

Foresters' Perceptions of Windthrow Dynamics in Northern Minnesota Riparian Management Zones

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ABSTRACT

A survey was mailed to foresters in northern Minnesota to identify their perceptions of what conditions result in higher incidence of windthrow in riparian management zones (RMZ) where the upland has been clearcut. Results indicate that foresters think many variables impact windthrow, often interacting in complex ways. Foresters considered topographic exposure, species, soil moisture, and aspect as the more important factors to consider when trying to mitigate windthrow in RMZs. In general, perceptions and rankings of windthrow factors by foresters are in agreement with the published literature. Based on foresters' perceptions, recommendations are provided to assist forest resource managers in making decisions about retaining trees within streamside RMZs.

Keywords: windfirmness, survey, tree species, tree diameter, topographic position

Windthrow, along with fire and disease, is considered to be one of the most important disturbance factors affecting forest management (Mitchell 1995, Quine 1995, Canham et al. 2001). Wind moving over a closed, relatively smooth canopy is fairly stable and causes minimal disturbance (Somerville 1980, Gardiner 1994). When an area of forest is clearcut, the remaining forest at the edge of the clearcut presents an abrupt obstruction to the wind. At the forest edge, the wind tends to be deflected up over the canopy as well as into it (Busby 1965, Raynor 1971, Somerville 1980). Wind approaching the forest edge has a higher velocity than in an intact forest because the frictional boundary that was above the canopy has now moved to ground level (Moore 1977, Chen et al. 1993). The wind can remain at an elevated velocity for several tree heights into the remaining forest (Raynor 1971, Burton 2001).

The distinct boundary change at the edge of a clearcut also enhances turbulence in the canopy near the exposed edge, creating further destabilization (Somerville 1980, Matlack and Litvaitis 1999). After clearcutting, trees that are not physiologically adapted to edge conditions are now suddenly exposed, becoming vulnerable to windthrow at lower wind speeds than in an interior forest (Senecal et al. 2004). Windthrow will occur when the resistive properties of the stem and roots are overpowered by the forces of the wind (Petty and Worrell 1981, Peltola et al. 2000).

Although damage caused by wind to residual trees in management settings is often high (Alexander 1967, Moore 1977, Beese 2001), it does not occur randomly. Damage along clearcut edges and in thinned stands often can be predicted based on site and stand conditions and the local climate regime (Cremer et al. 1982, Mitchell 1998). Knowing how wind affects residual trees can enhance management when it comes to designing riparian management zones (RMZ).

RMZs protect the functions and values of a water body and its associated riparian area from the impact of site-level activities such as timber harvesting by reserving trees within some distance of the water's edge (Blinn and Kilgore 2001). Clearcutting along RMZs creates an abrupt boundary between forest and open space that make RMZ edges vulnerable to windthrow. Excessive windthrow within the RMZ may reduce its width and functionality (Grizzel and Wolff 1998, Reid and Hilton 1998, McClure et al. 2004), making it a priority to identify major factors involved and to determine mitigation strategies.

Little information exists to guide managers on approaches to minimize windthrow in RMZs in northern Minnesota. Although Turner (2005) assessed the effect of species on one such site, no other published studies exist for this region of the country. To obtain information across a broad range of site and stand factors and to identify mitigation strategies, a survey of forest managers in northern Minnesota was conducted. Because foresters often have extensive field experience across a range of site and stand conditions, they are a readily available source of practical knowledge on windthrow in RMZs. The results of this survey of foresters' perceptions of windthrow in RMZs collectively represent the observation of perhaps thousands of RMZs. Although conclusions drawn from such observations do not quantitatively equate to those derived from empirical studies, the geographic expanse and sheer number of observations would be difficult to duplicate through empirical research methods. The purpose of this article is to present foresters' perceptions on the main drivers of windthrow in RMZs (after upland harvest), how they use such knowledge in their management decisions, and how their perceptions compare with the published literature. Where observations are similar to the literature, management recommendations are provided; where there are discrepancies,

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possible reasons are explored. In addition, we summarize how foresters manage to minimize windthrow in RMZs.

Approach

The survey was conducted using Dillman's (1978) total design method. A literature review and a series of focus groups were first conducted to determine what major factors needed to be addressed. Next, a draft survey was sent out to a limited group of foresters, with instructions to comment on how the survey questions and design could be improved. The final survey was mailed to 121 field foresters in January 2001. A reminder postcard was sent approximately 2 weeks after the initial mailing followed by a second mailing of the survey to nonrespondents.

Forester selection was restricted to those who had at least 5 years of field experience, were known to be available during the sampling period, and who lived in the Laurentian Mixed Forest Province of northern Minnesota, where the majority of the state's forest management activities take place and where clearcutting is the primary silvicultural prescription. These foresters represented federal, state, and county land departments, as well as private industry. Forest types in the region include conifer, mixed hardwood and conifers, hardwoods, aspen, and conifer peatlands. Topography and soils are variable, characterized by outwash plains, lowland peatlands, and mesic to xeric uplands, with soils in the orders Alfisol, Entisol, and Histosol (Minnesota Department of Natural Resources 2003, 2005).

The survey questions were concerned only with windthrow in RMZs where the upland had been clearcut. Eleven close-ended questions assessed perceived windfirmness for 11 site and stand factors (i.e., the stand factors included species windfirmness, dbh class, crown class, and residual basal area [rba], and the site factors included distance of a windthrown tree to the water's edge, slope, aspect of the RMZ cut edge, amount of topographic exposure, hill-slope position, soils, and residual tree age). Although more than 11 sites and stand factors were initially identified as possible variables to assess from a review of the literature, the list was pared to eliminate possible redundancy (e.g., dbh and tree height) and to respond to reviews of the draft survey that suggested that it was long. Ratings for these 11 questions were discrete, on a scale of one to three, with a rating of one for "least windfirm," two for "moderately windfirm," and three for "highly windfirm." Three additional close-ended questions asked foresters to (a) determine whether residual trees were older or younger than windthrown trees, (b) determine the type of windthrow most frequently observed (i.e., blowdown, snapped, brushed, or leaning), and (c) rate the importance of each factor on a scale of one to four, with one being "least important" and four being "most important." Through two open-ended questions, the survey also asked respondents to provide any techniques they use to minimize windthrow in RMZs and to share any additional comments, suggestions, or experiences concerning windfirmness.

Statistical Analysis

JMP (SAS Institute, Inc., 2002) was used for all statistical analyses using a one-way analysis of variance (ANOVA; $\alpha = 0.05$), where the null hypothesis was that there are no differences in perceived windfirmness across the varying degrees of a given factor. A Tukey test was performed on all site and stand factors to identify significantly different degrees of perceived windfirmness within each factor ($\alpha = 0.05$).

A Kendal's τ -rank correlation (Snedecor and Cochran 1980, Kendal and Gibbons 1990) was calculated between the species data and the results from Turner (2005) to see how well the foresters' ranking of species compared with empirical data from northern Minnesota ($\alpha = 0.05$). Techniques used to minimize blowdown and additional foresters' comments were integrated into the discussion where appropriate.

Because foresters were not selected at random, ANOVA results can not be interpreted in a strict sense because of the potential for bias due to the exclusion of some individuals from the sampling frame. Similarly, the regression models applied to selected variables should be interpreted as trends in the data rather than as predictive models. Because of the possible uncertainty in the way foresters interpreted some questions, we only included questions addressing species, dbh, rba, aspect, degree of topographic exposure, and hill-slope position in our analysis. Other questions were removed because possible uncertainty about the intent of the question may have led to obvious confusion among respondents. Although the question regarding soil type did not yield meaningful statistical results, comments about soils, when presented with various other factors, were consistent and important enough that they were retained for discussion.

Results and Discussion

Fifty-four surveys were returned for a response rate of 45%. Seven of the respondents did not answer any of the questions, reducing the number of useful surveys to 47 (39%). Although some of the blank returned surveys noted that the respondent did not observe windthrow in the forests in which they worked, most nonresponse was likely because of foresters not wanting to take the time to fill out a lengthy survey (17 pages). A comparison of respondents to nonrespondents by agency and location was performed. Results indicated relatively uniform response rates across agencies and locations, with the exception of county foresters. The low response rate from county foresters (24%) was likely because the surveys were not addressed directly to the individual, but rather to the department as a whole, reducing the chance that they reached the intended recipients.

The results for the factors included here indicate that significant differences existed in foresters' perception of windfirmness ($P < 0.05$). Stand factors generally exhibited a higher level of significance than site factors. Generally, forester's perceptions about the factors and species that led to windfirmness were similar to what is found in the literature (Table 1).

Stand Factors

Species

Foresters thought the most windfirm species were sugar maple, red oak, red maple, black ash, white pine, red pine, and American basswood (Figure 1). Paper birch, bigtooth, and quaking aspen, northern white cedar, and balsam poplar were thought to have moderate to low levels of windfirmness, while jack pine and balsam fir were considered to have the lowest windfirmness. Several foresters volunteered ratings for white spruce ($n = 11$) and black spruce ($n = 7$), suggesting that foresters believe that these species are about as vulnerable to windthrow as jack pine but more windfirm than balsam fir. Results from the rank correlation analysis yielded a Kendal τ -correlation coefficient of 0.67 ($P < 0.05$), suggesting a moderately strong relationship between the empirical (Turner 2005) and foresters' nonempirical rankings (Figure 2).

Table 1. Comparison of selected published literature with the perceptions of foresters in this study.

Source	Finding
Species	
Rich et al. 2007	Shade-tolerant species were generally more windfirm than shade-intolerant species with the exception of paper birch, which is moderately windfirm
Canham et al. 2001	Sugar maple was more windfirm than red maple; longer-lived (generally shade tolerant) species are more windfirm
Burns and Honkala 1990	White spruce and balsam fir were especially prone to windthrow
Webb 1989	Aspen species and red and white pine had higher windthrow incidence than sugar maple, red maple, or paper birch
Turner 2005	Aspen and balsam fir were more vulnerable to windthrow than paper birch, American basswood, red maple, sugar maple, northern white cedar, and black ash; northern red oak, white spruce, and white pine were most windfirm.
This article	Sugar maple, northern red oak, red maple, American basswood, black ash, red pine, and white pine rated most windfirm; birch, aspen species, and northern white cedar rated moderately windfirm; jack pine, spruce species, and balsam fir rated least windfirm
Diameter at breast height	
Canham et al. 2001	Increased windthrow susceptibility was reported with increased dbh
Steinblums et al. 1984	With the exception of true firs, windthrow increased with tree diameter
Lomander and Helles 1987	Windthrow probability increased with increasing tree diameter
This article	With the exception of trees in the largest diameter class, windthrow susceptibility increased with increasing tree diameter
Residual basal area	
Mitchell 1998	The damping effect of neighboring tree crowns reduces wind damage; thinning from below where this damping effect can occur will increase windthrow risk
Navratil 1995	Thin out small diameter trees, favoring larger diameter residuals, to reduce windthrow
McClure et al. 2004	Gradually increase rba from the clearcut edge inward to reduce windthrow
Ruel et al. 2001	Thinning intensity had no effect on windthrow incidence in a balsam fir forest
This article	Lower rba results in higher windthrow susceptibility
Aspect	
Ruel et al. 2001	Most damage occurred on the side of a cut facing the prevailing winds
Grizzel and Wolff 1998	The clearcut edge orientation did not affect windthrow incidence
Rollerson and McGourlick 2001	Edges facing prevailing winds were most vulnerable
Alexander 1967	Most (2/3) of blowdown occurred along edges facing prevailing stormwinds
This article	Clearcut edges facing prevailing winds were rated as least windfirm
Topographic exposure/hillslope position	
Ruel et al. 2001	Wind speed was highest at hilltop position compared with other topographic positions
Alexander 1967	Wind damage was highest on ridge tops
Miller 1985	A low elevation site with no adjacent high ground may be associated with high wind exposure
Foster and Boose 1992	The amount of wind damage was commensurate with degree of topographic exposure
This article	With increased topographic exposure comes decreased windfirmness; summits were least windfirm and foot and toeslopes were most windfirm
Most important variables affecting windthrow	
Steinblums et al. 1984	Species and topographic parameters were more important than RMZ width and stand age
Alexander 1967	Topographic position had the most influence on windthrow susceptibility of all variables addressed (including species and dbh)
Moore 1977	Soil, as it relates to effective rooting depth drainage, is one of the most important factors affecting windthrow
This article	Species, soil moisture, and effective rooting depth, topographic exposure were the most important factors affecting windthrow; edge aspect and rba were moderately important; dbh and hillslope position were the least important factors

The most frequent open-ended comment for species windfirmness was the suggestion to leave windfirm species in the RMZ and/or remove susceptible species where retention choices exist. Recommended species to leave were dominant pines, sugar maple, oaks, and shade-tolerant understory species. Susceptible species that foresters recommended for removal were older aspen, balsam fir, and white and black spruce. With the exception of aspen, hardwoods were usually favored as leave trees over conifers due to their higher wind firmness, a finding that is generally consistent with the literature (Ruel et al. 2001, Rich et al. 2007, Rosenvald et al. 2008). The exception is paper birch, which foresters rated as having relatively low wind resistance (Figure 1), but Turner (2005) and Rich et al. (2007) found paper birch to be fairly windfirm due to that species' ability to slough branches in high winds.

Respondents who volunteered commentary noted that other factors also influenced their decision whether to favor removing or reserving particular species in the RMZ. When considering other factors such as age, diameter, crown class, and soil properties, many foresters thought that species had to be taken into consideration at the same time. Older trees of species prone to decay or disease were

thought to be most vulnerable to windthrow. Foresters singled out aspen and balsam fir as being especially vulnerable to rot and decay as they age, consistent with trends in the literature (Perala 1977, Coates 1997). Foresters also commented that species with shallow rooting habits or that grew in areas where effective rooting depth was impeded were less windfirm than those with deeper rooting habits or that grew in soils that promote deeper rooting, which Frank and Bjorkbom (1973) also found to be the case. These results, and their consistency with the literature, provide good evidence that foresters understand the relationship between species and windthrow susceptibility, and that they use this information in their management decisions.

Diameter at Breast Height

Perceived windfirmness decreases as dbh increases, but trees in the 25.1- to 30.0-in. dbh class were thought to be marginally more windfirm than those in the previous two classes (Figure 3). Significant differences in foresters' ratings of windfirmness exist between the 0.1- to 5.0-in. and 5.1- to 10.0-in. and the 15.1- to 20.0-in. and 20.1- to 25.0-in. diameter classes ($P < 0.05$). These results are

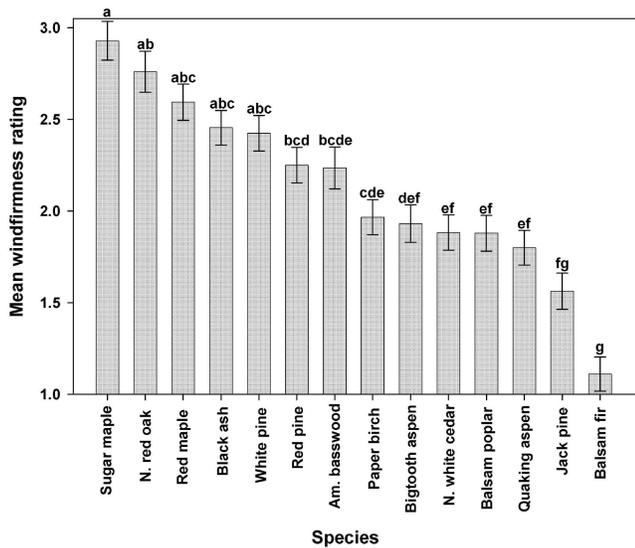


Figure 1. Mean respondent's rating of species' susceptibility to windthrow in an RMZ in northern Minnesota after upland clearcutting. Rating is on a scale of 1–3. A higher rating represents higher windfirmness. Standard error bars represent a pooled estimate of error variance. Means with dissimilar letters are significantly different ($P < 0.05$; n ranged from 25 to 36, depending on species).

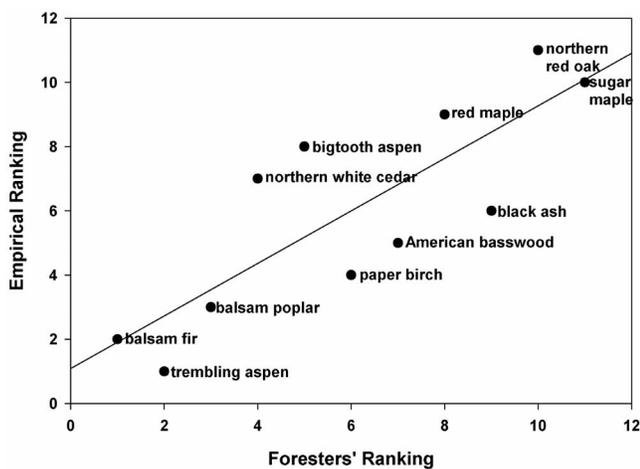


Figure 2. Empirical ranking from Turner (2005) versus foresters' ranking of 11 species susceptibility to windthrow in an RMZ in northern Minnesota where the upland has been clearcut. A ranking of 1 is the least windfirm species and 11 is the most windfirm.

consistent with empirical studies, which showed that windthrow generally increased with diameter across a broad range of species (Steinblums et al. 1984, Lohmander and Helles 1987, Gardiner et al. 2000).

The slight increase in windfirmness for the largest dbh class (Figure 3) reflects foresters' comments regarding what are perhaps supercanopy trees that have become acclimated to wind through constant exposure (Peterson and Pickett 1991). For instance, several respondents in our survey noted that large pines, which are generally well anchored due to the spread and depth of their root systems, tended to be quite windfirm. Other respondents noted that height needed to be accounted for when considering windfirmness by diameter, suggesting that diameter was often paired with other factors when considering a tree's windfirmness. The literature relies heavily

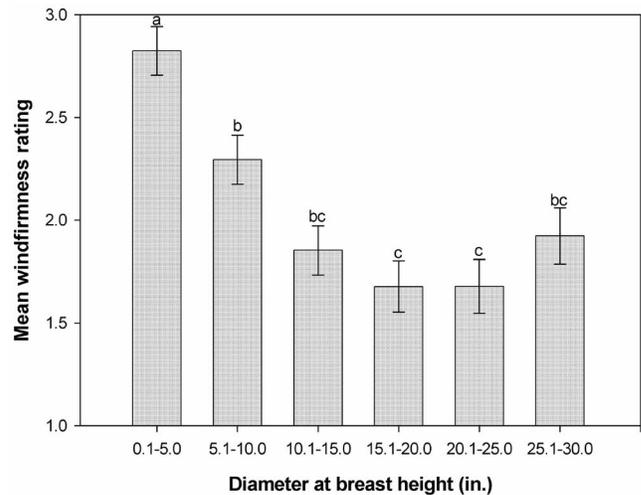


Figure 3. Mean foresters' rating of windfirmness by dbh on a scale of 1–3 in an RMZ in northern Minnesota where the upland has been clearcut. A higher rating represents higher windfirmness. Standard error bars represent a pooled estimate of error variance. Means with dissimilar letters are significantly different ($P < 0.05$; n ranged from 24–34, depending on diameter class).

on height to diameter ratios for predicting tree stability (Burton 2001, D'Anjou 2002). Considering foresters' open-ended comments on this factor, accounting for both height and diameter together may have yielded a more consistent response, because the height to diameter ratio of a given tree may actually be the management tool foresters apply when considering a tree's dimensions with regard to windfirmness.

Residual Basal Area

Based on foresters' ratings, rba below 40 ft²/ac are significantly less windfirm than those above 60 ft²/ac ($P < 0.05$). Foresters suggested keeping basal area high if possible, especially in high hazard areas, such as overmature stands, and removing susceptible species if necessary to promote overall windfirmness. Many noted that the amount of rba to leave was dependent on dominant tree species. A lower rba could be left with windfirm hardwoods, but a higher rba would have to be left with a residual stand of aspen or birch.

There is an abundance of literature investigating the relationship between rba and windthrow. It is generally accepted that heavy thinnings create more windthrow risk than light ones, and that those occurring in later stages of stand development will lead to greater windthrow susceptibility than earlier thinnings (Somerville 1980). The exception is Ruel et al. (2001), who found no relation between thinning intensity and wind damage in a balsam fir forest, possibly because of balsam fir's very high windthrow susceptibility. If rba is reduced to the point that the damping effect of a tree's neighbor is no longer present, windthrow will increase (Mayer 1989, Mitchell 1998). From a windfirmness perspective, thinning from below is better than from above (Navratil 1995, Rollerson and McGourlick 2001), except if much of the canopy is overmature or otherwise vulnerable. Rollerson and McGourlick (2001) reported significantly less windthrow along feathered versus straight edges, but part of this effect may have been caused by the removal of susceptible species along the former. McClure et al. (2004) also suggest feathering RMZ edges to reduce the incidence of windthrow. Foresters generally endorse the findings of the literature that manipulating the rba

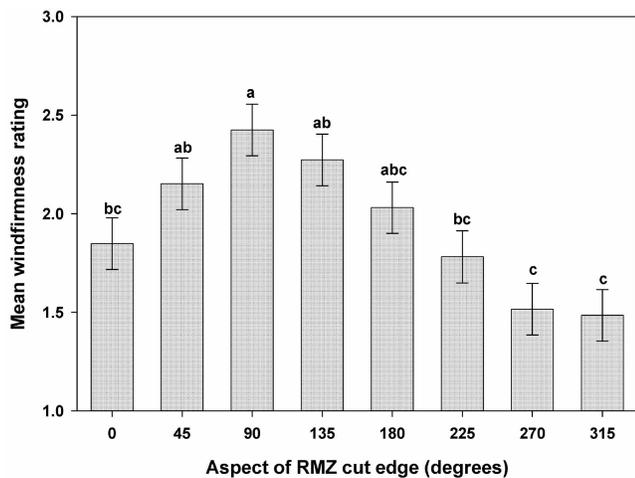


Figure 4. Mean foresters' rating of windfirmness by aspect of cut edge relative to the RMZ on a scale of 1–3 in an RMZ in northern Minnesota where the upland has been clearcut. A higher rating represents higher windfirmness. Standard error bars represent a pooled estimate of error variance. Means with dissimilar letters are significantly different ($P < 0.05$; $n = 33$ for all aspects).

can be effective at minimizing windthrow in RMZs. Again, however, another factor—species—was seen by many foresters to be so closely tied to decisions regarding rba that the two could not be easily decoupled.

Site Factors

Aspect

Foresters rated RMZ boundaries facing west and northwest as significantly less windfirm than those facing northeast, east, and southeast ($P < 0.05$; Figure 4). Foresters were consistent in their open-ended recommendations regarding RMZ edges and aspect. Wider RMZs are needed when they are directly exposed to prevailing winds from the west and southwest in summer and from the northwest in winter. Foresters noted that near the North Shore of Lake Superior, strong northeast winds may present unique hazards in the fall.

Most published studies report that windward aspects are most vulnerable (Ruth and Yoder 1953, Ruel et al. 2001), the only exception being where eddying creates instability on the leeward side of cuts (Alexander 1967, Beese 2001). Recommendations are to avoid straight edges facing prevailing winds or to have long edges parallel to prevailing winds (Moore 1977) and to leave wider RMZs along windward edges.

Degree of Topographic Exposure and Hillslope Position

Foresters agreed that the more topographically exposed RMZs were, the more likely they were to experience windthrow. Residual trees that had full exposure to wind due to their location at the cut edge of the RMZ were thought by foresters to be least windfirm. Partially exposed trees or those with limited or no exposure because of their more interior position or which were partially or entirely below the level of the surrounding landscape were thought to be considerably more windfirm ($P < 0.05$).

Comparing windfirmness by hillslope position, trees located on the summit were rated as significantly less windfirm than any other hillslope position, while those on a footslope or toeslope were rated as significantly more windfirm than either the summit or the shoul-

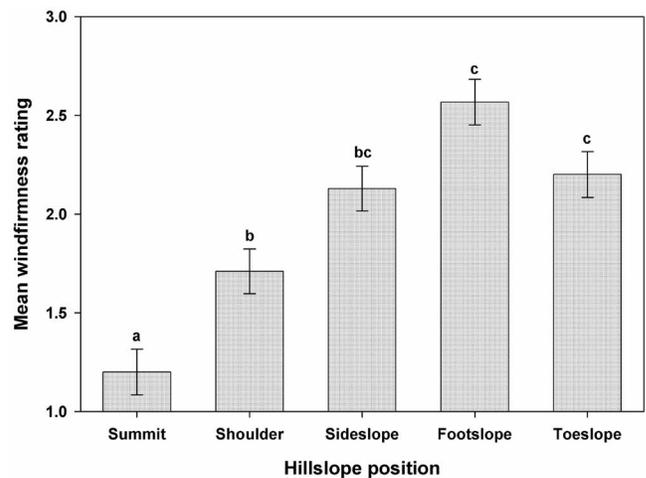


Figure 5. Mean foresters' rating of windfirmness by hillslope position on a scale of 1–3 in an RMZ in northern Minnesota where the upland has been clearcut. A higher rating represents higher windfirmness. Standard error bars represent a pooled estimate of error variance. Means with dissimilar letters are significantly different ($P < 0.05$; $n = 31$ for all hillslope positions).

der position ($P < 0.05$; Figure 5). Residual trees on a sideslope were not significantly different in windfirmness than those on the shoulder, footslope, or toeslope.

Results of other research generally agree with the findings of this study. Summits, especially those facing prevailing winds, are particularly vulnerable, as wind accelerates over ridgetops, catching the crowns of trees that are not protected by the slope (Alexander 1964, 1967). Deep draws and steep leeward slopes along RMZs protect trees from wind (Moore 1977).

Although these results compare well with the literature (e.g., Johnston 1977), other studies of exposure and hillslope position make it difficult to distinguish between the two, because exposure is necessarily a function of the protection afforded by hillslope position or distance from the clearcut edge. Looking at exposure in terms of shelter afforded by distance from the clearcut edge, Turner (2005) indicated that windfirmness generally increased as the distance from the clearcut edge increases, although his results were not statistically significant. However, it is unclear if this is because the trees closer to the stream were topographically sheltered or because they were more protected by the trees nearer the clearcut edge. Some studies found that wide valleys leave RMZ edges exposed and vulnerable (Miller 1985, Ruel et al. 2001). Summits, especially those facing prevailing winds, are particularly vulnerable, as wind accelerates over ridgetops (Alexander 1964, 1967). In contrast, deep draws and steep leeward slopes along RMZs protect trees from wind (Moore 1977).

Soils

Many respondents commented that soil moisture and other properties that determine effective rooting depth were important. They suggested that high soil moisture led to increased windthrow susceptibility, as did shallow, rocky, and gravelly soils. One forester noted that leaving RMZ edges along low wet areas can create particularly hazardous conditions for windthrow to occur. Based on the consistency of comments across several site and stand factors, soil moisture and effective rooting depth may be among the most important considerations when evaluating windthrow susceptibility within a site.

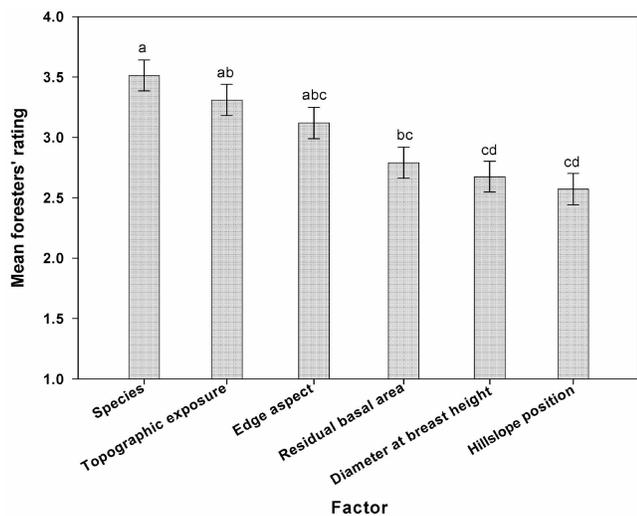


Figure 6. Mean rating of each factor's importance in influencing windthrow on a scale of 1–4 in an RMZ in northern Minnesota where the upland has been clearcut. A higher rating represents higher windfirmness. Standard error bars represent a pooled estimate of error variance. Means with dissimilar letters are significantly different ($P < 0.05$, n ranged from 41 to 43, depending on factor).

The literature generally agrees that soil moisture and effective rooting depth are important predictors of windthrow. Saturated soils create shallow rooting patterns (Day 1950), and wet, organic soils have weak shear strength or ability to anchor the roots (Busby 1965, D'Anjou 2002), leading to greater windthrow susceptibility. Areas with shallow soils overlaying bedrock or other impermeable layers will create shallow rooting patterns, leading to higher windthrow potential (Moore 1977). However, D'Anjou (2002) also found that stand attributes such as the height-to-diameter ratio of trees and stand structure were more accurate in predicting windthrow than site factors such as soil.

Relative Factor Importance

When all factors were considered for their relative importance in influencing windthrow in RMZs where the upland had been clearcut, species was rated by foresters as being significantly more important than rba, tree dbh, and hillside position ($P < 0.05$; Figure 6). Topographic exposure was rated as having a significantly higher influence on windthrow than tree dbh or hillside position. The rated importance of edge aspect for influencing windthrow did not significantly differ from the other factors. Overall differences in importance between adjacent factors in Figure 6 were small due to high variation in foresters' responses. This suggests that although there was some consistency of opinion about which factors were most important in determining windthrow risk, foresters were not in agreement on others. It should also be noted that although this question did not address soil moisture and effective rooting depth, many foresters wrote in the open-ended comments section that this was one of the most important variables to consider when assessing the windfirmness of RMZ edges. Species, topographic exposure, and dbh are the three variables most frequently reported in the literature as being related to windthrow (e.g., Steinblums et al. 1984, Canham et al. 2001).

Management Recommendations

The decision about how to design an RMZ to minimize windthrow should consider management objectives as well as stand and site conditions for the area. In some instances, the options about what trees to leave are limited because of local conditions (e.g., few species present). Based on the compilation of data from this research on field forester's perceptions of windthrow as well as the conclusions from other literature, some recommendations for northern Minnesota streamside RMZs are presented in the following:

- Assess stand and site conditions for hazards such as high topographic exposure, soil conditions that create weak or shallow rooting patterns, and prevailing wind direction. Develop a plan that minimizes the impact of the identified hazards.
- Leave a wider RMZ, reserve more windfirm species, and provide a gradual increase in rba as you approach the water's edge (i.e., feather the cut edge).
- Reserve supercanopy trees that have become acclimated to wind. Susceptible species such as balsam fir, white spruce, black spruce, and aspen should be considered first for removal near the RMZ edge adjacent to the clearcut. Reserve longer-lived species including sugar maple, red maple, red oak, black ash, white pine, and basswood.
- Large-crowned or large diameter trees may be reserved if they are windfirm species that are well anchored in the soil and relatively free of decay.
- Thin from below in mature stands as a first thinning. Thin from above if the canopy trees are not windfirm. Selectively removing vulnerable trees in each crown class may enhance stand stability, as long as the rba does not drop too low.
- Avoid exposing stand edges to prevailing west and northwest winds in flat areas and on summits.
- In northeastern Minnesota along the North Shore of Lake Superior, avoid abrupt, northeast-facing clearcut edges because these will take the brunt of autumn storm gales in this unique situation.
- Use topographic position within the RMZ to protect trees, especially in low wet areas. On leeward slopes, locate the RMZ edge so as to keep the canopy below the level of the summit, or remove tall, exposed trees.
- Locate leave-tree islands within an upland clearcut closer to the exposed RMZ edge rather than farther out in the clearcut to reduce topographic exposure.

The foresters that responded to this study appeared to have a general understanding of the main drivers of windthrow in northern Minnesota and consider these when making management decisions. Not all the variables explored in this article carried equal importance in determining windthrow risk, according to the responding foresters. Most responding foresters indicated that species, soil moisture, effective rooting depth, and topographic exposure were the most important factors to consider when designing a windfirm RMZ edge, with edge aspect and rba being moderately important, and dbh and hillslope position were less important. Some of the results were more consistent with the published literature than others, although as Table 1 shows, there is also variation in what is found in the literature. Generally, stand factors produced more significant results than site factors. Stand factors may have more significant results than site factors because stand factors such as species and diameter are more readily quantified during stand assessments whereas site

factors such as soil type are more difficult to observe. Windthrow management also has a specific, local component outside of general recommendations gleaned from the literature (e.g., along the North Shore of Lake Superior, strong northeast winds may present unique hazards in the fall). In general, local site and stand conditions and field experience in one geographic area all play roles in determining what variables foresters identify when making management decisions concerning windthrow. Additional empirical research on actual windthrow will be needed to more conclusively determine which drivers of windthrow are most important for management considerations and to refine mitigation strategies for northern Minnesota conditions.

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