reduction percentages are 25.8%, 28.5%, and 29.0%, respectively. Similar results can be seen at 1 and 2 meter heights from surface, which are related to the trunk.

The average wind speed at leeward regions of the windbreaks with different gaps of 0.50, 0.75 and 1.00m at the height of 5-meters above the ground are 2.02, 2.24 and 2.51m s-1. it is seen that wind speed reduction in the area behind the windbreaks is highest for a 0. 50m gap in comparison with 0. 75m and 1m gaps.

4.1.3.2. Rectangular two-rows tree windbreaks

Comparing the results of velocity reduction values at different heights from surface with 0.50, 0.75 and 1.00 m gap shows that the maximum wind speed reduction is observed at 5 meter height with 0.50 m gap. At this height, reduction for 0.50, 0.75 and 1 m gap at 1.5H (16 meter) distance are 54.0%, 50.7%, and 38.6%, respectively. Furthermore, at 6H the corresponding values are 39.6%, 34.0%, and 27.9%, respectively. Results indicate that the best wind speed reduction occurs at 0.5 gap distance for both close and further area in comparison to 0.75 and 1 m gap. The percentage of reduction for 5-meter height from the surface with a 0.5m gap at 1.5H, 6H, 9H distances are 59.7%, 36.0%, and 21.6%, respectively. Also, the results of wind speed decrease at 1, 2 and 3 m height from ground shows the highest percentage of wind speed decline at the closer distance behind the windbreaks at 1.5H is related to 1 meter gap, while in other areas the 0.5 meter gap shows the best results of wind speed reduction.

Also, the wind speed reductions at the height of 4-meter from the ground for the 0.50m gap at 1.5H, 6H, and 9H distance are 38.9%,38.6%, and 29.5%, respectively. The average of wind speed on the leeward side of the rectangular two-row arrangement for 3, 4 and 5-meter height from the surface with a 0.5m gap are 2.19, 2.04 and 1.85m/s -1, respectively. This is similar to the corresponding values of single-row arrangement.

4.1.3.3. Triangular two-rows tree windbreaks

The wind speed reductions for a triangular two-row arrangement with 0.50, 0.750 and 1.00 m gap at a 5-meter height from the surface at a 1.5H distance are 41.0%, 38.3%, and 27.0%, respectively. the values of decrease at 6H and 9H with a 0.50m gap are 23.5% and 22.8%, respectively. Since 0.75m gap shows the best results for this arrangement at 3H, and 9H, the data of this gap distance are discussed here for abbreviation. Corresponding results of the two mentioned distances are 26.3% and 25.2%, respectively. In addition, at 4-meter height from the surface at 1.5H, 6H, 9H distance wind speed reduction is 20.4%, 22.9%, and 24.5%, respectively. The average of wind speed at 0.5 gap for triangular two-row planting is 2.56 m/s-1, while for rectangular two-row and single-row planting the reduction is 2.01and 2.18 m/ s-1 in, respectively.

Comparing the results obtained from using the three mentioned tree arrangements, it is obvious that rectangular two-row pattern is more effective for reducing wind velocity in comparison with the two other patterns. The average wind speed for single-row, rectangular two-row, and triangular two-row planting patterns are 2.02, 1.85 and 2.40 m/s-1, respectively. This is in good agreement with the overall conclusion stated above. As the results show, at the height of 4 and 5-meter, wind speed reduction in single row arrangement is better than irregular row planting.

It is obvious that rectangular has a significant impact on wind speed reduction. Also, the two-row planting with rectangular arrangement provides the highest effective resistance against wind. Designing a proper windbreak is an effective way to halter severe winds. Trees with different crown shapes have different effects on wind speed reduction. In the current study, the investigations are conducted for Quercus which is a typical tree with an irregular crown shape that is planted in many regions all around the world. Further studies may concern investigations about trees with other crown shapes.

velocity increase seen in Tables 2,3 and 4 are due to the gaps in the windbreak trees acting as tunnels where the wind flow is concentrated. Therefore, it is expected that the effectiveness of the windbreak decreases in the vicinity of the gaps between trees. It is clearly obvious in Figure 3 where the top view of velocity distribution is presented.

Table 2. Percentage decrease (%) of wind velocity measured at 1 m height

Number of rows/arrangement	Gap distance(m)	Distance from the trees (H: tree height)										Average speed	
		-2H	-1H	1.5H	3H	4H	———	6H	7H	8H	9H	wind	Lee
			10H									ward	ward
One row	0.50	1.38	5.35	6.4	18.4	24.5	24.9	23.8	21.1	19.7	19.9	3.39	2.86
	0.75	1.07	4.54	18.5	20.2	22.3	23.1	22.3	20.7	19.9	18.7	3.40	2.75
	1.00	0.97	4.38	21.0	18.4	18.5	18.4	18.0	18.0	18.8	22.8	3.40	2.80
Rectangular Two-rows	0.50	1.45	6.07	36.4	27.3	27.3	29.8	30.9	29.5	28.6	27.7	3.35	2.47
	0.75	1.36	5.96	31.6	24.4	23.1	24.8	26.6	27.8	28.0	27.5	3.35	2.55
	1.00	1.26	5.47	45.2	31.4	28.5	28.3	28.1	27.8	28.0	31.5	3.36	2.35
Triangular Two-rows	0.50	1.51	6.59	-3.6*	4.77	12.8	28.5	35.9	27.1	29.2	34.5	3.33	2.84
	0.75	1.40	6.15	-2.5*	5.44	10.7	19.7	27.8	30.1	28.4	29.3	3.34	2.94
	1.00	1.33	5.80	-3.5*	3.94	9.27	17.3	24.2	27.0	25.5	26.0	3.35	3.00

*: means wind speed increase

Table 3. Percentage decrease (%) of wind velocity measured at 2 m height.

Number of rows/arrangement	Gap Distance (m)	Distance from the trees (H: tree height)										Average speed	
		-2H	-1H	1.5H	3H	4H	———	6H	7H	8H	9H	wind	Lee
		10H										ward	ward
One row	0.50	1.07	4.92	13.1	26.5	29.9	28.2	25.2	22.0	20.1	18.5	3.38	2.69
	0.75	0.86	4.10	22.8	24.3	25.3	24.7	23.2	21.0	20.0	19.0	3.39	2.60
	1.00	0.80	3.91	25.4	19.7	19.3	18.8	17.9	16.9	16.9	19.5	3.39	2.65
Rectangular Two-rows	0. 5	1.17	5.62	31.9	28.3	30.1	32.0	32.1	30.3	28.9	27.7	3.34	2.32
	0.75	1.15	5.45	30.4	22.9	24.0	26.1	27.3	27.8	27.7	26.5	3.34	2.43
	1.00	1.03	4.97	48.8	27.4	25.7	26.9	26.8	26.3	26.3	28.4	3.35	2.32
Triangular Two-rows	0. 5	1.27	6.10	-0.90	5.60	11.9	25.4	32.9	25.9	26.9	31.6	3.32	2.83
	0.75	1.18	5.58	0.31	7.29	11.3	19.1	26.2	28.7	27.3	27.0	3.33	2.86
	1.00	1.09	5.31	-0.55	6.24	10.2	17.0	32.2	25.6	24.4	24.2	3.34	2.87

*: means wind speed increase

Table 4. Percentage decrease (%) of wind velocity measured at 3 m height.

Number of rows/arrangement	Gap distance(m)	Distance from the trees (H: tree height)										Average speed	
		-2H	-1H	1.5H	3H	4H	———	6H	7H	8H	9H	wind	Lee
			10H									ward	ward
One row	0.50	1.08	4.94	25.8	37.2	35.7	31.7	27.3	23.4	21.0	17.6	3.34	2.40
	0.75	0.86	4.06	28.5	29.0	28.0	27.1	24.3	21.7	20.4	18.1	3.35	2.45
	1.00	0.79	3.89	29.2	22.6	21.0	19.9	18.4	16.8	16.1	16.6	3.35	2.64
Rectangular Two-rows	0. 5	1.16	5.56	33.6	34.6	36.6	35.7	34.0	31.2	29.5	25.9	3.29	2.19
	0.75	1.12	5.36	28.1	26.0	27.4	28.7	28.7	28.2	27.8	26.0	3.30	2.31
	1.00	1.02	4.95	34.0	24.8	25.3	26.8	26.6	25.4	25.0	25.9	3.31	2.37
Triangular Two-rows	0. 5	1.25	-4.5	7.15	9.19	13.6	23.9	30.7	25.7	25.4	28.7	3.28	2.71
	0.75	1.17	5.53	6.46	11.7	14.0	19.5	25.3	27.6	26.8	25.6	3.30	2.75
	1.00	1.08	5.22	4.97	10.5	12.3	17.3	22.7	24.3	23.8	22.9	3.30	2.82

*: means wind speed increase

Table 5. Percentage decrease (%) of wind velocity measured at 4 m height.

Number of rows/arrangement	Gap distance(m)	Distance from the trees (H: tree height)										Average speed	
		-2H	-1H	1.5H	3H	4H	6H	———	7H	8H	9H	wind	Lee
		10H										ward	ward
One row	0.50	1.07	5.06	43.1	47.0	41.8	34.5	28.9	24.3	21.8	17.0	3.27	2.18
	0.75	0.83	4.08	38.3	35.6	32.4	28.8	25.0	22.0	20.5	17.8	3.29	2.33
	1.00	0.78	3.91	32.1	26.1	22.6	20.7	18.8	16.6	15.4	14.4	3.30	2.55
Rectangular Two-rows	0. 5	1.16	5.48	38.9	42.6	42.2	38.6	35.2	31.7	29.5	24.8	3.25	2.01
	0.75	1.01	5.27	33.1	34.2	33.1	31.8	30.1	28.5	27.6	25.1	3.26	2.18
	1.00	1.00	4.82	29.8	26.9	26.9	27.3	26.6	24.5	23.8	23.9	3.27	2.27
Triangular Two-rows	0. 5	1.22	5.85	20.4	15.3	16.6	22.9	28.1	25.3	24.2	24.5	3.23	2.56
	0.75	1.16	5.48	18.03	17.9	17.8	20.9	24.7	26.7	26.1	24.5	3.25	2.59
	1.00	1.07	5.16	13.7	16.1	16.0	18.8	22.5	23.6	23.3	21.6	3.26	2.69

Table 6. Percentage decrease (%) of wind velocity measured at 5 m height.

Number of rows/arrangement	Gap distance(m)	Distance from the trees (H: tree height)										Average speed	
		-2H	-1H	1.5H	3H	4H	6H	———	7H	8H	9H	wind	Lee
			10H									ward	ward
One row	0.50	1.00	5.06	59.7	55.8	45.3	36.0	29.6	24.2	21.6	16.3	3.21	2.02
	0.75	0.82	3.97	47.6	41.1	35.1	29.3	25.1	21.4	19.9	17.2	3.25	2.24
	1.00	0.78	3.91	32.1	26.1	22.6	20.7	18.8	16.6	15.4	14.4	3.26	2.51
Rectangular Two-rows	0. 5	1.13	5.38	54.3	52.1	46.4	39.6	35.2	30.7	28.4	23.2	3.21	1.85
	0.75	1.05	5.12	50.7	44.1	38.3	34.2	30.6	28.1	26.9	23.8	3.21	1.98
	1.00	0.96	4.73	38.6	32.4	29.3	27.9	26.3	23.4	22.2	22.1	3.23	2.20
Triangular Two-rows	0. 5	1.19	5.73	41.2	25.1	21.0	23.5	26.5	24.5	22.8	23.5	3.20	2.40
	0.75	1.14	5.34	38.3	26.3	22.1	23.1	24.7	25.6	25.2	23.1	3.22	2.44
	1.00	1.02	4.95	27.0	22.2	21.0	20.9	22.2	22.7	22.1	20.2	3.22	2.58

4.1.4. Comparing the current study with the previous studies

Bitog et al. (2009) indicated that the distance can be regarded as the most effective factor in reducing the wind speed (Bitog et al., 2009). They continued their work by studying the simulated Black pine trees where the obtained results showed that the 0.5m gap was more effective in wind speed reduction in comparison 0.75m and 1m gap distances. Also, the triangular two-row arrangement of planting Black pine trees was able to reduce the wind speed more than single-row and rectangular two-row arrangements and protected a larger area on the leeward of the windbreak form annoying winds. This conclusion is in good agreement with the results obtained from the current study which are about a specific type with the specific crown shape. Wu et al., (2012) illustrated that at a rather far distance from the obstacles, the effect of rows number decreased significantly (Wu et al., 2013). According to the results obtained

by Cornelis and Gabriels (2005), single-row barriers with high gap have a better influence on wind speed reduction (Cornelis and Gabriels, 2005). This is in good agreement with the overall results of this research. Such a conclusion is made in the current investigation, which was discussed before.

Although, there has been no study comparing different crown shapes, results of the current study and also the results obtained by previous works state that any crown shape affects the optimum conditions of planting patterns. This leads to the conclusion that it is so important to investigate all typical crown shapes separately, as well as comparing them to each other. Different forms of canopy and porosity of plant species re suggested to investigate in future researches. Also, it is suggested to validate findings using wind-tunnel in laboratory which was the main limitation of the current research.

5. CONCLUSION

The current study numerically investigated the effect of different parameters such as gap distance between trees in a row, number of trees rows and planting arrangement to evaluate the ability of the natural windbreaks (here

Quercus trees) for reducing wind speed at different heights from the surface and different distances behind the windbreak.

Major results are briefly brought as follows:

- At 1, 2-meter height from the surface, 0.75m gap shows the best results for single-row arrangement, while for rectangular and triangular two-row arrangements, 0.5m gap shows better results. About rectangular two-row arrangement, it should be mentioned that comparing rectangular and triangular results, shows that rectangular arrangement is better than triangular for wind speed reduction at lower heights.
- For 3, 4, and 5-meter height from the surface, 0.50m gap shows better results for all three arrangements, which is due to crown spread at that height.
- Totally, rectangular two-row arrangement demonstrates the best and most effective performance in reducing wind speed at large extents of the investigated area behind the windbreak.

The average percentage decrease in wind velocity influenced by shape of barrier, barrier porosity, height, planting pattern and distance between the adjacent barriers. The simulation results showed that the air penetration into tree canopies is highly influenced by the canopy shape, size of tree canopy and density. As the canopy depth, tree height, and canopy density increased, the wind velocities inside the canopy were mostly decreased.

REFRENCES

Basnet, K. (2015). Flow around porous barriers: fundamental flow physics and applications.

Bird, P.R., Bicknell, D., Bulman, P.A., Burke, S.J.A., Leys, J.F., Parker, J.N., Van Der Sommen, F.J., and Voller, P. (1993). "The role of shelter in Australia for protecting soils, plants and livestock," in *The Role of Trees in Sustainable Agriculture: Review papers presented at the Australian Conference, The Role of Trees in Sustainable Agriculture, Albury, Victoria, Australia, October 1991*, ed. R.T. Prinsley. (Dordrecht: Springer Netherlands), 59-86.

Bitog, J.P., Lee, I.-B., Hwang, H.-S., Shin, M.-H., Hong, S.-W., Seo, I.-H., Kwon, K.-S., Mostafa, E., and Pang, Z. (2012). Numerical simulation study of a tree windbreak. *Biosystems Engineering* 111, 40-48.

Bitog, J.P., Lee, I.B., Hwang, H.S., Shin, M.H., Hong, S.W., Seo, I.H., Mostafa, E., and Pang, Z. (2011). A wind tunnel study on aerodynamic porosity and windbreak drag. *Forest Science and Technology* 7, 8-16.

Bitog, J.P., Lee, I.B., Shin, M.H., Hong, S.W., Hwang, H.S., Seo, I.H., Yoo, J.I., Kwon, K.S., Kim, Y.H., and Han, J.W. (2009). Numerical simulation of an array of fences in Saemangeum reclaimed land. *Atmospheric Environment* 43, 4612-4621.

Blocken, B., Stathopoulos, T., and Carmeliet, J. (2007). CFD simulation of the atmospheric boundary layer: wall function problems. *Atmospheric Environment* 41, 238-252.

Brandle, J.R., Hodges, L., Tyndall, J., and Sudmeyer, R.A. (2009). "Windbreak Practices," in *North American Agroforestry: An Integrated Science and Practice*.), 75-104. Caborn, J.M. (1957). *Shelterbelts and microclimate.* HM Stationery Office Edinburgh.

Campi, P., Palumbo, A.D., and Mastrorilli, M. (2009). Effects of tree windbreak on microclimate and wheat productivity in a Mediterranean environment. *European Journal of Agronomy* 30, 220-227.

Cornelis, W.M., and Gabriels, D. (2005). Optimal windbreak design for wind-erosion control. *Journal of Arid Environments* 61, 315-332.

Dong, Z., Mu, Q., Luo, W., Qinan, G., Lu, P., and Wang, H. (2008). An analysis of drag force and moment for upright porous wind fences. *Journal of Geophysical Research: Atmospheres* 113.

Franke, J., Hirsch, C., Jensen, A., Krüs, H., Schatzmann, M., Westbury, P., Miles, S., Wisse, J., and Wright, N. (Year). "Recommendations on the use of CFD in predicting pedestrian wind environment", in: *Cost action C*).

Gardiner, B., Berry, P., and Moulia, B. (2016). Wind impacts on plant growth, mechanics and damage. *Plant Science* 245, 94-118.

Grala, R.K., Tyndall, J.C., and Mize, C.W. (2010). Impact of field windbreaks on visual appearance of agricultural lands. *Agroforestry Systems* 80, 411-422.

Gromke, C., and Ruck, B. (2008). Aerodynamic modelling of trees for small-scale wind tunnel studies. *Forestry* 81, 243-258.

Heisler, G.M., and Dewalle, D.R. (1988). Effects of windbreak structure on wind flow. *Agriculture, Ecosystems & Environment* 22-23, 41-69.

Jacobs, A.F. (1985). The normal-force coefficient of a thin closed fence. *Boundary-layer meteorology* 32, 329-335.

Khalil, S.M. (2008). "The use of sand fences in barrier island restoration: experience on the Louisiana Coast". ENGINEER RESEARCH AND DEVELOPMENT CENTER VICKSBURG MS ENVIRONMENTAL LAB).

Kozmar, H., Procino, L., Borsani, A., and Bartoli, G. (2012). Sheltering efficiency of wind barriers on bridges. *Journal of Wind Engineering and Industrial Aerodynamics* 107-108, 274-284. Lee, K.H., Ehsani, R., and Castle, W.S. (2010). A laser scanning system for estimating wind velocity reduction through tree windbreaks. *Computers and Electronics in Agriculture* 73, 1-6.

Lee, S.-J., and Lim, H.-C. (2001). A numerical study on flow around a triangular prism located behind a porous fence. *Fluid Dynamics Research* 28, 209.

Li, B., and Sherman, D.J. (2015). Aerodynamics and morphodynamics of sand fences: A review. *Aeolian Research* 17, 33-48.

Mcclure, S., Kim, J.J., Lee, S.J., and Zhang, W. (2017). Shelter effects of porous multi-scale fractal fences.

Journal of Wind Engineering and Industrial Aerodynamics 163, 6-14.

Müderrisoğlu, H., Eroğlu, E., Özkan, Ş., and Ak, K. (2006). Visual perception of tree forms. *Building and Environment* 41, 796-806.

Pickard, J. (2005). Post and rail fences: derivation, development, and demise of rural technology in colonial Australia. *Agricultural history*, 27-49.

Plate, E.J. (1971). The aerodynamics of shelter belts. *Agricultural Meteorology* 8, 203-222.

Raine, J.K., and Stevenson, D.C. (1977). Wind protection by model fences in a simulated atmospheric boundary layer. *Journal of Wind Engineering and Industrial Aerodynamics* 2, 159-180.

Rosenfeld, M., Marom, G., and Bitan, A. (2010). Numerical Simulation of the Airflow Across Trees in a Windbreak. *Boundary-Layer Meteorology* 135, 89-107.

Sanz, C. (2003). A Note on k - ε Modelling of Vegetation Canopy Air-Flows. *Boundary-Layer Meteorology* 108, 191-197.

Slusher, J.P., Robinson, J., and Solomon, C. (1983). Planning tree windbreaks in Missouri.

Speckart, S.O., and Pardyjak, E.R. (2014). A method for rapidly computing windbreak flow field variables. *Journal of Wind Engineering and Industrial Aerodynamics* 132, 101-108.

Tominaga, Y., Mochida, A., Yoshie, R., Kataoka, H., Nozu, T., Yoshikawa, M., and Shirasawa, T. (2008). AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings. *Journal of Wind Engineering and Industrial Aerodynamics* 96, 1749-1761.

Vercauteren, K.C., Lavelle, M.J., and Hygnstrom, S. (2006). From the Field: Fences and Deer-Damage Management: A Review of Designs and Efficacy. *Wildlife Society Bulletin* 34, 191-200.

Wilson, J.D. (1985). Numerical studies of flow through a windbreak. *Journal of Wind Engineering and Industrial Aerodynamics* 21, 119-154.

Wilson, J.D. (1987). On the choice of a windbreak porosity profile. *Boundary-Layer Meteorology* 38, 37-49.

Wilson, J.D., and Yee, E. (2003). Calculation of winds disturbed by an array of fences. *Agricultural and Forest Meteorology* 115, 31-50.

Wu, T., Yu, M., Wang, G., Wang, Z., Duan, X., Dong, Y., and Cheng, X. (2013). Effects of stand structure on wind speed reduction in a Metasequoia glyptostroboides shelterbelt. *Agroforestry systems* 87, 251-257.

Zhou, X.H., Brandle, J.R., Mize, C.W., and Takle, E.S. (2005). Three-dimensional aerodynamic structure of a tree shelterbelt: Definition, characterization and working models. *Agroforestry Systems* 63, 133-147.

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