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USING A WIND FLOW MODEL TO IDENTIFY
HARVEST DESIGNS THAT REDUCE WINDTHROW

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1. INTRODUCTION

Reducing the risk of windthrow can be an important criterion in designing a partial-cut forest harvest system. Yet our understanding of how harvesting patterns influence the risk of subsequent windthrow of unharvested trees is incomplete. How might a forest manager identify a harvest design that provides effective wind protection?

Computer wind flow models are a potential means of investigating the wind pattern associated with a harvest design. The cost is negligible relative to that of full scale or wind tunnel trials, and the number of harvest configurations that can be simulated is limitless. The objective of this study is to demonstrate the use of a wind model for identifying harvest systems that minimize windthrow. Our context, and observational basis, is a management trial under way in Alberta, Canada, at a location called Hotchkiss (Navratil et al., 1994).

2. SHELTERWOOD HARVESTING SYSTEM

In the aspen (*Populus tremuloides*) and white spruce (*Picea glauca*) dominated boreal mixedwoods of western Canada, researchers and foresters are investigating harvesting techniques that preserve the immature spruce understory, with
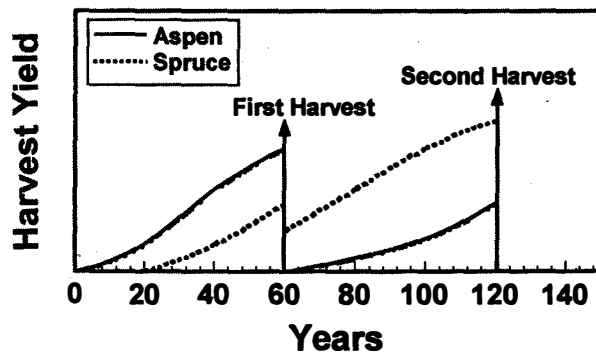

Fig. 1. Generalized two-stage harvest model for an aspen-spruce mixedwood forest (from Brace and Bella 1988).

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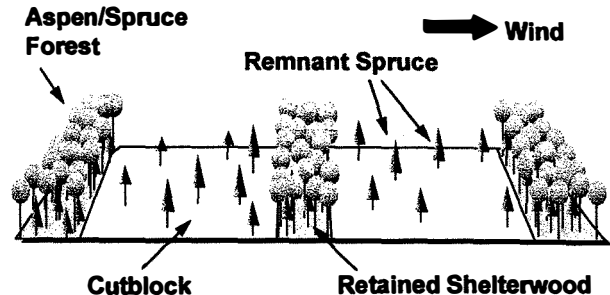

Fig 2. Idealised view of cutblocks

a goal of perpetuating a healthy mixedwood. One approach is the "two-stage" harvesting and stand tending model (Brace and Bella 1988) in which the overstory aspen is harvested at 60 years, leaving the immature understory spruce (Fig. 1). Sixty years later a second harvest is scheduled to remove the spruce that has grown to maturity, as well as a second cohort of regenerated aspen.

An obstacle to this two-stage harvest is the susceptibility of the immature spruce to windthrow after aspen removal. One approach is to employ a one-pass modified uniform shelterwood (hereafter referred to as a shelterwood design). In this system the aspen is harvested in narrow cutblock strips that are left surrounded by unharvested "shelterwood" (Fig. 2). These shelterwood strips provide wind shelter for immature spruce in the cutblocks. Flesch and Wilson (1999a) found the average wind velocity (U) and the turbulent kinetic energy (k) were strongly reduced along the upwind edge of these cutblocks, and field observations confirm this translates into reduced windthrow.

The question that immediately arises is, how wide ought the cutblocks and protecting shelterwood strips be, relative to forest canopy height (h), for adequate wind protection?

3. PREDICTING WIND SHELTER

3.1. *Relating Wind Statistics to Windthrow*

We consider the instantaneous wind "force" acting on a tree as (proportional to) $u|u|$, where u is the instantaneous horizontal wind velocity (in the x, i.e., alongwind, direction) at a nearby point. Flesch and Wilson (1999b) noted that the variance of the

wind force ($\sigma^2_{u|u|}$), observed at height z = 0.4h, correlated closely with the variance (σ_θ^2) of the sway angle of a sample of remnant spruce (of height $h_r \approx$ 0.5h) surveyed at the Hotchkiss site. While this correlation may not be universally true, it can be exploited at Hotchkiss: by assuming greater sway means greater strain on the tree/soil complex, and greater likelihood of windthrow, we may use $\sigma_{u|u|}$ as a "flag" to identify zones of likely windthrow. We approximate $\sigma_{u|u|}$ as

$$\sigma_{u|u|} \approx \sqrt{3(c_u k)^2 + 4U^2(c_u k) + 4U(c_u k)^{3/2}} , \quad (1)$$

by assuming $\sigma_u^2 \propto k$ (with fixed proportionality constant), and setting skewness $Sk_u = 1$ and kurtosis $Kt_u = 4$ (values representative of the Hotchkiss flows; Flesch and Wilson, 1999a). Taking typical k partitioning $\sigma_u:\sigma_v:\sigma_w = 2:2:1.3$, we have $c_u = 0.82$. We may now map the relative probability of windthrow using a wind model which diagnose the spatial pattern of U and k across a harvest design.

3.2. Wind Flow Model

Our wind model, shown by Wilson and Flesch (1999) to agree well with measurements of U, k in cutblocks at Hotchkiss, is based on the mean momentum equations, closed using eddy viscosity $K \propto k^{1/2} \lambda$; k is obtained from a simplified transport equation, and the turbulent lengthscale λ is specified algebraically. For the present work crosswind (y) symmetry is assumed, and a flow near-normally incident to the forest edges is simulated by varying the tree drag coefficient with along-wind position (x), the drag coefficient vanishing within cutblocks.

Being only local in its scope, i.e., covering a horizontal domain of only a few kilometers, a wind model is able to diagnose not $\sigma_{u|u|}$, but only a ratio $\sigma_{u|u|}/U^2_{clr}$, where U_{clr} is a normalising reference velocity. This was chosen to be the average windspeed as specified/measured in a nearby "reference clearing," large enough to be considered as approximating a local "weather station." Given a history of average windspeed (and direction) at such a station, and if it were the case that our model was properly three-dimensional, and if we had specified (mechanically) each of the remnant trees in question, and if knew what threshold value for $\sigma_{u|u|}$ would suffice to "knock down" such trees, then we could interpret on a theoretical basis the windthrow losses, hour by hour, over that season, at that location, of that tree-type.

The trees actually blown down at Hotchkiss over the period of record available to us were variable in their particulars; having blown down at unknown times, during unknown winds, and wind directions. Thus several circumstances prevent us from testing our theory in a rigorous manner, though none compromise the methodology we suggest - for the model can be extended to three dimensions, linked to an actual climatology, and tested relative to data gathered storm-by-storm.

Here we resorted to a "calibration," in the following sense. We noted that two years after aspen harvest at Hotchkiss, remnant spruce windthrow in a particular cutblock (width $X_c = 6.1h$) was common beyond distances 2.5h downwind from the forest edge. A wind simulation for that cutblock suggested that beyond x = 2.5h, the normalised wind force $\sigma_{u|u|}/U^2_{clr}$ (hereafter labeled Φ) exceeded 0.25. So we defined as a threshold for severe incidence of windthrow, the value $\Phi = 0.25$. Of course the criterion is strictly valid (if at all) specifically for that 2 year wind climatology, and the particular tree characteristics at Hotchkiss.

4. ACCURACY OF MODEL PREDICTIONS

We investigated five of the harvest designs at Hotchkiss, each "design" being a periodic series of cutblocks and forest blocks, of proportions (X_c, X_f). For each of these cases we used the flow model to create a dichotomous risk map: identifying the risk zone(s) where $\Phi > 0.25$. To each harvest design we assigned a windthrow severity rating, based on the fractional area with $\Phi > 0.25$ (see Table 1). These were subsequently (and independently) compared with "observed" ratings, based on the actual proportion of remnant spruce losses.

Table 1. Definition of windthrow ratings

Model Rating		Observed Rating	
% area with $\Phi > 0.25$	rating	% uprooted trees	rating
< 10	1	< 5	1
10 - 30	2	5 - 10	2
30 - 50	3	10 - 15	3
50 - 70	4	15 - 25	4
> 70	5	> 25	5

According to Fig. 3, modelled and observed-ratings compare quite well. The model correctly predicted the increased risk as cutblock widths increased from $X_c = 2h$ to 4h to 6h. We acknowledge the ambiguity inherent in our using

different (and rather loose) criteria to arrive at model- and observed- ratings of windthrow. Nevertheless, we do not think Fig. 3 is just a spurious result of the respective (and independent) choices made by the two teams (University of Alberta, wind model; Canadian Forest Service, windthrow survey).

5. INVESTIGATING AN OPTIMUM DESIGN

One might ideally define an optimum shelterwood design as one eliminating windthrow while minimizing the percentage of forest retained as windbreak strips (maximizing aspen harvest), and maximizing the width of the individual cutblocks (for efficient use of harvest equipment). The wind model was used to search for an optimum design (for the circumstances at Hotchkiss).

Designs were examined in which the harvest domain (sequence of cutblocks and shelterwood strips) spanned approximately 40h. We simulated designs where 10%, 20%, 25%, 30%, and 35% of the forest was retained as shelterwood strips (of varying width X_f). For each retention level, cutblock width was varied from $X_c = 1$ to 6h. The resulting cutblock/shelterwood strips were distributed across the harvest domain. For example, a 20% forest retention with $X_c = 2h$ would have a recurring pattern $X_c, X_f = (2h, 0.5h)$.

Fig. 4 shows the predicted patterns of U, k, and the normalised wind force Φ, for a design in which only 10% of the forest was retained, and $X_c = 2h$. In
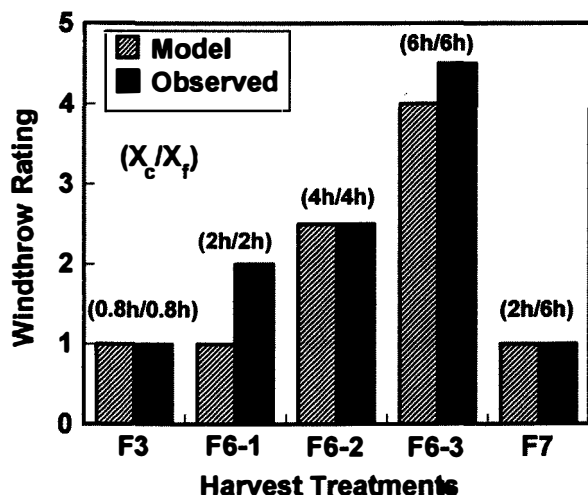
this case both U and k were high compared with designs retaining more forest, but the overall wind pattern was common to all the designs. In all cases U and k were low at the upwind edge of the harvest domain, and initially increased as x increased. Maximum U occurred between $x = 10h$ and 15h, while the maximum k was between $x = 3h$ and 6h. This gave a maximum Φ between $x = 3h$ and 10h. We conclude therefore, that the maximum likelihood of windthrow will be in the area between $x = 3$ and 10h, regardless of the design. For locations $x > 20h$, there was a plateau in Φ, with succeeding cutblocks being essentially identical to each other.

In Fig. 5 we plot the percentage of risk area (where $\Phi > 0.25$) associated with our hypothetical designs, showing the effect of forest retention and cutblock width. Several conclusions are evident. First, the greater the amount of retained forest, the greater the wind protection. This is intuitive: the more forest, the greater the wind drag, and the lower are U and k. Particularly impressive was the large drop in risk area as the retained forest increased from 10 to 20%. Our predictions indicate that a 10% level of forest retention is inadequate to provide effective wind shelter (for typical remnant spruce under the recent Hotchkiss wind climatology).

The second conclusion we draw from Fig. 5 is that the risk area increases as the cutblock width increases. Looking at the 30% forest retention curve we see that the risk area increased from 0 to 49% as X_c increased from 1h to 6h. Most of this
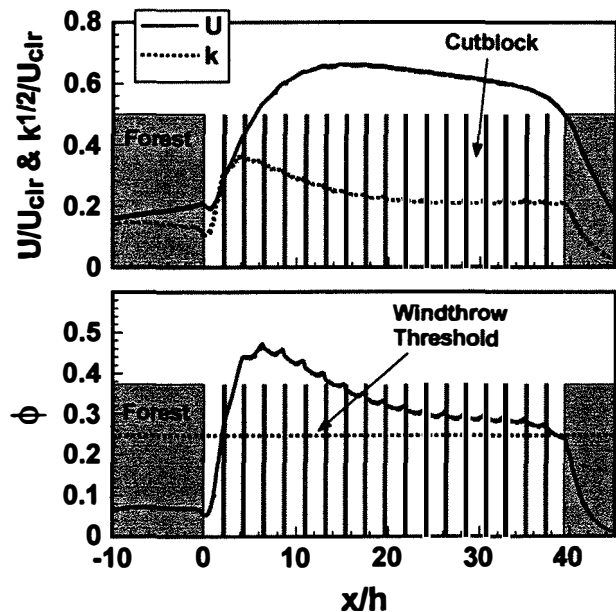
Fig 3. Comparison of windthrow risk rating from the wind model ("model") with the rating based on observed windthrow ("observed"), for five harvest designs. A rating of 1 is low risk and 5 is high risk. The ratio of the cutblock width (X_c) to forest width (X_f) is given above the bars.

Fig 4. Predicted average wind velocity (U), turbulent kinetic energy (k), and normalised wind force (ϕ) across a harvest design ($X_c = 2h$, $X_f = 0.2h$). Shaded areas are unharvested forest.
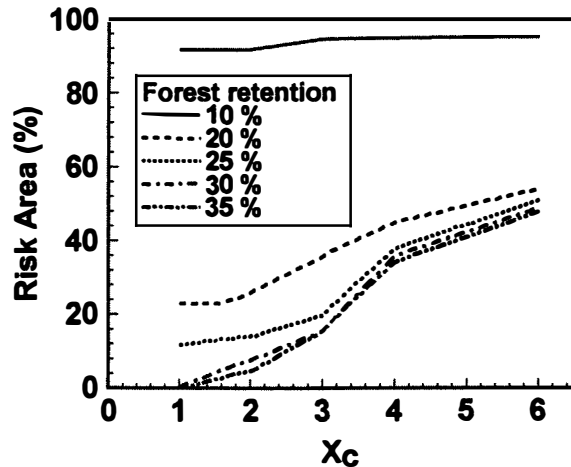
Fig. 5. Predicted windthrow risk area in harvest domain (40h in width) plotted as a function of cutblock width (X_c), for five forest retention levels (10, 20, 25, 30, and 35%).

increase occurred as X_c increased beyond 2h: in other words X_c = 1h was not greatly superior to X_c = 2h. This suggests that cutblock width should not much exceed X_c = 2h, in order to minimize windthrow risk. Delineation of a truly optimal design requires economic and engineering judgements to supplement these "environmental" calculations. But Fig. 5 does lay out likely bounds to an optimum design. Clearly 10% forest retention does not provide adequate wind protection, while retaining more than 30% is unnecessary. Cutblocks with X_c > 3h are at significantly higher risk than narrower cutblocks, while little benefit comes from using cutblocks narrower than X_c = 2h.

6. CONCLUSIONS.

We used a wind flow model (and a supplementary site-, season-, tree-specific criterion) to predict windthrow likelihood in various shelterwood harvest designs, demonstrating the potential of wind models as an easy, inexpensive, and quick means of assessing harvest designs. We consider the risk area percentages we have cited as carrying some uncertainty, and one ought certainly

to be cautious about assuming them broadly valid (i.e., as covering other sites with other tree types and wind climatologies). We reiterate the principal approximations and restrictions introduced: that winds in the y direction are unimportant in these designs; that $\sigma_{u|u|}$ at z = 0.4 h is well correlated with tree sway; that tree sway is an adequate index for windthrow; and that regions where Φ > 0.25 correspond categorically to "severe" long term windthrow.

We consider that the proper role for a wind flow model is in guiding field trials. A wind model allows the testing of large numbers of possible harvest configurations, from which a set of promising designs could be chosen. The end result would be a smaller and less costly experiment than would otherwise be the case.

7. REFERENCES

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