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A model to evaluate windbreak protection efficiency

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Abstract. The effectiveness of windbreaks in windspeed reduction is often evaluated without regard to the objects to be protected. In fact, many objects may have different sensitivities to wind and often require different degrees of wind protection. Since commonly used indexes do not consider the sensitivity to wind, a concept of specific protection efficiency is developed. A critical windspeed is used to represent the sensitivity of each object. Windspeeds greater than this value are considered damaging. A dimensionless protection index is defined to evaluate windbreak efficiency. The maximum index value is 1 for the highest protection, and the index is negative when sheltered windspeed is greater than the critical windspeed. This index can be compared, summed, and averaged across different windbreaks, objects, and leeward locations. A sample of critical windspeed values was compiled from the literature. The index was evaluated using actual wind data measured under both sheltered and open conditions. The results indicated that the index can be used for evaluating windbreak effectiveness in terms of objects protected under various conditions. This model could be used as a tool for windbreak-related research and policy making.

Introduction

Windbreaks provide protection to plants, animals, homes, and humans. The effectiveness of windbreaks in reducing windspeed ultimately determines the final benefits received. From an economic point of view, windbreaks involve costs for establishment and maintenance, consequently, the ability to appropriately evaluate windbreak effectiveness is both an important theoretical and practical question.

The effectiveness of windbreaks can be evaluated in many ways. Several common indexes have been used in the literature: relative windspeed η [Seginer and Sagi, 1971/1972], relative windspeed reduction η_1 [Plate, 1971; van Eimern et al., 1964], the location or distance of minimal leeward windspeed [Heisler and DeWalle, 1988; Loeffler et al., 1992], and the maximum or effective protected distance [Wei et al., 1987]. Jensen [1961] proposed a shelter index, which he defined as the integrated relative windspeed reduction over the distance under windbreak protection. Seginer [1972, 1975] used an efficiency coefficient defined as the ratio of the surface shear reduction coefficient to the drag coefficient. In order to obtain the former, Seginer integrated a function of relative windspeed $(1 - \eta^2)$ over the distance from the windbreak. Raine and Stevenson [1977] defined a total velocity index which they described as a double integration of relative windspeed over the distance of protection and the height of the windbreak. The lowest total velocity gave the best overall protection.

Although these indexes represent different approaches, they all are indexes of general efficiency of windbreaks. Unfortunately, none of these indexes gives any consideration to the windbreak protection effect relative to the protected object. We propose an index which considers the requirements of protected objects, with protected objects defined as anything benefitting from changes in the natural flow of air.

Different protected objects generally require different degrees of wind protection. For example, agricultural crops may require a different level of protection compared to domestic animals. Southern peas [*Vigna unguiculata* (L.) Walpers] were found to have withstood five times more blowing sand injury than carrots (*Daucus carota* L.) and three times more than cotton (*Gossypium hirsutum* L.) [Fryrear and Downes, 1975]. In these cases, the same windbreak may not provide the same degree of protection to each of these objects. An appropriate protection combination, defined as one of various possible ways to combine the windbreak and protected objects, must be sought in order to achieve optimum benefit. As our understanding of the requirements of protected objects improves, it will become possible to design windbreaks to meet specific needs of various protected objects. Therefore, the concept of *specific protection efficiency* is proposed.

The objectives of this paper are to develop a model to determine the relative effectiveness of a windbreak with respect to a specific object to be protected, and to evaluate the model using actual measured windspeed data.

A model of windbreak protection efficiency

The concept of specific protection efficiency is based on the critical windspeed (U_C) for the protected object. This windspeed is defined as the windspeed which causes initial damage to a protected object and is different for different objects. If sheltered windspeed (U_S) is less than U_C for a given object, the windbreak provides appropriate protection; on the other hand, a sheltered windspeed greater than U_C implies that the windbreak did not provide the protection required by the object. This could result from an inappropriate windbreak design, improper location of the protected object, or higher windspeeds in the open. In any case, specific protection efficiency can be used to determine which factor or factors need to be adjusted in order to improve protection.

The magnitude of the specific protection efficiency is expressed by the dimensionless specific protection index (f). It was designed with the following objectives or assumptions: a) Sheltered windspeeds (U_S) less than U_C are beneficial and f values are positive; b) Sheltered windspeeds greater than U_C are damaging and f values are negative; c) When sheltered windspeeds are greater than U_C, a penalty (a greater weight) is given for a negative f; d) The index should be able to be averaged over time, distance from the windbreak, and height above the ground, providing an overall evaluation and allowing comparisons between different situations; and e) The index evaluates only the effect of windspeed and not the possible accompanying effects of temperature or other changes caused by windspeed differences.

The specific protection index is defined as:

$$f = 1 - \frac{U_S}{U_C} \qquad when\ U_S \le U_C \tag{1}$$

or:

$$f = 2\left(1 - \frac{U_S}{U_C}\right) \qquad when\ U_S > U_C \tag{2}$$

The maximum value of f is 1 when sheltered windspeed (U_S) is 0. When U_S is greater than U_C, a factor of 2 is applied to the calculation. The assumptions are made that when U_S exceeds U_C by even a small amount, a significant effect of windspeed is immediately observed and that the magnitude of the damage exceeds the possible benefits received when U_S is slightly less than U_C by a similar windspeed amount. Furthermore, within a specific windspeed range for certain protected objects, an increase of windspeed from 5 m s^{-1} to 10 m s^{-1} increases the damage level by a factor of around 2 (see Table 1) [Campbell et al., 1980; Grace, 1977; Moyer, 1990].

In order to calculate the specific protection index, the critical windspeed (U_C) must be available for the object to be protected (Table 2). For plants, U_C values are in the range of 2–5 m s^{-1}. These windspeeds may be physiologically harmful to plants, and cause disturbances of plant water relations, photosynthesis, growth, and reproduction processes [Baldwin, 1988; Cao, 1983; Wei et al., 1987; Winter, 1965]. Compared to no-wind controls, growth of potato shoots was retarded when plants were exposed to a windspeed of

Table 1. The relative response of various objects to windspeed increase from 5 m s^{-1} to 10 m s^{-1} with response at 5 m s^{-1} taken as 1.

	Relative windspeed response	References
Decrease in leaf area relative growth rate	1.64	Grace [1977]
Flag leaf damage	2.12	Grace [1977]
Reduction of animal coating	1.60	Campbell et al. [1980]
Increase in heat infiltration	1.80	Moyer [1990]

Table 2. Critical windspeeds (U_C) for various protected objects.

Protected objects	U_C (m s^{-1})	References
Agricultural crops		
Gossypium hirsutum L.	5	Wei et al. [1987]
Oryza sativa L.	4–5	Wei et al. [1987]
Sorghum vulgare Pers.	4	Wei et al. [1987]
Triticum spp.	3	Wei et al. [1987]
Zea mays L.	4–5	Wei et al. [1987]
Horticultural crops		
Brassica spp.	4	Wei et al. [1987]
Capsicum frutescens L.	4	Wei et al. [1987]
Cucumis sativus L.	4	Wei et al. [1987]
Lycopersicon esculentum Mill.	2.4	Winter [1965]
Solanum tuberosum L.	2.4	Winter [1965]
General vegetables	4.4	Baldwin [1988]
Trees/shrubs		
Agave rigida Mill.	4	Wei et al. [1987]
Coffea canephora Pierre	4	Wei et al. [1987]
Elaeis guineesis Jacq.	3	Wei et al. [1987]
Hevea brasiliensis Muell.	2–3	Wei et al. [1987]
Piper nigrum L.	3	Wei et al. [1987]
Theobroma cacao L.	4	Wei et al. [1987]
Humans	5	Gandemer [1981]
Animals		
Sheep	5	Johnson and Beck [1988]
Rabbit	8	Johnson and Beck [1988]
Swine	3.6	Johnson and Beck [1988]
General livestock	2	Campbell et al. [1980]; Parker and Gillingham [1990]
Mobile home energy conservation	3–4	Heisler and DeWalle [1988]; Moyer [1990]
Soil erosion	5.4	Aase et al. [1985]
Sand drifting	4–5	Wei et al. [1987]

2.4 m s^{-1} imposed during 12 hour light periods [Winter, 1965]. The rate of water loss from tomato plants was accelerated during 8 hour light periods at the same windspeed [Winter, 1965]. Most vegetable crops in Australia would suffer in yield, quality and profit if windspeeds exceed 4.4 m s^{-1} [Baldwin, 1988]. Soil abrasion may also cause physical damage to plant parts resulting in a physiological response and a critical value of 5.4 m s^{-1} for soil movement has been reported [Aase et al., 1985].

Values of U_C for domestic animals are derived from the amount of heat loss resulting from winds penetrating the coat [Johnson and Beck, 1988], and a value of 2 m s^{-1} is typical. This value was obtained based on reports by Campbell et al. [1980] and Parker and Gillingham [1990], which indicated that within the windspeed range of 1 to 10 m s^{-1}, animal whole body resistance was reduced by 16% when windspeed increased from 1 to 2 m s^{-1}. The 16% figure is acceptable as initial damage.

According to Moyer [1990], air infiltration accounts for most of the heat exchange of buildings. For windbreaks designed for energy conservation, lower windspeeds mean less air infiltration, lower air exchange rates, and lower convective heat loss. For mobile homes, a greater infiltration rate generally occurs if the windspeed exceeds 3–4 m s^{-1} [DeWalle and Heisler, 1988; Moyer, 1990].

In order to calculate f, sheltered windspeed is needed and can be either measured directly or predicted from various models. Since sheltered windspeed is determined by exposed windspeed and windbreak related characteristics such as porosity, comparisons of f values should be made under similar exposed wind conditions.

The advantages of this model lie in its ability to evaluate specific protection efficiency from different perspectives. Given a specific object in need of protection, a windbreak or windbreak system can be designed for the greatest f value. Using various available models or actual measurements, windbreak parameters can be manipulated using computer simulations to achieve predetermined goals. On the other hand, if a windbreak or windbreak system is in place, the location and orientation of protected objects can be arranged to achieve the maximum f value. In both cases, historical windspeed values and distribution frequency data can be used for the simulation. Cost factors for each of the available combinations can be included. Since all calculations can be done using computers, significant savings in time and money can be expected. Another advantage of this model is that comparisons can be made in terms of f values for various situations, including windbreak systems, windbreak species and structures, or protected objects. This process can be very beneficial in both research and practice.

During calculations of average f values over time or spatial locations (distance and height), two more indexes are useful: negative ratio and negative deviation (d).

The negative ratio is defined as the number of negative f values over the total number of f values and is a measure of the number of times that sheltered windspeed exceeds critical windspeed. A small negative ratio means that sheltered windspeeds rarely exceed the critical windspeed for the object.

The negative deviation is a measure of the relative magnitude of the negative f values and is defined as:

$$d = \sqrt{\frac{\sum (negative\ f\ value)^2}{n}} \tag{3}$$

where n is the number of negative f values. A small d value indicates that negative values of f are small and therefore less influential on the average f value. Currently, there is limited information on the tolerance of various objects to high d values.

During the evaluation, it is suggested that d be used together with the negative ratio. A high negative ratio and a high d should be avoided during windbreak design and selection of protected objects. An ideal protection combination (of windbreaks and objects) would mean a greater average f value (approach 1), lower negative ratio (approach 0), and smaller negative deviation (approach 0).

Using the ideas of Jensen [1961] and Raine and Stevenson [1977] on the evaluation of windbreaks by general indexes, similar specific protection indexes can also be developed. Values of f can be calculated from windspeed measurements in shelter at a series of distances. An integration of such f values gives an overall specific shelter index of the windbreak. If wind profiles at different distances are available as well, a double integration can be used to combine the horizontal and vertical f values. The advantage of such integration is that the effect of windbreak porosity can be incorporated, since the porosity can change the patterns of windspeed distribution in shelter.

Materials and methods

Windbreak systems used for the evaluation of specific protection are located at the University of Nebraska Agricultural Research and Development Center (ARDC) near Mead, Nebraska. Two systems with different porosities were used in this study. The first (SH2) is composed of two rows of alternating *Juniperus virginiana* L. and *Pinus sylvestris* L. The second system (SH3) is composed of two rows of alternating *Fraxinus pennsylvanica* L., *J. virginiana* and *P. nigra* Arnold and has a greater porosity than the first.

Measurements were taken at distances of 0.5, 1, 2, 5, 7, and 10 times the respective windbreak height. All windspeed measurements were made at a height of 1 m above the ground surface. A summary of the measurement schedule is presented in Table 3.

Windbreak optical porosities were estimated using digitized color images aided by an image processing program called 'Digit' (developed by G.E. Meyer). Color slides of the windbreaks were taken from both sides using Kodachrome daylight film (KR 135–24, ASA 64). The slides were digitized using a Nikon 35 mm Film Scanner Model LS-3500 and Aldus Photostyler under Microsoft Windows. Color images were produced in 24-bit TARGA format and converted to 8-bit color images to be used by 'Digit'. Optical porosities obtained are expressed as a percent.

Table 3. A summary of wind measurements. Windspeeds with directions between SSE and SSW were used. WB Ht = average windbreak height.

Time frame	Windbreaks	Distance (H)	Instr. Ht (m)	WB Ht (m)	Porosity (%)
May 1991	SH3	0.5, 1, 2, 5, 7, 10	1	11.8	47.9
	CK3	0.5, 1, 2, 5, 7, 10	1	–	–
May–September 1991	SH3	5	2.5	11.8	47.9[a]
	CK3	5	2.5	–	–
April–September 1992	SH2	5	2.5	9.1	40.2[a]
	CK2	5	2.5	–	–
	SH3	5	2.5	11.9	52.7[a]
	CK3	5	2.5	–	–

[a] Porosity measurements were made in early May 1991 and late April 1992 and were assumed to remain unchanged during the growing season.

Results and discussion

*For corn (*Zea mays *L.) at ARDC, Mead, Nebraska*

Using windspeed data measured during two growing seasons at ARDC, average f values for a corn crop in shelter were calculated. Critical windspeed was 4.5 m s^{-1}. The values of f changed as expected when distance increased (Table 4). Greater f values (greater protection efficiency) occurred near the windbreaks and f decreased as the distance increased. The f values for May 1991-SH3 were high (from 0.75 to 0.83), an indication that U_S rarely exceeded U_C in the sheltered area. A comparison of average f values between SH2 and SH3 indicated that SH2 provided greater wind protection to corn, which probably was the result of the lower porosity of SH2. The following conclusions can be drawn:

Table 4. Specific protection indexes (f) for windbreaks SH2 and SH3 and corn at ARDC, Mead, Nebraska. The critical windspeed used was 4.5 m s^{-1}. The whole season was the time period from May to September. Std Dev = standard deviation of f and d = negative deviation.

Time frame	Windbreaks	Distance (H)	Avg. f	Std Dev	Negative ratio	d
May 1991	SH3	0.5	0.802	0.170	0.00	0.000
		1	0.816	0.134	0.00	0.000
		2	0.828	0.114	0.00	0.000
		5	0.790	0.135	0.00	0.000
		10	0.746	0.220	0.00	0.043
Whole season 1991	SH3	5	0.829	0.143	0.00	0.234
Whole season 1992	SH2	5	0.762	0.233	0.01	0.227
	SH3	5	0.751	0.234	0.01	0.266

1) Wind reduction from the windbreak system 3 (SH3) is appropriate for corn if windspeeds are similar to May 1991, and the protected distance is less than 10 H.
2) Windbreak system 2 (SH2) provided greater seasonal protection for corn than SH3 at a distance of 5 H.

For horticultural crops using wind data from ARDC, Mead, Nebraska

Using the same windspeed data as used above, a hypothetical situation using horticultural crops as the protected objects was developed, and a prediction of various f values was made. A value of 4 m s^{-1} was used for the critical windspeed (Table 2) for crops such as *Brassica* spp., *Capsicum frutescens* L. and *Cucumis sativus* L. The results are presented in Table 5.

Using the windspeeds of May 1991, all f values are greater than 0.7, which is high in terms of specific protection. All negative ratios are either small (0.009 for 10 H but rounded to 0 in Table 5) or zero, which indicate that rarely did sheltered windspeeds exceeded 4 m s^{-1} in May 1991. These f values show that the above horticultural crops would be properly protected by the windbreak if they were to experience similar windspeed conditions. The protected distance would be at least 10 H.

A comparison of seasonal f values shows that these windbreaks provide high specific protection to these crops. Within the year 1992, SH2 provides greater seasonal specific protection than SH3, which is probably the result of lower porosity for SH2. All seasonal f values were calculated based on the distance of 5 H from the windbreak. Compared to the f values for corn in the previous example, all f values in this example were reduced but are still relatively high (Table 5). More negative f values were seen in this example as evidenced by greater negative ratios for 10 H of May 1991 and seasonal values for 1992. Greater negative deviations were also seen.

Table 5. Specific protection indexes (f) for windbreaks SH2 and SH3 and horticultural crops at ARDC, Mead, Nebraska. The critical windspeed used was 4 m s^{-1}. The whole season was the time period from May to September. Std Dev = standard deviation of f and d = negative deviation.

Time frame	Windbreaks	Distance (H)	Avg. f	Std Dev	Negative ratio	d
May 1991	SH3	0.5	0.776	0.191	0.00	0.000
		1	0.793	0.151	0.00	0.000
		2	0.807	0.129	0.00	0.000
		5	0.764	0.151	0.00	0.000
		10	0.713	0.250	0.01	0.298
Whole season 1991	SH3	5	0.803	0.164	0.00	0.366
Whole season 1992	SH2	5	0.751	0.247	0.02	0.383
	SH3	5	0.735	0.257	0.02	0.453

Conclusions

An index of windbreak specific protection efficiency is proposed as a means to evaluate the ability of a windbreak to provide adequate protection to specific objects. This index measures the relative difference between the sheltered windspeed and the critical windspeed. The greater the index, the greater the specific protection efficiency of the windbreak. The index can be used for either evaluating existing protection combinations or designing new combinations. Since the index can be averaged, it is possible to use it to make comparisons for different situations, such as windbreak systems, time periods or spatial locations. In hypothetical simulations, it is also possible to use windspeed data from local weather stations, from which various scenarios can be evaluated on the computer. The index evaluates the specific protection only in terms of windspeed reduction by the windbreak; no attempt has been made at this point to evaluate the possible accompanying effects of windspeed change. Due to the limited information on the critical windspeeds in the literature, further improvements in this model could be made by expanding the table of critical windspeeds to include more protected objects and by experimenting with different windspeed sensitivities at various stages of crop growth. By incorporating this model into various windspeed prediction models, it will provide the possibility of making computerized windbreak designs and evaluations of windbreaks for specific goals.

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