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ARTICLE

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Effects of windbreak Forest according to tree species and planting methods based on wind tunnel experiments

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ABSTRACT

To provide a basis for the effective and efficient design of windbreak forests, wind tunnel tests were conducted to analyze the protection against wind afforded by the use of various species and various structures of planted trees. Various row-based planting structures were used in an attempt to find the most effective arrangement of a windbreak forest. Four types of structures were studied: a simple structure of coniferous trees (1, 2, or 3 rows of *Pinus thunbergii*), a simple structure of broadleaf trees (1, 2, or 3 rows of *Quercus acutissima*), mixed structure 1 (3 rows: *P. thunbergii, Q. acutissima and P. thunbergii*) and mixed structure 2 (3 rows: *Q. acutissima, P. thunbergii and Q. acutissima*). The testing materials were 3-year-old *P. thunbergii* and 8-year-old *Q. acutissima*. As the height of the testing part was 2.0 m, the height of trees was cut to make it 1.5 m based. The trees were fixed in a vase of 30 cm (Width) × 30 cm (Height). The experimental simulation model was designed 3meter (Width) × 2meter (Height) × 9 meter (Length). Putting porosity between trees aside, it was appropriate with the 7.5% of black ratio. All arrangements of *P. thunbergii* rows decreased the wind speed at every measurement point; especially, the 3-row structure of *P. thunbergii* showed a wind speed reduction of more than 15% greater than the two single-row structures studied. The wind speed reduction of *P. thunbergii* was maximized at a distance 1 m downwind from the last row, with wind speed increasing further downwind. Also, comparing the effect of decreasing wind speed according to the height in one-layered structure, middle-height marked the best decrease and lowered as it goes far from the middle-height. This can be explained with the cone-shaped water pipe. However, observing that the same phenomenon does not happen in three-layered structures, it was found that the difference due to different shapes of the water pipe can be offset by adding a row of plants. Therefore, using the alternating structure of coniferous, broadleaf, and coniferous rows would be a better choice, offering a similar effect with less risk of loss to disease and insects.

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Windbreak forest; wind velocity; wind tunnel experiment; *Pinus thunbergii*; *Quercus acutissima*

Introduction

The Republic of Korea is a country having a highly dense human population and limited land resources. Thus, coastal areas with poor crop production and the residential environment must be utilized for cultivation; also, territorial expansion by means of land reclamation projects has been actively pursued. Owing to its developed tidelands, shallow waters and ria coasts, the southwest coast of Korea is naturally suited for the development of wide areas of land even after building seawalls for reclamation.

However, there are many difficulties in cultivating coastal areas, chief among which is the damage to plants caused by the strong, saline winds as well as tsunamis. In the case of ordinary, less saline wind, photosynthesis begins to decrease under exposure to wind faster than 6 m/s and rapidly decreases at 10 m/s or more; in general, photosynthesis and respiration become severely restricted above 17 m/s (Wadsworth 1959; Whitehead 1962; Whitehead and Luti 1962; Grace 1988; Zak and Denton 1998). However, coastal winds are stronger and more saline than interior winds. It has been reported that increases in wind velocity affect the boundary layer, increasing the effects of contaminants (Ashenden and Mansfield 1977); also, plants physiologically lacking salt glands suffer under exposure to sea breezes, experiencing inhibition of growth or withering under stress from salt spray and electrolyte imbalance (Grace 1988; Zhu 2001; Munns 2002).

Such damage could be mitigated by constructing windbreak forests. Generally, windbreak forests have been constructed worldwide thanks to its various benefits (Bitog et al. 2011), have been formed along the coast so as to intercept the wind and reduce its velocity (Brandle et al. 2000; Cornelis and Gabriels 2005;

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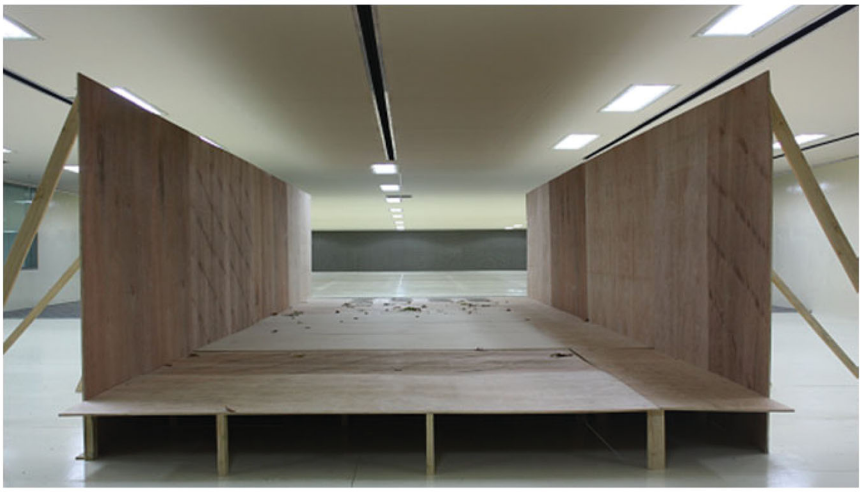

Figure 1. Structure of small-scale simulation model set up at the 30 cm height from the ground.

Zhou et al. 2005) and have been designed to protect houses and farmlands from sea breezes or tsunamis, as well as to prevent damage from drifting sand or movement of salinity (Lee et al. 2010). In addition to protecting against strong winds, these forests also create micrometeorological environments, typically including a heat reserving effect of 1–4 °C. The construction of wind protection forests is also highly desirable to protect farmlands that similarly experience wind damage to crops, arable land and other facilities; these include riverside, plateau and mountain foot areas (An 2006). There are many studies on the effects of windbreaks on the growth of potato plants (Sun and Dickinson 1997), the yields of wheat, lupin and mungbean (Sudmeyer et al. 2002) and the yield of wheat plants (Campi et al. 2009).

The effect of a windbreak forest in decreasing wind velocity depends on its height, width, density, porosity, arrangement and structure (Bitog et al. 2011). Windbreak forests can be classified by the degree to which they surround a protected area including line shapes, L shapes, U shapes and square shapes; and by the number of rows of protective trees planted in the shape of a fan.

Credible information on a variety of windbreak forests is required to optimize the construction and management of functional and efficient windbreak forests, but windbreak forests along the west coast of Korea are comprised mainly of *Pinus thunbergii*, which is a coniferous tree (Kim et al. 2012). *Pinus thunbergii* grows naturally in coasts and other places affected by sea breeze and is distributed from the latitudes of 29°00′N to 41°34′N (Kim and Kil 1983). It is a main afforestation tree species used in Korean coastal areas (Kim 2003), suitable for coastal disaster prevention, such as protection from wind and prevention of drifting sand and is valued as an ornamental species. Hence, for efficient construction and management of wind protection forests in the future, it is desirable to collect data regarding the wind protection effect of *P. thunbergii* and to develop effective means of estimating its effect in forest designs.

It is normal to plant wind protection forests comprising mixtures of coniferous trees and broadleaf trees. The sawtooth oak, *Quercus acutissima*, is a typical broadleaf tree of Korea, growing naturally in sunny mountain foot areas (Kim et al. 2009). It grows mainly from Jeju-do to Hamgyong-do from the altitude of 100 to 200 m, is resistant to drought, cold and shade, and can be easily seen near houses, on waysides and covering entire mountains (Chung and Lee 1965). *Quercus acutissima* is currently used in windbreak forests in Japan, along with *Q. dentata* (Korea Forest Service 2014).

Accordingly, the typical coniferous tree, *P. thunbergii* and the typical broadleaf tree, *Q. acutissima*, were selected for study as wind-protective species in the present research and wind tunnel experiments were carried out on various arrangements of these species to provide a fundamental source of data supporting the future design of efficient windbreak forests.

Materials and methods

Study materials

The present work was conducted to identify the most effective arrangement of a windbreak forest among several row-based planting structures. Four types of structures were studied: a simple structure of coniferous trees (1, 2 and 3 rows of *P. thunbergii*), a simple structure of broadleaf trees (1, 2 and 3 rows of *Q. acutissima*), mixed structure 1 (3 rows: *P. thunbergii, Q. acutissima* and *P. thunbergii*) and mixed structure 2 (3 rows: *Q. acutissima, P. thunbergii* and *Q. acutissima*). The testing materials were 3 year-old *P. thunbergii* seedlings and 8 year-*old Q. acutissima* seedlings. As mentioned in the Introduction section, those species were chosen because they are the typical windbreak tree species in Korea and Japan.

Table 1. Main data of experimental facilities.

List	Scale
Form	Closed-circuit wind tunnel
Size of experimental section	5m (W), 2.5m (H), 20m (L)
Wind velocity	0.3–13 m/s, 0.5–31 m/s
Turbulence intensity	Below 1.5%

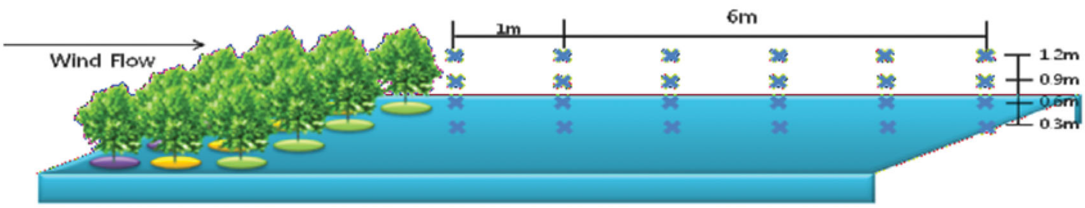

Figure 2. Wind tunnel experimental arrangement including locations of trees and measurement points.

Wind tunnel experiment was conducted using the giant wind tunnel facilities of the KOCED Wind Tunnel Center at Jeonbuk National University in Jeonju, Korea. In August 2012, the experiments were carried out in the low-speed portion of 2.3 m/s which is the mean wind speed of Gunsan over the recent 3 years (Korea Meteorological Administration 2009, 2010, 2011), under wind speeds ranging from 0.3 to 13 m/s. Table 1 lists the experimental parameters used.

Structure of simulation model for wind tunnel experiment

The small-scale simulation model was installed at the 30 cm height from the ground to avoid the effect of the atmospheric boundary layer.

Considering the height of the testing part was 2.0 m, the bottom part of the stem of trees was cut to make it 1.5 m based. The trees were fixed to a vase of 30 cm (W) × 30 cm (H). The experimental simulation model was designed 3 m (W) × 2 m (H) × 9 m (L). Putting porosity between trees aside, it was appropriate with the 7.5% of black ratio. This small-scale model additionally installed the walls of 2 m (H) × 9 m (L) in both sides of the model to avoid blending the main flow with the minor flow from out of sides due to the small scale of the simulation model (Figure 1).

Measuring method

Figure 2 schematically illustrates the arrangement used in the wind tunnel experiments and measurements were taken at 24 measurement points along a central plane of the test volume. Eight different row planting structures were used, three each of single species and two mixed: 1-, 2- and 3-row arrangements of *P. thunbergii*, 1-, 2- and 3-row arrangements of *Q. acutissima* (1-, 2- and 3-row arrangements), a mixed arrangement of *P. thunbergii* + *Q. acutissima* + *P. thunbergii* and a mixed arrangement of *Q. acutissima* + *P. thunbergii* + *Q. acutissima*.

Statistical analysis

PASW statistic software ver. 18 (Predictive Analytics Software) was used to identify the range of the effect of wind speed reduction among the different planting arrangements tested of the coniferous tree *P. thunbergii* and the broadleaf tree *Q. acutissima*. One-way analysis of variance was used as the major statistical method. Also, Duncan analysis was conducted to classify the same collective groups.

Table 2. Wind velocity and reduction ratio at each sample point for *P. thunbergii*.

Classification	Distance (cm)	Velocity (m/s)	Reduction ratio (%)
1 row	−10	2.300 ± 0.000^{c}	
	100	0.931 ± 0.355^{a}	60
	200	1.036 ± 0.272^{ab}	55
	300	1.084 ± 0.276^{ab}	53
	400	1.132 ± 0.246^{b}	51
	500	1.206 ± 0.157^{b}	48
	600	1.210 ± 0.140^{b}	47
2 rows	−10	2.300 ± 0.000^{b}	
	100	0.680 ± 0.487^{a}	70
	200	0.708 ± 0.344^{a}	69
	300	0.763 ± 0.281^{a}	67
	400	0.815 ± 0.227^{a}	65
	500	0.835 ± 0.205^{a}	64
	600	0.864 ± 0.177^{a}	62
3 rows	−10	2.300 ± 0.000^{b}	
	100	0.570 ± 0.444^{a}	75
	200	0.600 ± 0.345^{b}	74
	300	0.610 ± 0.328^{b}	73
	400	0.600 ± 0.309^{b}	74
	500	0.627 ± 0.286^{b}	73
	600	0.668 ± 0.241^{b}	71

Results and discussion

This study used the same instruments with wind tunnel experiment and 1 row, 2 rows and 3 rows of each species, mixed 3 rows (*P. thunbergii* + *Q. acutissima* + *P. thunbergii and Q. acutissima* + *P. thunbergii* + *Q. acutissima*) were measured in eight different shapes according to the change rate of average wind speed (1–6 m). The statistically analyzed results by using the mean of height (30, 60, 90, 120 cm) according to the distance is as follows.

Simple structure of a coniferous species (P. thunbergii)

Table 2 lists the wind speed data collected for the arrangements of 1, 2 and 3 rows of *P. thunbergii*. For the 1-row arrangement, the correlation between distance and average wind speed decrease was statistically significant at $\alpha = 0.05$, with $F = 60.469$ and $p = 0.000$. The effect of the protective rows in decreasing wind speed was considerable, with η^2 of 0.953, greater than the large-effect benchmark of 0.14. Therefore, it can concluded that the wind speed varied according to the distance. Similarly, the 2-row arrangement of *P. thunbergii* showed a large effect statistically significant at $\alpha = 0.05$, with $F = 55.134$, $p = 0.000$ and $\eta^2 = 0.948$; the 3-row arrangement of

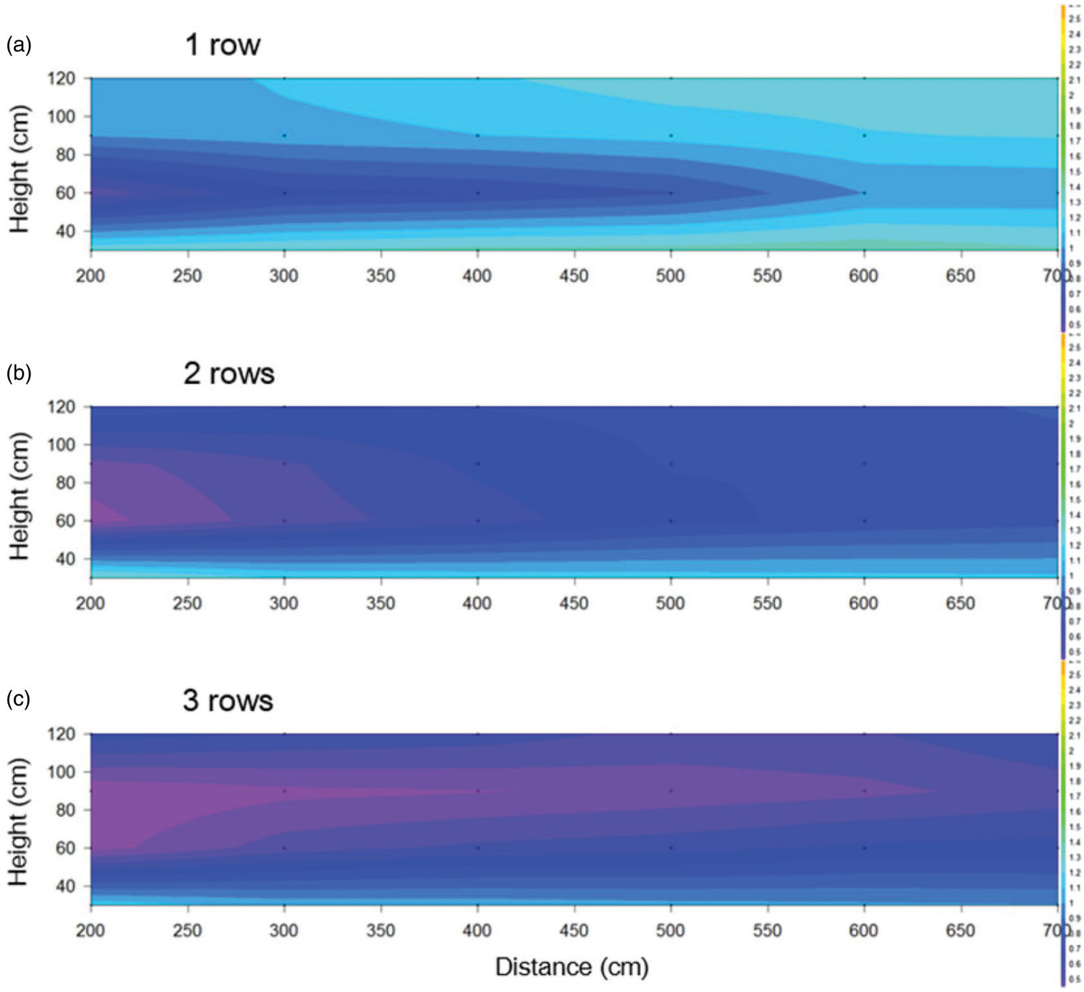

Figure 3. Spatial distributions of mean velocity by number of planting lows of *Pinus thunbergii*.

P. thunbergii also showed a statistically significant result at $\alpha = 0.05$, with $F = 71.843$, $p = 0.000$ and $\eta^2 = 0.960$ (Figure 3).

The *P. thunbergii* material proved to be effective in reducing the wind speed, to as little as one-fourth at the height of 1.5 m, but the same after 1 m point. As shown in Table 2, as the number of rows was increased, the effect was increased somewhat. Park (2009) claimed that in the case of multi-layered windbreak forests, the height of the tallest row of trees decides the magnitude of the windbreak effect.

Simple structure of broadleaf tree (Q. acutissima)

Table 3 lists the effects of using various numbers of rows of *Q. acutissima*. The effect of decreased wind speed was large and statistically significant at $\alpha = 0.05$ for each of the 1-, 2- and 3-row arrangements. The *Q. acutissima* rows proved to be effective in reducing the wind speed, to as little as one-fourth at the height of 1.5 m. However, the 1- and 2-row arrangements showed a decreased effect after the 3 m point. The 3-row arrangement showed a decreased effect after the 4 m point. As shown in Table 3, as the number of rows was increased, the reduction of wind speed near these rows also increased.

Table 3. Wind velocity and reduction ratio at each sample point for *Q. acutissima*.

Classification	Distance (cm)	Velocity (m/s)	Reduction ratio (%)
1 row	−10	2.300 ± 0.000^b	
	100	1.134 ± 0.868^a	51
	200	1.104 ± 0.835^a	52
	300	1.092 ± 0.753^a	53
	400	1.115 ± 0.651^a	52
	500	1.143 ± 0.585^a	50
	600	1.165 ± 0.497^a	49
2 rows	−10	2.300 ± 0.000^b	
	100	0.722 ± 0.525^a	69
	200	0.680 ± 0.493^a	70
	300	0.673 ± 0.462^a	71
	400	0.680 ± 0.472^a	70
	500	0.727 ± 0.396^a	68
	600	0.788 ± 0.320^a	66
3 rows	−10	2.300 ± 0.000^b	
	100	0.611 ± 0.784^a	73
	200	0.615 ± 0.750^a	73
	300	0.582 ± 0.682^a	75
	400	0.572 ± 0.634^a	75
	500	0.784 ± 0.401^a	66
	600	0.950 ± 0.208^a	59

However, comparing the 2- and 3-row arrangements, the 2-row arrangement yielded greater wind speed reduction at greater distances from the windbreak rows (Figure 4).

This is unlike the trend observed for *P. thunbergii*, whereby the wind speeds at all positions observed decreased more with increasing row number. This likely arose from variations in the porosity of

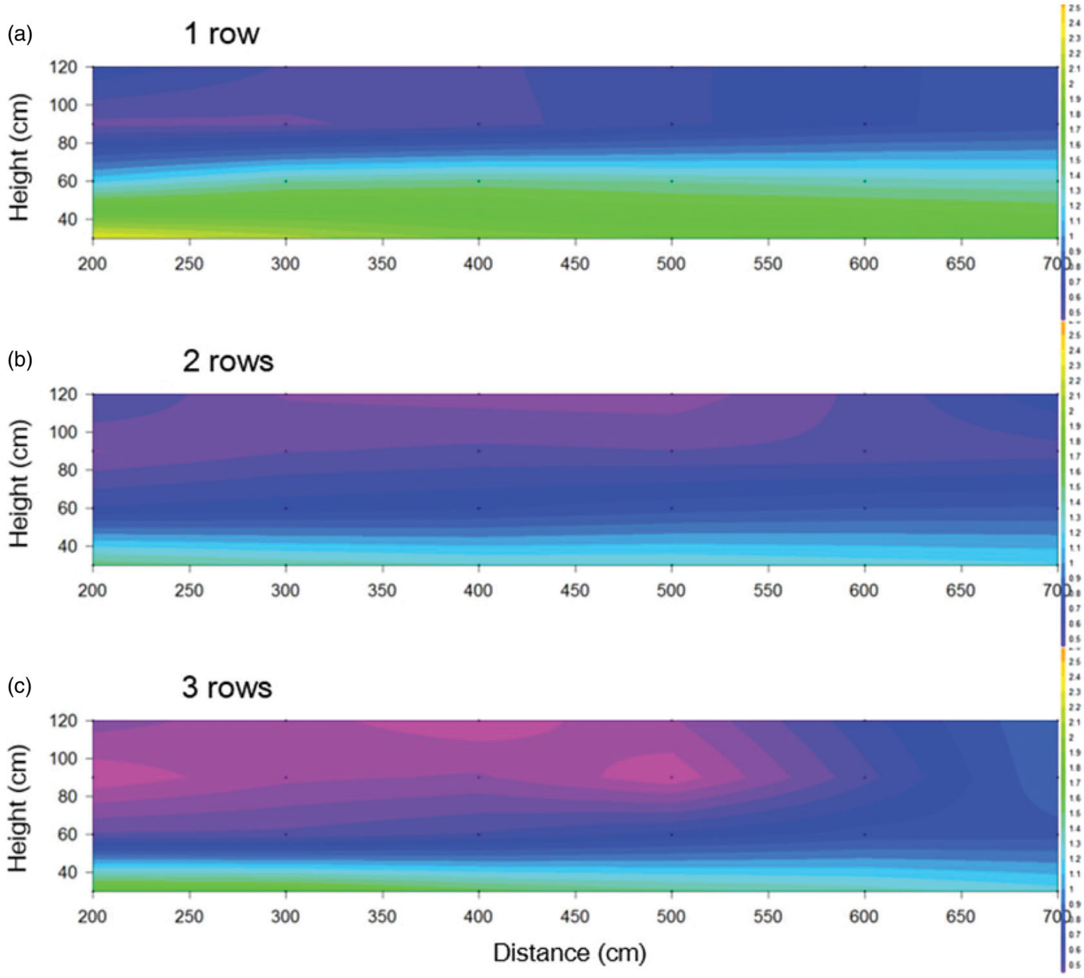

Figure 4. Spatial distributions of mean velocity by number of planting lows of *Quercus acutissima*.

Q. acutissima according to the planting space. You (2009) also mentioned that the height of the tree and the planting space are key factors in the windbreak effect.

Mixed structure

The three-row mixed structure of *P. thunbergii* + *Q. acutissima* + *P. thunbergii* lowered wind speed; this effect was large and statistically significant at $\alpha = 0.05$, with $F = 65.037$, $p = 0.000$ and $\eta^2 = 0.921$. Similarly, the three-row mixed structure of *Q. acutissima* + *P. thunbergii* + *Q. acutissima* reduced wind speed as a large effect statistically significant at $\alpha = 0.05$, with $F = 42.366$, $p = 0.000$ and $\eta^2 = 0.934$.

The mixed planting rows reduced the wind speed to about one-fourth of the original speed at 1.5 m distance. However, the effect weakened after the 4 m point. As shown in Table 4, the mixed row arrangement of *Q. acutissima* + *P. thunbergii* + *Q. acutissima* was more effective. Therefore, when building up the windbreak forest vertically, it is expected that planting coniferous trees at the windward side, followed by broadleaf trees and then coniferous trees again, would yield the most effective structure (Figure 5).

Coniferous trees protect well against wind when used in windbreak forests because they maintain their leaves during the winter. Two rows of coniferous trees have the same effect in reducing wind velocity as 5–8 rows of broadleaf trees; however, they are not always suitable for use because they are difficult to root, are sensitive to soil conditions and grow slowly. Contrastingly, broadleaf trees grow more quickly and thus can afford wind protection more quickly; in designing wind protection forests composed of broadleaf trees only, it is advisable to plant at least 5 rows of trees and in general when using broadleaf trees it is better to include some coniferous trees (Kim and Son 2000).

Table 4. Wind velocity and reduction ratio at each sample point for mixed structures of *P. thunbergii* and *Q. acutissima*.

Species	Classification	Distance (cm)	Velocity (m/s)	Reduction ratio (%)
P. thunbergii	3 rows	−10	2.300 ± 0.000^b	
+ *Q. acutissima*		100	0.675 ± 0.580^a	71
+ *P. thunbergii*		200	0.581 ± 0.616^a	75
		300	0.558 ± 0.587^a	76
		400	0.557 ± 0.520^a	76
		500	0.565 ± 0.463^a	75
		600	0.613 ± 0.370^a	73
Q. acutissima	3 rows	−10	2.300 ± 0.000^b	
+ *P. thunbergii*		100	0.717 ± 0.507^a	69
+ *Q. acutissima*		200	0.707 ± 0.426^a	69
		300	0.697 ± 0.395^a	70
		400	0.675 ± 0.419^a	71
		500	0.717 ± 0.359^a	69
		600	0.768 ± 0.292^a	67

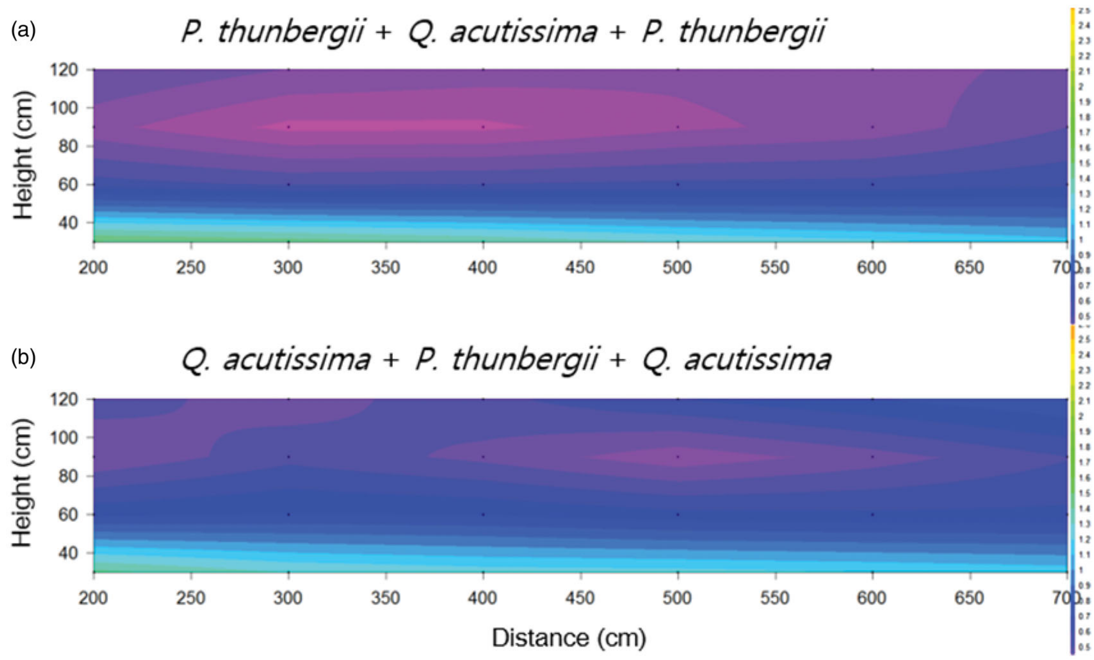

Figure 5. Spatial distributions of mean velocity by planting order.

Conclusions

The wind speed decreasing effect was studied of rows of coniferous trees and broadleaf trees, including 1-, 2-, and 3-row arrangements of single representative species of each, as well as 3-row mixed arrangements. The 1-, 2-, and 3-row arrangements of *P. thunbergii*, the representative coniferous tree, all showed a 75% wind speed reduction at the height of 1.5 m. Among eight wind tunnel experiments, a significant decrease in wind speed was observed as the number of rows of *P. thunbergii* was increased. Therefore, when making a windbreak forest composed of *P. thunbergii*, increasing the number of planted rows is advisable.

Similarly, the use of multiple windbreak rows of *Q. acutissima* yielded wind speed reductions of 75% near the rows, at 1.5 m. However, the 2-row arrangement actually showed a greater effect than the 3-row arrangement at a distance of 4 m. This suggests that we cannot conclude that adding *Q. acutissima* rows always increases the windbreak effect. In conclusion, broader leaves do not necessarily yield more reduction in wind speed. Also, to support the use of windbreak forests composed of broadleaf trees, further study is advisable regarding the effect of row spacing upon the trees porosity.

Both mixed structures studied, *P. thunbergii* + *Q. acutissima* + *P. thunbergii* and *Q. acutissima* + *P. thunbergii* + *Q. acutissima*, showed wind speed reductions of approximately 75% at 1.5 m; the former structure performed slightly better. In the wind tunnel tests, the 3-row structure of only *P. thunbergii* showed the greatest windbreak effect. However, in practical scenarios, using the alternating structure of coniferous, broadleaf, and coniferous rows would be a better choice, offering a similar effect with less risk of loss to disease and insects.

Disclosure statement

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