Saving irrigation water by accounting for windbreaks

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Abstract

Water for irrigation in the Canterbury region of New Zealand is becoming an increasingly precious commodity, as it is in many other areas of the world. Adequate use of this resource will define the economical and environmental future of the region. Current irrigation systems, even under best management practices, over-apply water, as they do not account for spatial variability of crop water needs in fields. Over-application of water is wasteful and has environmental and economical repercussions. Water requirements are determined by crop evapotranspiration (ET). Key factors affecting ET in Canterbury are wind and solar radiation. Both of these are significantly affected by windbreaks, resulting in variability in ET and water requirements across a field. Understanding the variability in ET caused by windbreaks will enable for the correct application of water through precision irrigation systems.

A theoretical model was developed to estimate savings in irrigation by accounting for windbreaks in the Canterbury region. Windbreaks reduce evapotranspiration and therefore crops/pasture behind windbreaks needs less water than those in other parts of the field. Results for a case study in Canterbury show that windbreaks can potentially reduce the annual on-farm water consumption by 10 to 20%, while still maintaining ideal crop/pasture yields. In the short term, the application of precision irrigation systems in fields with windbreaks can have the farm level benefits of improved water use and reduced nitrogen/phosphorus leaching. In the long term this could translate directly into cost savings because of a potential decrease in energy used for irrigation (running pumps, etc.).

Keywords: irrigation modelling, evapotranspiration, windbreaks, water saving.

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1 Introduction

The Canterbury region lies in the Eastern part of the South Island of New Zealand. This area stretches from the Southern Alps in the West down to the Pacific Ocean in the East. Due to the rain shadow effect of the Southern Alps, rainfall averages only 650mm per year, with occasional long dry spells, especially during the summer. A large part of the region is dominated by the Canterbury plains, one of the prime agricultural areas in New Zealand. The region was originally mostly under dryland sheep farming and arable cropping; however, since the 1990s there has been a significant increase in intensive dairy farming (Wilson [1]). Most dairy farms in the region use direct grazing only with a stocking rate of 2.5-4 cows/ha. This practice in combination with the low rainfall means irrigation has become essential for economic viability. Large irrigation schemes have been completed and more are proposed to cope with the increased demand. This has increased the pressure on both surface and groundwater resources and water in many areas of the region is now either fully allocated or even over allocated. In addition there is an increased demand for energy (through pumping) and an increased risk of groundwater nitrate contamination associated with increased dairying and irrigation.

In addition to low rainfall and intensive grazing, another influence on irrigation requirements are the high wind speeds Canterbury experiences. To reduce the effect of the wind on crop evapotranspiration and soil erosion, many farms have established windbreaks. The development of windbreaks started in the 1850s and by the 1990s extended for a combined length of nearly 300,000 km (Price [2]). While a large number of fields have barriers on all four sides, most have at least a barrier in the East-West direction. This is to protect crops and livestock from the southwesters which, although not the prevailing wind, are the most damaging as they tend to bring storm-force winds straight from Antarctica (the temperature differential between northerlies and southerlies can be 15-20 ºC and can occur is very short periods of time).

Windbreaks work by the adsorption of momentum from the wind flow, which results in a decrease of the wind velocity and turbulence (Vigiak et al. [3]). The influence of the windbreak depends on the height and porosity and extends from around 5 times the height on the windward side to 35 times the height on the lee side (Figure 1). As shown wind speeds can be reduced up to 90%, which may have a considerable influence on a crops growing in the influence zone of a windbreak.

Evapotranspiration (ET) rates of a crop are dependent on many factors such as net radiation, air temperature, vapour pressure, but also wind speed. Any change in the wind speed is likely to have an effect on the ET. In the case of a well-watered crop reduced wind speeds behind a windbreak will result in a drop in ET (Cleugh [4]). At low wind speeds this drop will be minimal, but with high wind speeds and low humidity this drop may be up to 45% (Doorenbosch and Pruitt [5]). Both conditions are a common occurrence on the Canterbury Plains during the summer.

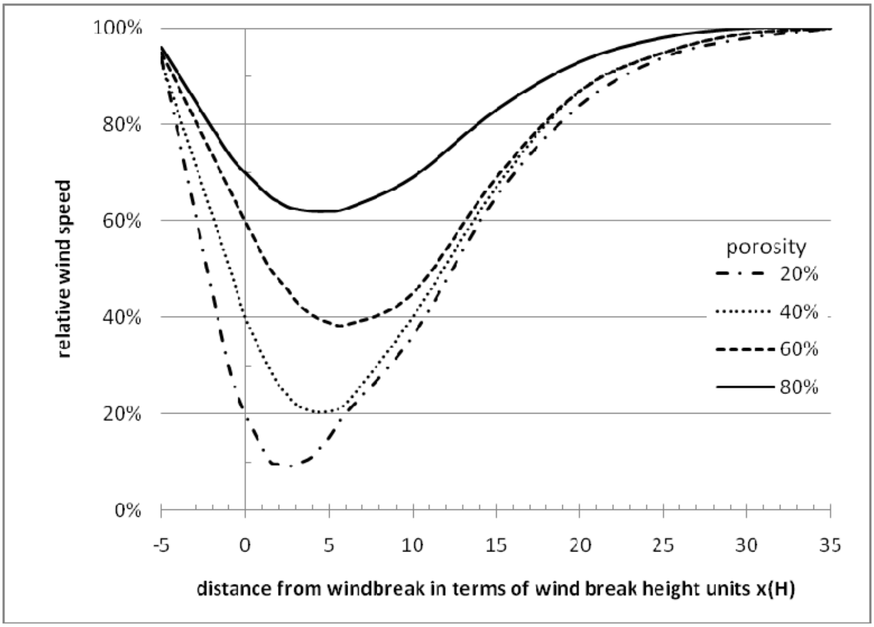

Figure 1: Reduction in wind speed behind wind breaks of different porosities (after Vigiak et al. [3]).

Windbreaks also create a shadow close to the barrier which further reduces ET. Shadows can significantly reduce the radiation received by a crop close to the wind break and thus reduce the ET. Although the wind reducing effect extends much further into the field, the shading can affect the first 20-50m. If the distance between two windbreaks is as small as 100m, as happens often in Canterbury, this may affect total ET in a field considerably, especially during the early and late season (as a result of the lower solar angle).

Accounting for a drop in ET in parts of a field has very little practical application if there is no possibility to translate this drop into a reduced irrigation water requirement and reduced water application. Until recently most irrigation systems in the Canterbury area were fixed rate centre-pivots or linear move sprinklers which offer very little opportunity to adjust application rates. The recent development of variable rate applicators combined with GPS systems has now changed this. Therefore the aim of this paper is to model and quantify the influence of windbreaks on irrigation water requirements for a typical field in the Canterbury area of New Zealand.

2 Methodology

Irrigation water requirements for typical fields with windbreaks in Canterbury were estimated by calculating actual ET for a pasture crop at various distances from a windbreak. Wind break characteristics, climatic data, ET equations, and computational assumptions are described below.

2.1 Windbreak characteristics in Canterbury

Canterbury windbreaks are characterised by single or multiple rows of Monterey pine (Pinus radiata) and Monterey cypress (Cupressus macrocarpa), similar to the “Line 1” class proposed by Vigiak et al. [3] shown in Table 2. The Canterbury windbreaks tend to be somewhat lower and more closed at the bottom than the described Line 1 class; therefore the height has been adjusted to 10m with a porosity of 0.40. The distance between two windbreaks can be as low as 100-250m, but can also reach distances of 500-1000m. For modelling purposes the orientation of the windbreak has been set to East-West. The main purpose for irrigation is pasture for dairy farms and the dominating soil type is a sandy clay loam.

2.2 Climatic data

Climatic data was obtained from the National Climate Database of New Zealand (NIWA [6]). This included hourly measurements of temperature, dew point temperature, wind speed, direct solar radiation, rainfall and sunshine hours. Evapotranspiration was modelled for three months, March, June and December in 2004 and 2008, representing average autumn/spring, winter and summer months in the region. Evapotranspiration was calculated with the ASCE standardised reference ET equation for three scenarios as described below.

Table 1: Characteristics of windbreak classes[1].

Class	Description	Height (m)	Width (m)	Porosity (-)
Hedgerow	Low, mostly hawthorn	2.1	1.1	0.25
Hedge	Higher than hedgerow, uniform vertical screen mixture of species	8.8	4.8	0.32
Line 1	Single or multiple lines of coniferous trees	15.1	9.5	0.49
Line 2	Single line of deciduous species, mostly oak	12.5	6.2	0.46
Line 3	Multiple lines of trees, deciduous or mixed	16.2	16.6	0.25
Wood	Small woods, width/height ratio >1	15.4	29.0	0.17

[1] Source: Vigiak et al. [3].

2.3 Scenarios

Three scenarios were chosen for modelling:

- **W**, wind only, evapotranspiration is affected by windbreaks through a reduction in wind speed:

$$ET = f(u, x) \tag{1}$$

where ET = reference evapotranspiration; u = wind speed; and x = distance from windbreak.

- **S**, shade only, evapotranspiration is affected by the effect of the shade from the windbreak on the net radiation:

$$ET = f(R_n, x) \tag{2}$$

where R_n = net solar radiation.

- **WS**, wind and shade, evapotranspiration is affected by both reduced wind speeds and the shade from the windbreak:

$$ET = f(u, R_n, x) \tag{3}$$

In all scenarios the evapotranspiration is influenced by the height, width and porosity of the windbreak.

2.3.1 Wind speed *u*

Vigiak et al. [3] describe the windbreak model as used by WEPS, a process based wind erosion model. This model will be used to calculate the reduction in wind speed across a field.

$$f_{xh} = 1 - \exp[-axh^2] + b \exp\left[-0.003(xh + c)^d\right] \tag{4}$$

where f_{xh} = friction velocity reduction; xh = distance from the windbreak in windbreak heights; and a, b, c and d = coefficients depending on windbreak porosity θ.

$$a = 0.008 - 0.17\theta + 0.17\theta^{1.05} \tag{5}$$
$$b = 1.35 \exp(-0.5\,\theta^{0.2}) \tag{6}$$
$$c = 10(1 - 0.5\theta) \tag{7}$$
$$d = 3 - \theta \tag{8}$$

Windbreak porosity is dependent on the optical porosity, width and height

$$\theta = op + 0.02\frac{w}{h} \tag{9}$$

The friction velocity is related to the average wind speed through the following

$$U(z) = \frac{u*}{k} \ln\left(\frac{z}{z_0}\right) \tag{10}$$

where *U(z)* = average wind speed; $u*$ = wind friction velocity; k = von Kármán constant (0.4); z = height; and z_0 = roughness height.

The friction velocity at a weather station can then be used to calculate the friction velocity on a field

$$u_*^R = u_*^{WS} \left(\frac{z_0^R}{z_0^{WS}} \right)^{0.067} \tag{11}$$

where u_*^R = friction velocity at the field; u_*^{WS} = friction velocity at the weather station; z_0^R = roughness height at the field; and z_0^{WS} = roughness height at the weather station.

2.3.2 Net radiation R_n

The shade produced by a windbreak varies with the time of day as well as with the time of year. The length of the shadow can be calculated from the angle of the sun above the horizon and the solar hour angle

$$L(h) = \frac{cos\omega}{\tan\beta} \tag{12}$$

where *L(h)* = the length of a shadow in units of windbreak height; ω = angle of the sun above the horizon; and β = solar hour angle.

Figure 2 shows the difference between the effect of reduced radiation as a result of an overcast day and as a result of shading by a windbreak. On an overcast day the radiation is reduced to diffuse radiation only. On March 20th, 2004, the first graph in the example, the radiation is reduced to approximately 0.4 MJ h^{-1} m^{-2} throughout the day. The second graph of April 20th show how the effect of shading reduces the radiation to around 0.1 MJ h^{-1} m^{-2}, only to rapidly rise to normal levels once the sun rises high enough. The shadow effect only occurs on sunny days, which have been defined as days with a cloudiness of 6 octa or less.

2.4 Evapotranspiration

Evapotranspiration was calculated using the ASCE standardised reference evapotranspiration equation (Allen et al. [7]). This equation is based on the ASCE Penmann-Monteith and associated equations. The equation takes into account a variety of factors including parameters affected by windbreaks such as radiation, temperature, and wind speed.

$$ET_{sz} = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \tag{13}$$

where ET_{sz} = standardised reference crop evapotranspiration (mm d^{-1} or mm h^{-1}); Δ = slope of saturation vapour pressure-temperature curve kPa °C^{-1}); R_n = calculated net radiation at the crop surface (MJ m^{-2} d^{-1} or MJ m^{-2} h^{-1}); G = soil heat flux density (MJ m^{-2} d^{-1} or MJ m^{-2} h^{-1}); γ = psychrometric constant

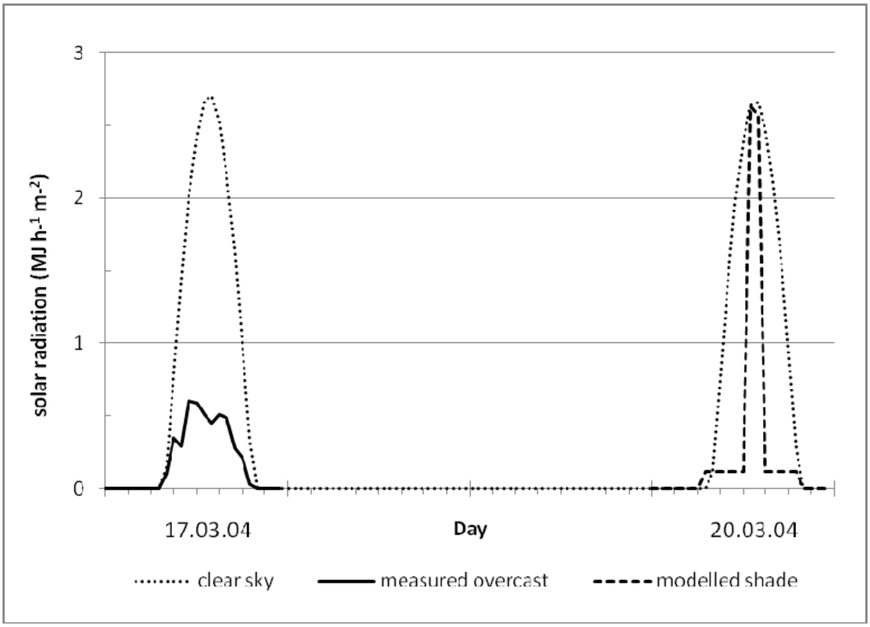

Figure 2: Comparison of (theoretical) clear sky radiation, measured radiation on an overcast day and radiation in the partially shaded area behind a wind barrier.

Table 2: Values for C_n and C_d.

Calculation time step	Short reference, ET_{os}		Tall reference crop, ET_{rs}	
	C_n	C_d	C_n	C_d
Daily	900	0.34	1600	0.38
Hourly, daytime	37	0.24	66	0.25
Hourly, night time	37	0.96	66	1.70

Source: Allen et al. [7].

(kPa ºC^{-1}); C_n = numerator constant dependent on reference crop type and calculation time step (K mm s^3 Mg^{-1} d^{-1} or K mm s^3 Mg^{-1} h^{-1}); T = mean air temperature (ºC); u_2 = wind speed at 2m height (m s^{-1}); e_s = saturation vapour pressure (kPa); e_a = mean actual vapour pressure (kPa); C_u = denominator constant that changes with reference crop type and calculation time step (s m^{-1}).

Eqn (13) is valid for both short reference crop evapotranspiration, ET_{os}, and tall reference crop evapotranspiration, ET_{rs}. Values for C_n and C_d are given in Table 2. As the modelled crop is pasture, ET_{os} was used.

2.5 Irrigation requirements

Reference evapotranspiration was calculated for hourly periods and summed to obtain daily values. Crop evapotranspiration was calculated from

$$ET_c = ET_{os} * K_c \tag{14}$$

where ET_c = crop evapotranspiration; and K_c = crop factor. The K_c for a well established grass pasture is 1.0.

Irrigation requirements were calculated from

$$I = \frac{(ET_c - P)(1 + LR)}{E_a} \tag{15}$$

where I = irrigation requirement; P = effective rainfall; LR = leaching requirement; and E_a = application efficiency. For the purpose of this study the leaching requirement was set to 0.1 and the application efficiency to 0.9.

3 Results and discussion

Results from modelling ET when considering the effect of wind only, shading only, and the combined effect of both are shown in Figure 3 for a single day (27/12/2004), when the wind is flowing perpendicular to the barrier. This

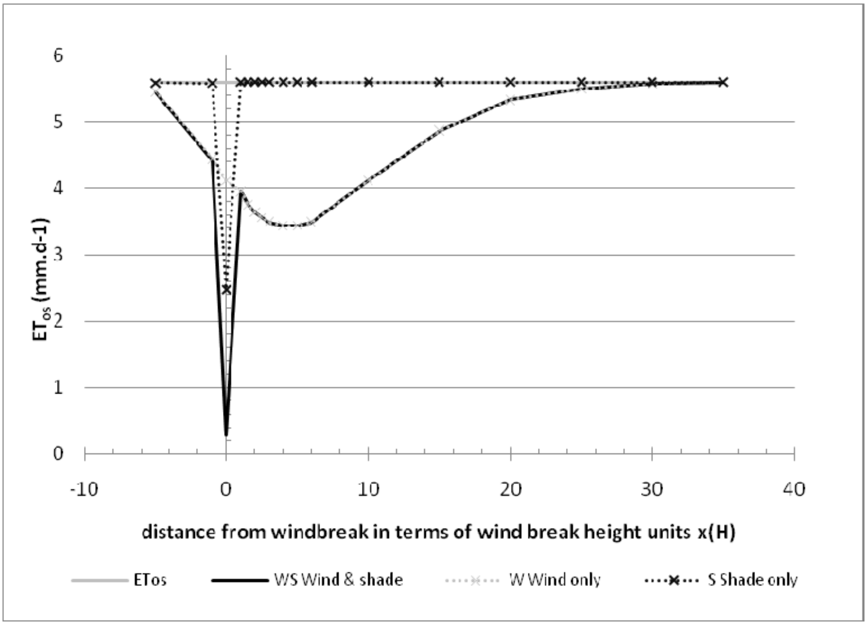

Figure 3: Reduction in evapotranspiration (ET_{os}) as a result of wind speed reduction, shade and both (27-12-2004).

example clearly illustrates that a reduction in wind due to wind barriers has a greater spatial influence on ET than changes in radiation due to shading. The effect of shading is limited to short distances from the barrier during summer, but extends up to 4 times the barrier height (H) during the winter months.

Results of modelling changes in ET (including windbreak induced changes in both wind and shade) over the months of December, March and June are shown in Figure 4. The percent reduction in ET at a distance of 5 times the height of the barrier is 26%, 22%, and 50% for the months of December, March, and June respectively. Higher wind speeds and more overcast days contributed to larger reductions in ET for the month of December compared to the month of March.

Using results from the changes in ET due to wind and shading, irrigation requirements were estimated for a pasture crop for the months of December, March and June of 2004 in Canterbury (Table 3 and Figure 5). Significant savings in water are possible if precision irrigation systems are used to apply required amounts of water behind barrier. For a 200 by 200 meter field this would translate to a yearly savings of over 16% of total irrigation water requirements.

Changes in temperature from barriers were also considered; however, preliminary simulations show that the changes in ET due to changes in temperature behind barriers are relatively small compared to the direct effects of

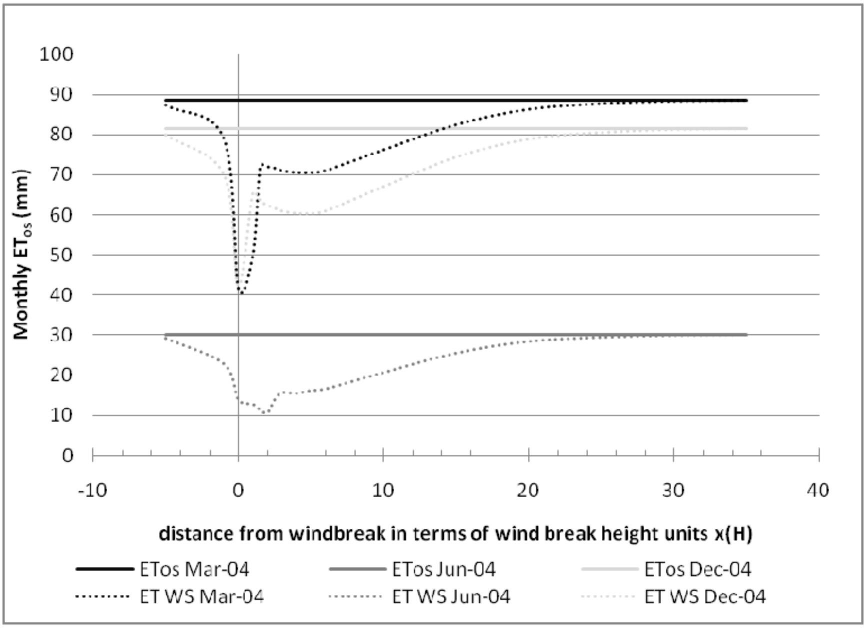

Figure 4: Modelled ET for March, June and December, 2004 at distance x(H) behind a 10 metre windbreak with shade and wind reductions.

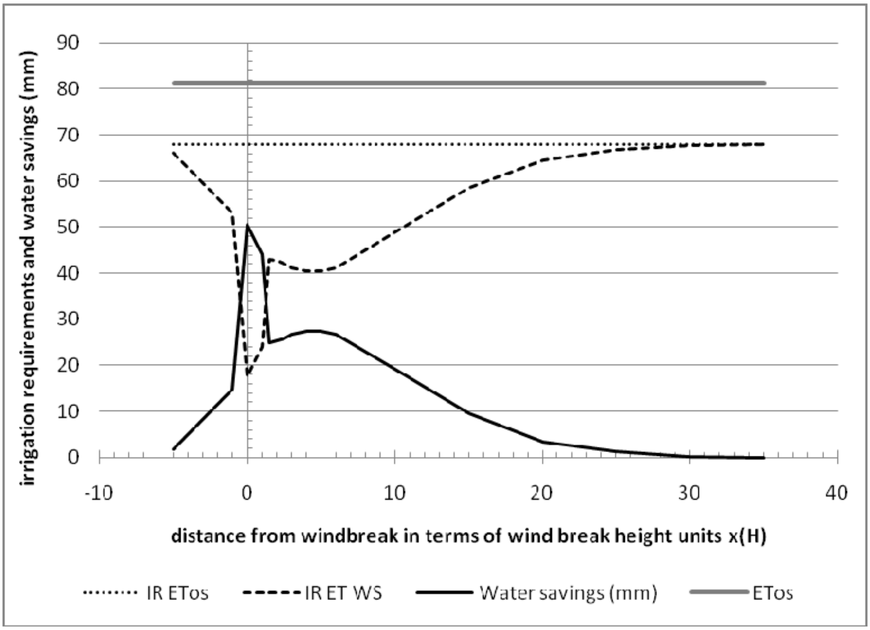

Figure 5: Comparison irrigation requirements, December 2004.

Table 3: Water saving comparison across months.

	water savings(mm)			water savings (%)		
x(H)	Mar-04	Jun-04	Dec-04	Mar-04	Jun-04	Dec-04
-5	1.18	0.88	1.54	1	3	2
-1	9.65	7.25	11.37	11	24	14
0	47.08	16.14	38.87	53	54	48
1	38.73	17.25	15.90	44	57	20
2	16.62	19.43	18.95	19	65	23
3	17.60	14.37	20.41	20	48	25
4	18.08	14.55	20.97	20	48	26
5	18.08	13.82	20.97	20	46	26
10	12.39	9.36	14.33	14	31	18
15	6.10	4.56	7.02	7	15	9
20	2.24	1.66	2.57	3	6	3
25	0.84	0.62	0.96	1	2	1
30	0.17	0.12	0.19	0	0	0
35	0.00	0.00	0.00	0	0	0

wind reduction or shading. Furthermore, it is inconclusive whether net temperatures would increase or decrease due to the indirect reduction of wind or increased shading.

4 Conclusions

Significant savings can be made by incorporating a windbreak model in the calculation of irrigation requirements in the Canterbury region in New Zealand. These savings are dependent on the field and windbreak configuration and the position in a field, but can amount up to 50% in summer and even more during the winter months.

Average annual savings of 10-20% may be possible if this model were to be used in combination with precision irrigation systems. In Canterbury this translates to significant savings, if the model was applied to all fields with windbreaks.

Work is currently underway to extend this model into a 2 dimensional model that accounts for wind direction and multiple barriers.

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