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Living windbreak design for wind erosion control in arid regions: A case study in Dehloran, Iran

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Abstract

Wind erosion is considered as one of the main processes of land degradation in different parts of the world. Among the most effective ways to control wind erosion is to cover land surface with natural vegetation area. In this study, 3 replica soil samples were collected, at a depth of 0-3 cm, from various land uses in Dehloran, Ilam Province, Iran. Physical and chemical characteristics of soil samples were determined in the laboratory to allow the application of the ENVI_met Headquarter model commonly used to design biological windbreak. The threshold friction velocity (TFV) is the basic parameter for effective construction of a windbreak. To determine its values, a wind tunnel test was conducted. Based on simulation results with the pattern designed with *Prosopis juliflora* species, it was observed that the wind speed decreased in front of the windbreak but returned to the initial speed at a larger distance behind the windbreak. Therefore, the designed windbreak for this species is able to reduce the wind speed to a far distance while in the designed windbreak with *Haloxylon aphyllum* species the wind returns to the initial speed within a shorter distance. According to the results, the wind speed reduction is directly related to the height of windbreak. Moreover, the designed windbreak with *P. juliflora* species, more effectively reduce the wind speed and protect longer distances behind the windbreak; thus it can be proposed as a suitable windbreak for the study area.

Keywords: Wind tunnel; TFV; Biological windbreak; ENVI-met

1. Introduction

Today, erosion phenomena (including water and wind erosion) are considered as one of the main processes of land degradation in different parts of the world, obviously including Iran (Ahmadi, 2012). Wind erosion occurs when the wind speed reaches a point (erosion threshold) where it can carry particles (Refahi, 2012). The basis of the biological and mechanical erosion control, in particular the creation of a windbreak, is the calculation of the wind speed erosion threshold (Karimzadeh, 2006).

The amount of wind erosion depends on wind speed and ground characteristics, so there are two basic ways to control wind erosion:
1. Control the wind speed near the surface to a level below the threshold of erosion
2. Control the factors that affect soil properties such as moisture and plowing (Ahmadi and Shayganpour, 2011).

When the climatic, ecological, and geographical factors of the ecosystem tend to drier conditions, the vegetation cover contributes decisively maintaining the ecosystem equilibrium (Jafari *et al.*, 2012). Therefore, preservation of existing plants and efforts to revive vegetation must have a special priority in arid lands and desert management programs, and each plan should ultimately lead to the establishment of plants that are compatible with ecological conditions (Gholami Tabasi *et al.*, 2013).

Windbreaks are narrow strips of trees, shrubs and/or grasses planted for protection of farms, buildings, chanals, and other areas from the wind and blowing sand storms (Udhaya Nandhini and Sakthinathan, 2017).

He and Harazono (1997) concluded that the most suitable process to reduce wind speed and

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prevent the erosion and movement of sandy soils is to plant vegetation on sandy soils. Furthermore, windbreak trees can reduce carbon emissions (Baallesteros-Possu *et al.,* 2017). Therefore, essential and effective measures must be taken to control sand dune movement and fix them permanently by cost-effective methods (Nosrati *et al.,* 2017).

Shamsutdinov *et al.,* (2016) evaluated the pattern of changes in ecological factors like illumination level, air and soil temperatures, humus and salt contents in the soil in a phytogenic field of *H. aphyllum* in self-sown saxaul stands spontaneously formed in areas between shelterbelts. Their results showed that the environment-forming influence of this species leads to noticeable changes in the air and soil moisture, temperature regimes, light regime, salt contents, and soil humus.

Reducing wind speed to 50% leads to decreasing the wind erosion to one-eighth of the initial speed (Hagen, 1996). As a principle, a good windbreak can protect an area up to 10 times its height (Ahmadi, 2012). Studies and experiments have shown that one or two rows of tall and thick grass plants with 9m intervals can reduce wind speed and wind erosion up to 90% (criteria and principles for the construction of a biological windbreak, 2015). The windbreaks guide the blowing wind upwards, which, after a certain distance - depending on the height of the windbreak – will return to surface level (Arazi *et al.,* 2011). So far, several studies have been conducted on the reduction of wind erosion due to the creation of windbreaks. These include the studies by Mohammad *et al.,* (1996) in Sudan, Foereid *et al.,* (2002) in Denmark, Cornelis and Gabriels (2005) in Belgium, along with Ghasemi *et al.,* (2011) and Madadi zadeh *et al.* (2014) in Iran.

In Iran, afforestation was first started in 1959 in Albaji area of Ahvaz in order to stabilize sandy dunes. Then, this strategy was developed on a large scale in the central and southern parts of the country. What is nowadays introduced as stabilization of sandy dunes using plant species dates back to 59 years ago, which was initiated and continued by planting species such as *Haloxylon* (Ekhtesasi, 2004).

In designing of a suitable windbreak, the following points should be considered:

i) selection of windbreak trees according to the climatic and geographical conditions of the site

ii) studying the soil, especially in terms of structure and texture, in order to determine the threshold velocity of erosion as well as the EC and pH

iii) the maximum wind speed and its main direction

iv) the distance between windbreak rows, length, width, and density of the windbreaks (Kardavani, 1994).

Dehloran city (Figure 1) has a critical wind erosion problem. This research tried to design an optimum windbreak for the study area using the ENVI-met Headquarter model which is a three-dimensional microclimate model designed to simulate the surface-plant-air interactions in urban environment by numerical computer simulations using the best techniques and methods in microclimate modelling. As a novelty, we applied this model for designing windbreaks in a desert area. The main point of this model is that it simulates the main atmospheric interactions of the study area based on physical rules, such as fluid dynamics and thermodynamics laws (Bruse, 2009).

2. Materials and Methods

2.1. The Study area

The Ain-Khosh watershed in Ilam province is located between 47° 33' 39"E and 47° 43' 33"E longitudes and 32° 27' 25"N to 32° 40' 19"N latitudes (Figure 1). Geologically, the study area is located in the folded Zagros zone, southwest of Iran. All formations of the region belong to the Cenozoic period; therefore, the studied area is quite young and has a high sensitivity to wind and water erosion. The geological formations of this region include the sandstone of Aghajari (Mplaj) and the Plbra sections, distributed in the southern regions. Sediment transport, by rainstorms and floods, occurs in numerous oueds of the region in the lower slopes and central, eastern, and western parts of the region, which in warm seasons have a high sensitivity to wind erosion.

The rainfall regime of the study area is Mediterranean, with an average annual rainfall of 279.8 mm distributed unevenly in temporal and spatial scale; maximum precipitation occurs in January and February. Average annual temperature across the region is 26.2$^{\circ C}$, and based on available data, average annual potential evaporation is 3857.5 mm. According to the De-Martonne classification, the climate of region is dry warm. Winds blow, dominantly westward, across the region with a mean speed of 1.7 knots (Ilam Meteorological Organization, 2016).

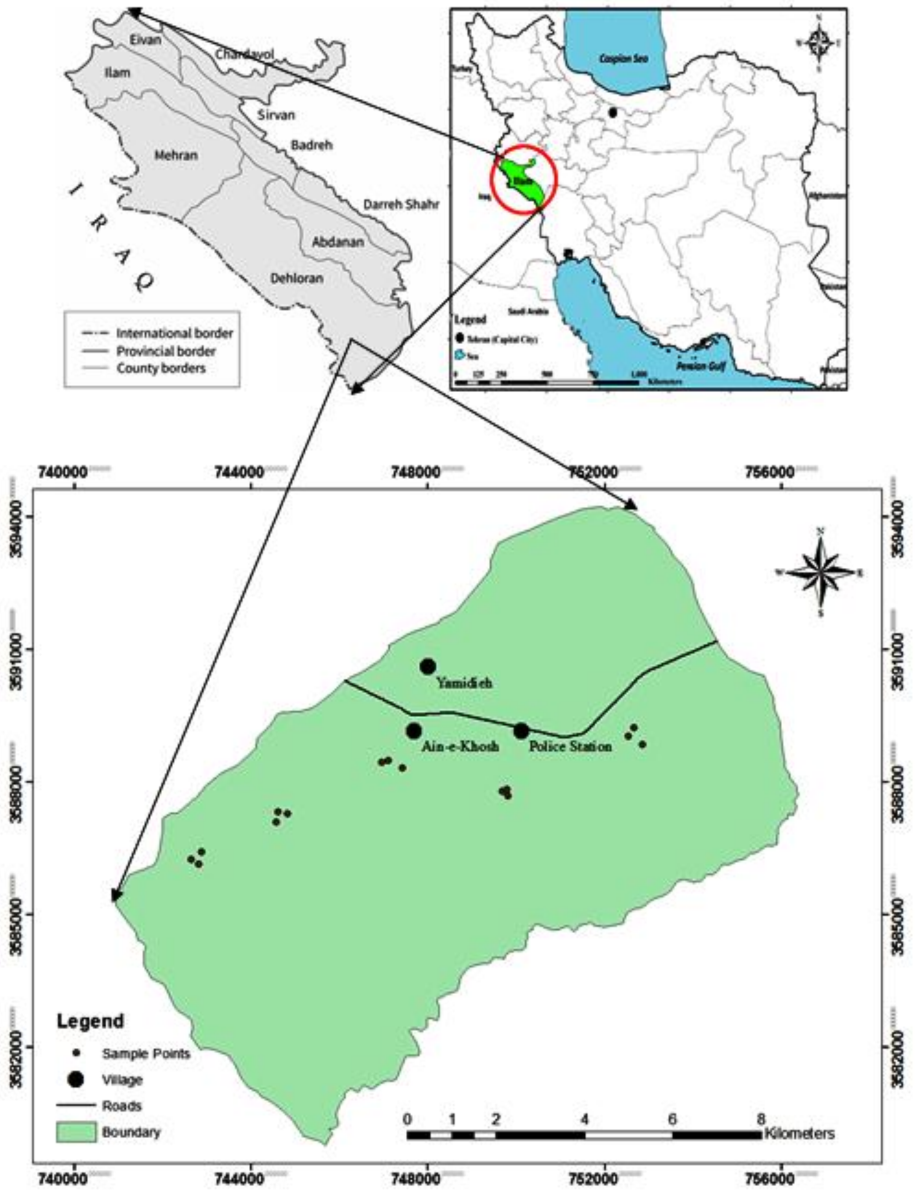

Fig. 1. Location of study area in Iran and Ilam Province

2.2. Research Method

As the first step, satellite imagery was used to determine existing land coverage across the study area, including *Ziziphus Nummularia* (Burm. f) Wight & Arn. natural forests, agricultural lands, rangelands, planted *Prosopis Juliflora* (Swartz) DC. forests, and sand dunes. Then, soil samples were collected from every different land use coverage at a depth of 0-3 cm in 3 replications.

2.2.1. Laboratory studies

The soil samples were exposed to dry air before soil physical properties tests. Then, soil texture was evaluated by the hydrometry method, Bulk Density (BD) by the cylinder method, and soil moisture by weighing method. Regarding chemical properties, dissolved Na-cation was determined using flame photometer, Ca and Mg cations contents were evaluated through titration (Rhoades, 1982), pH of soil was measured by a pH meter, EC of saturated extraction by EC meter, Organic Carbon (OC) content by Walkley and Black (1934) method, and lime content by titration method (Pansu and Gautheyrou, 2007).

2.2.2. Wind tunnel experiments

In this research, a wind tunnel at Agriculture Faculty of Ilam University was used. This machine consists of four main parts: 1) engine, propeller, and the laminar plate to unilaterally control the wind speed; 2) main body of the wind tunnel, which is made up of galvanized and fiberglass components to observe the effect of wind on soil samples and assess the wind speed using an anemometer device; 3) outlet, throughout which soil particles leave the tunnel; and 4) inverter, which is a high-power electronic oscillator controlled by changing its power voltage to simulate the desired wind speed (Figure 2) (Bazgir and Namdar Khojasteh, 2017). The wind tunnel can create wind speeds up to 20 m/s at 30 centimeters above the soil surface. To determine the threshold velocity, undisturbed sandy surface soil were placed in the wind tunnel. Then, by adjusting the flow rate of the wind, which was made possible by the inverter, threshold velocity was measured using the manometer. Afterwards, wind velocity was increased gradually, and the threshold velocity was determined as the velocity at which the first particle began to move (observed by naked eye and also by photography with a high-sensitivity camera).

Soil samples (3 replicas) were exposed to 4 wind speeds of 2, 9, 16 m/s and the wind erosion threshold speed for 5 minutes at each speed. Wind tunnel experiments revealed that the most erodible soil was sandy soil, so windbreaks were designed to face sandy soils characteristics.

Fig. 2. A: Soil sample, B: Anemometer, C: Wind tunnel

2.2.3. Selecting the appropriate tree species for windbreak design

In this study, among the common species used in the stabilization of sandy soil, two types of *Prosopis juliflora* and *H. aphyllum* were selected for simulation. Also, during past years, this species was planted by Forest, Range and Watershed Management Organization of Ilam and revealed a good adaptation with the present-day conditions of the region.

2.2.3.1. Prosopis juliflora

Prosopis juliflora is a spiny shrub or small tree of the family *Mimosaceae* which grows to a height of up to 12 meters, or more, in appropriate conditions (Najafi Tireh Shabankareh, 2007). This shrub is bulky with a large canopy and grow in warm, humid weather but is very vulnerable to frost (Elnur Elsiding, 2006). Because it can withstand temperatures above 50$^{\circ C}$, it is used for sand fixation in desertic environments (Jazirei, 2007, quoted by Akbarian and Biniaz, 2012). Between 2005 and 2009, *P. juliflora* species were planted in the study area (Fig. 3). Despite some spatial irregularity, they play an effective role in reducing wind erosion in the field.

Fig. 3. *P. juliflora* in Ain-Khosh, Dehloran

2.2.3.2. Haloxylon aphyllum

Haloxylon species has three main types of xerophyte, halophyte, and psammophytes and is widely used in biological stabilization of sandy areas. According to the botanists, *Haloxylon* contains three important species of *H. persicum*, *H. aphyllum* and *H. ammodendron* (Bahrami *et al.*, 2004 and Safarnejad, 2006). Studies have shown that *H. aphyllum*, unlike other species, has a good adaptation to loamy silt and highly salty lands, and the value of its forage is twice as *H. ammodendron* (Le Houerou, 1985). Therefore, in this study, among different species, *H. aphyllum* was selected. Moreover, this species grows in the deserts and sandy areas of the southern, eastern, and central parts of Iran (Alipour, 2002). In areas where rainwater is less than 100mm, it provides the required groundwater (Ekhtesasi, 2004).

2.2.4. ENVI-met Head quarantine model

The ENVI-met software is a non-hydrostatic 3D model. It provides a wide range of modeled variables that calculate the energy currents (long and short wavelengths, latent and sensible heats). This model calculates the weather conditions (temperature, wind, and humidity) at different levels and range of structures (buildings, types of vegetation, types of impervious and impenetrable surfaces) (Rezazadeh and Aghajan Biglou, 2012). ENVI-met software includes five software groups: Atmospheric model, Surface model, Vegetation model using LAD (Leaf Area Density) and RAD (Root Area Density) indices, Soil model, and Bio-meteorological model (Bruse and Fleer, 1998).

2.2.5. Setting the conditions of the ENVI-met model

The initial data required to run the model is based on the geographic location of the study area (latitude and longitude), soil texture, air temperature conditions, wind velocity and direction, and relative humidity (Tables 1 and 2).

Tables 1. Model input data for the study area

Simulation time	Simulation Date	Soil texture	Geographical location
8:00	05.08.2017	Sandy	47° 33' - 32° 27'

Table 2. The atmospheric data used for modeling

Wind direction	Average maximum wind speed (m/s)	Average maximum relative humidity (%)	Average minimum relative humidity (%)	Average maximum temperature (k)	Average minimum temperature (k)
North	16	32	13	323.15	306.15

2.2.6. Data analysis method

Leonardo software, which is a part of the ENVI-met model, was used to analyze wind tunnel data graphically. Results produced include wind speed and its changes, temperature, humidity, etc. These are necessary to plot the changes in height and in different axes direction. Also ENVI-met database provides a wide variety of plant species.

3. Results

3.1. Average of soil properties and TFV

Tables 3 and 4 show the mean physical and chemical properties of soil. Soil analysis showed that the soil was sandy and light-textured and its low organic matter, moisture, calcium, and magnesium lead to the lack of concrete and adhesive between sand particles; therefore, it became sensitive to wind erosion.

Table 5 shows the mean wind speed erosion threshold in the study area. Its average speed of the erosion threshold is 4.84 m/s.

Table 3. Average physical properties of soil

CS (kg/cm^2)	MWD (mm)	P (%)	SP (%)	BD (g/cm^3)	Clay (%)	Silt (%)	Sand (%)	Land cover
0.616	1.42	44	19.1	1.47	7.5	0.61	91.88	Sand dune

Abbreviations: BD: Bulk Density, SP: Saturation Percentage, P: porosity, MWD: Mean Weight Diameter, CS: compressive strength

Table 4. Average soil chemical properties

SAR	Na (mg/l)	Mg (mg/l)	Ca (mg/l)	OC(%)	$CaCO_3$(%)	EC (ms/cm)	pH	Land use
3.93	15.08	22.29	8.68	0.128	25.58	0.334	7.87	Sand dune

Abbreviations: EC: Electrical Conductivity, OC: Organic Carbon, SAR: Sodium Absorption Ratio

Table 5. Average TFV (30 cm above the soil surface)

Land use	TFV
sand dune point1	4.78
sand dune point2	4.88
sand dune point3	4.86
Average	4.84

3.2. Simulation results in ENVI-met environment

Figure 4 illustrates the simulated plan for the *P. juliflora* at 3 meters above surface level. In this figure, the wind blows from the north and the first row of the windbreak in front of the wind is the highest one. Also, Figure 5 display the wind velocity changes which derived from windbreak rows of *P. juliflora* species.

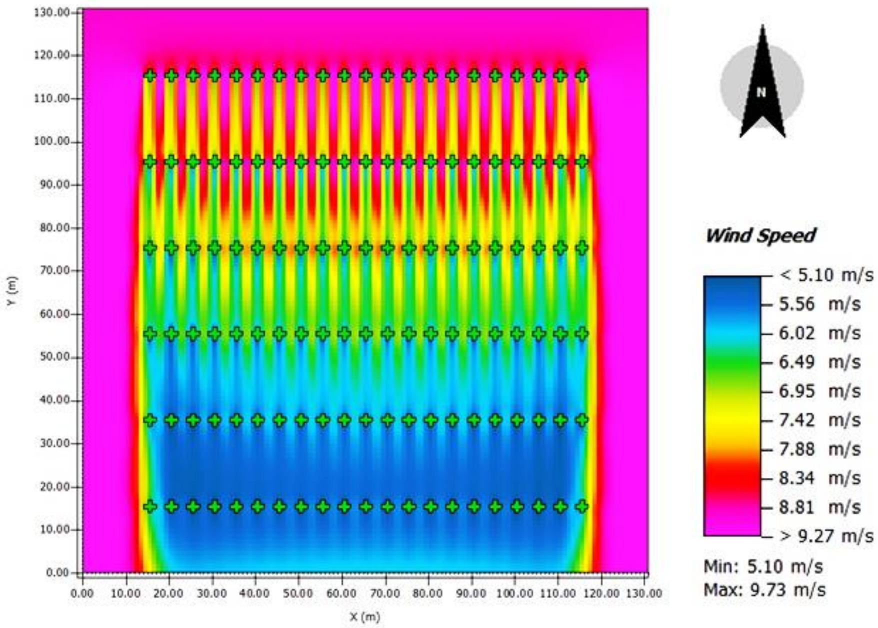

Fig. 4. Simulated plan for *P. juliflora* species

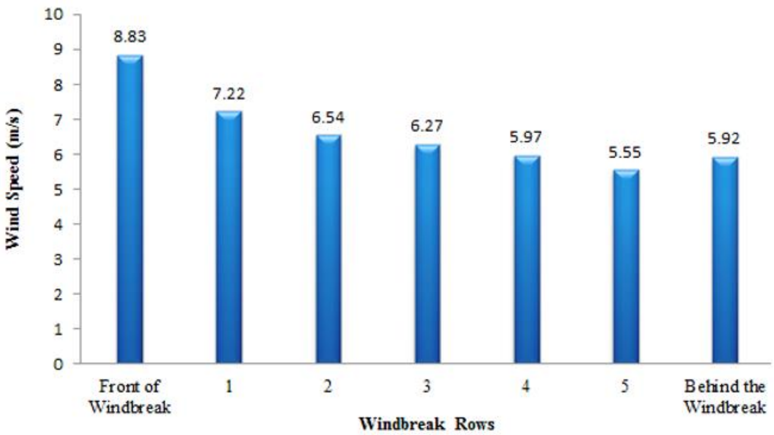

Fig. 5. Wind velocity changes by *P. juliflora* species - Horizonal axis (x/y)

In this study, two species of *P. juliflora* with a height of 10 meters and a canopy width of about 5 meters, and a *H. ammodendron* with a height of 2 meters and a canopy width of about 3.5 meters were selected. For *P. juliflora*, a pattern with 6 rows of windbreaks, with 20 meter interval between rows and the distance between each tree based on a canopy width of 5 meters (total of 126 trees per hectare) were considered. Figures 6 and 7 show simulated patterns for vertical axis patterns.

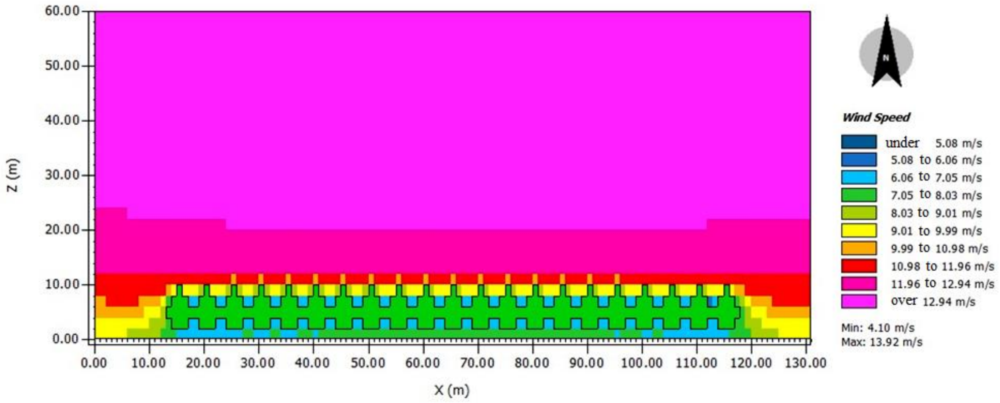

Fig. 6. Simulated pattern for the *P. juliflora* species - vertical axis (x/z)

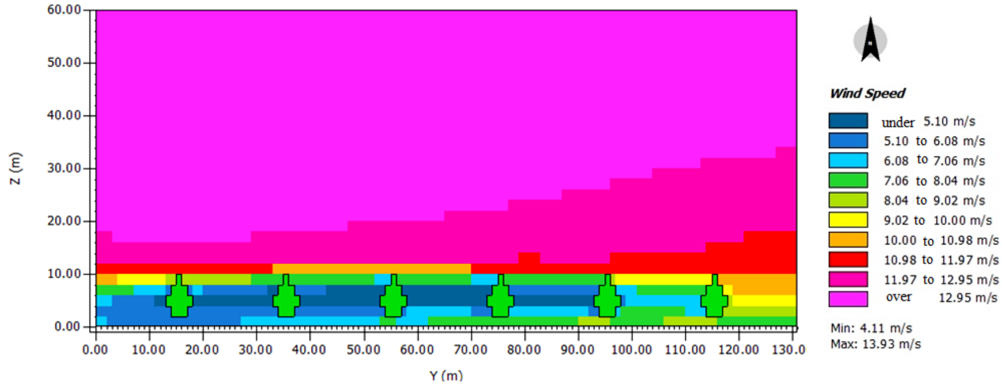

Fig. 7. Simulated pattern for the *P. juliflora* species - vertical axis (y/z)

Figures 6 and 7 exhibit the wind speed changes in front and across the windbreak, respectively. In the vertical axis of the windbreak, the maximum wind speed is about 14 m/s. The wind velocity decreases gradually after collision with the windbreak rows, and in the last row, the wind speed reaches about 4 m/s, which reduces the wind speed to less than the threshold speed. After the last row, the wind speed begins to increase. Figure 8 shows a simulated plan for the *H. ammodendron* species at a height of 1 meter above surface level, in which the wind blows from the north and the highest row is the first row of the windbreak. Moreover, Figure 9 displays the wind velocity changes caused by the windbreak rows of *H. ammodendron* species.

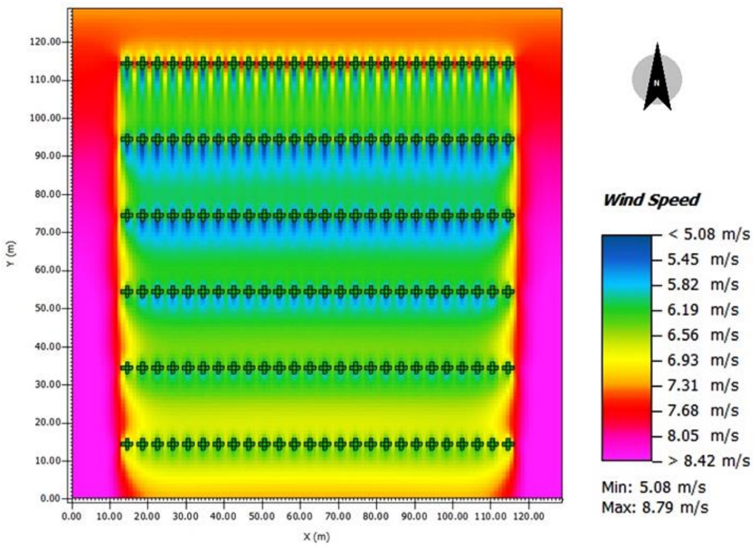

Fig. 8. Simulated wind velocity plan for the *H. ammodendron*

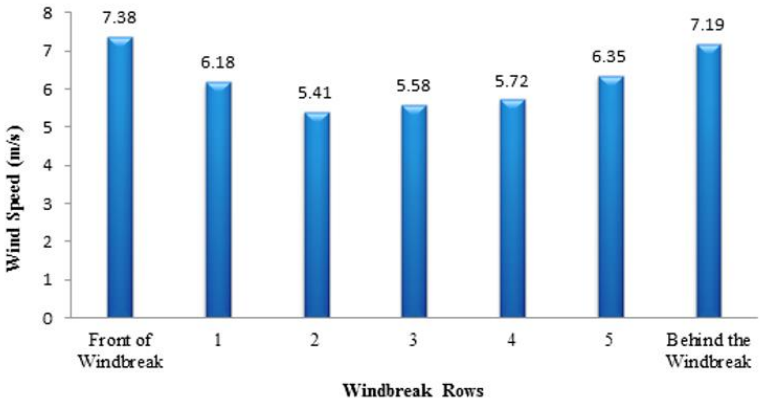

Fig. 9. Wind velocity changes by *H. ammodendron* species - Horizonal axis (x/y)

For the *H. ammodendron* about 156 trees per hectare were considered, with a pattern with 6 rows of windbreaks, with 20 meter interval between rows and the distance of each tree based on a canopy width of 4 meters. Figure 9 presents the wind speed variations at 1 meter above surface level. Figures 10 and 11 show the simulated patterns for the *H. ammodendron* in the vertical axis.

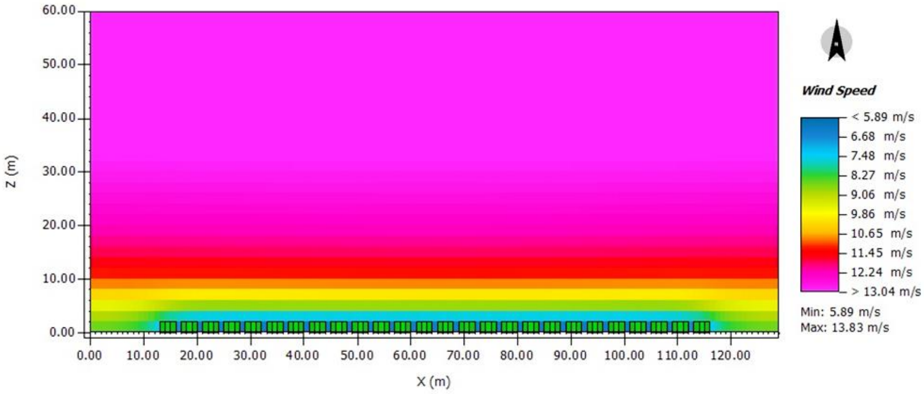

Fig. 10. Simulated pattern for the *H. ammodendron* species - vertical axis (x/z)

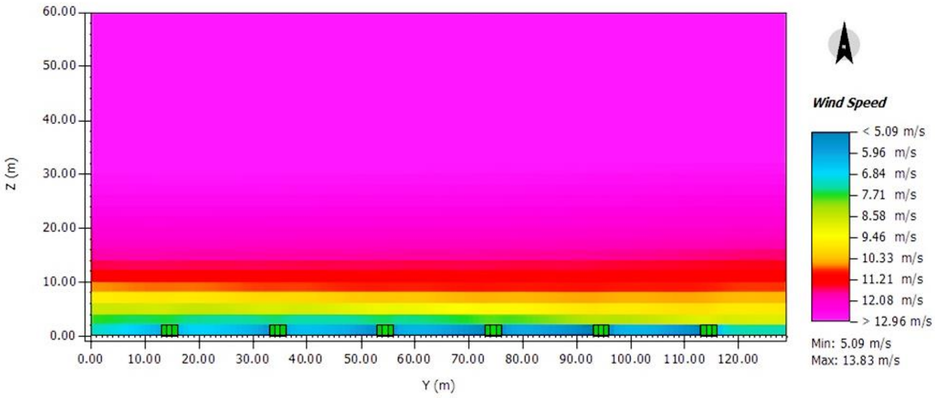

Fig. 11. Simulated pattern for the *H. ammodendron* species - vertical axis (y/z)

In Figures 10 and 11, wind speed variations are shown on the front and alongside of the windbreak, in which the vertical axis of the windbreak, the maximum and minimum wind speeds are about 14 m/s and 5 m/s, respectively.

4. Discussion

The results of wind tunnel tests indicated that the average wind speed erosion threshold for the study area is about 4.84 m/s. Based on the simulation results, in a pattern designed with 10 meter height *P. juliflora* with (Fig. 4), at 3-meter-above surface level, the wind speed decreased to 8.83 m/s in front of the first row (Figure 5).

Between 20 to 60m behind the first row of the windbreak (h= height of *P. juliflora*), the wind speed decreased slightly, but at 80 to 120m it starts to decrease at a faster rate. The wind at 100m behind the first row of the windbreak had the highest decrease. However, in the pattern designed with *H. ammodendron* at 2 meters height (Figure 11), in front of the first row and at 1 meter above surface level, the wind speed decreased to 7.38 m/s (Figure 9).

On the other case study, 40 to 60m behind the first row of the windbreak (h= height of *H. ammodendron*), the wind speed decreased to 5.69 m/s. However, the highest wind speed decrease occured behind the second row of the windbreak. From the 80m behind the first row, the wind speed accelerateed rapidly and approacheed the initial speed. The results of this study are in agreement with the results of Cook & Goyens (2008); Madadi zadeh *et al.*, (2014), and Refahi (2012).

In the pattern designed for *P. juliflora*, the initial wind speed started to decrease from 80-120m before the first windbreak row. The simulation results also showed that in the designed pattern for *P. juliflora*, and in contrast to the *H. ammodendron*, the wind speed decreased in front of the windbreak but it reached the initial speed more slowly after the windbreak. This suggests that the designed windbreak for P. juliflora will be able to reduce the wind in larger distances from the initial windbreak.

In patterns designed in vertical axes for *P. juliflora* and *H. ammodendron* species (Figures 6, 7, 10 and 11), the minimum wind speed is about 11.4 and 5.8 m/s, respectively. Therefore, based on the results of wind tunnels and these figures, it can be concluded that the simulated pattern for the *P. juliflora* could reduce the wind speed from 16 m/s to less than the TFV (4.11 m/s).

5. Conclusion

According to the simulation results, it seems that the designed windbreak of *P. juliflora* which protects more distance behind the initial windbreak and effectively reduces the wind speed, can be proposed as a suitable windbreak for the study area. But more studies are needed in this area and all aspects of the adaptation should be considered.

The wind speed reduction is directly related to the height of the windbreak, and the higher windbreak leads to less wind speed, less wind erosion, and more protected area.

Finally, the designed windbreak for *P. juliflora* acts as a non-dense windbreak, so that the wind speed decreases gradually after the initial windbreak, and in a longer time and distance it approaches the initial speed and its effect is far away. But the *H. ammodendron* is similar to a dense windbreak; the wind speed is significantly reduced before the windbreak, and after the initial windbreak, the speed of the wind is reduced rapidly and behind the windbreak it quickly returns to the initial speed.

In this research, among the species used in seedling for stablization of sandy soils, *P. juliflora* and *H. ammodendron* species were selected for simulation, but in the study area, there are other species such as ash, *Ziziphus sp.*, *Tamarix sp.*, *Eucalyptus sp.*, etc. So, evaluation of the impact of these trees, along with other issues such as socio-economic issues, underground water levels, etc., can provide a suitable way to improve the condition of the desert areas.

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