Windstorm Damage in Boundary Waters Canoe Area Wilderness (Minnesota, USA): Evaluating Landscape-level Risk Factors

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Moser, W.K. and Nelson, M.D. 2009. Windstorm Damage in Boundary Waters Canoe Area Wilderness (Minnesota, USA): Evaluating Landscape-level Risk Factors. *Baltic Forestry*, 15 (2): 248–254.

Abstract

Ecosystem management requires an understanding of disturbance processes and their influence on forests. One of these disturbances is damage due to severe wind events. In an ideal model, assessing risk of windstorm damage to a forested ecosystem entails defining tree-, stand-, and landscape-level factors that influence response and recovery. Data are not always available for all three scales, but a wealth of geospatial datasets provides consistent opportunities for analysis at the landscape level. This paper examines landscape-level factors that influenced tree damage from a 1999 windstorm in the Boundary Waters Canoe Area Wilderness in northern Minnesota, USA. A geospatial analysis was conducted using a suite of data variables derived from land cover, topographic, and climatic datasets. Land type association, distance to the nearest lake, and elevation were the most significant factors influencing wind storm damage. These variables highlight the importance of exposure to the wind as determinants of damage, reflecting the severity of this particular storm.

Key words: Landscape, windstorm, blowdown, risk, wilderness, Minnesota USA

Introduction

Disturbances are an important factor modifying forests throughout the world. Whether biotic, like insect and disease attacks, or abiotic, like windstorms or fire, such events shape forest composition and structure. A great deal of research has estimated the actual damage and risk of potential damage by these disturbances (Gardiner et al. 2000, 2008, Moore and Quine 2000, Talkkari et al. 2000, Wilson 2004, Xi et al. 2008), and some research has developed guidelines for management to reduce or mitigate risks (Gardiner and Quine 2000, Slodičak and Novak 2006). Initial risk assessment was focused primarily on reducing damage to timber resources, but the technique has broadened recently to include estimation of effects upon the full suite of ecosystem services. While such disturbances are a natural part of ecological functioning, expanding human development and conversion to other land uses have resulted in an increased emphasis on maintaining remaining forest resources (Perry and Amaranthus 1997). Accordingly, there is value in identifying management strategies that provide for desired ecological services while taking into account the potential for windstorm damage.

Historically, large and small windstorms have been responsible for significant damage to forested ecosystems. Whether hurricanes, tornadoes, or derechos – widespread, convectively induced windstorms (Johns and Hirt 1987), wind events have shaped forest landscapes (Gresham et al. 1991, Foster and Boose 1992, Dyer and Baird 1997, Ennos 1997, Schulte and Mladenoff 2005). Artificially regenerated forests particularly suffer from wind storms (Gardiner et al. 2008), especially when human-prescribed tree species and densities differ from natural conditions. A better understanding of the susceptibility of forests to wind damage could result in improved management practices that reduce wind damage severity. We assess a variety of biotic and abiotic factors as potential predictors of forest susceptibility to wind damage severity following a large blowdown event.

On 4 July 1999, a long-lived, straight-line windstorm or "derecho" traversed the Quetico-Superior region. Heavy rains and winds exceeding 41 m s^{-1} caused extensive forest blowdown and flooding in northeastern Minnesota, USA, and adjacent Ontario, Canada. More than 12 million trees on 193,000 hectares were blown down across the Superior National Forest, mostly within the Boundary Waters Canoe Area

Wilderness (BWCAW) (148,000 ha) (Moser et al. 2007). This event triggered a need for information on areal extent of forest disturbance and severity of damage following the storm, resulting in a temporary intensification of the Forest Inventory and Analysis (FIA) sampling design on the BWCAW. Moser et al. (2007) analyzed FIA data for the BWCAW and found that some forest types were impacted by the windstorm more heavily than others. In particular, aspen (*Populus tremuloides*) and jack pine (*Pinus lambertiana*) stands were heavily damaged. Research by Rich et al. (2007) also found these early-successional species to be heavily impacted. Given the path of the storm and the lack of on-site measurements of wind speed, microbursts, and down drafts, one can only hypothesize as to the local storm intensity. Nonetheless, the concentration of damage within certain landscapes and forest types suggested that severity of damage could be associated with susceptibility factors.

Wind Damage Potential

The ability to resist damage from wind events can be examined at two scales: 1) tree- or stand-level and 2) landscape-level. At the tree level, one can further break down characteristics into wind-loading (i.e., crown resistance to wind), stem response (i.e., "bend or break"), and wind-firmness, or how well the tree is anchored into the ground. Each one of these categories is a function of the tree species. Additional factors include, in the case of wind-firmness, the soil type and depth, and in the case of wind loading, the canopy structure (Foster 1988, Gresham et al. 1991, Gardiner et al. 2000). Wind loading depends upon the height of the tree, the amount of leaf area on the tree and the position of the tree relative to the force of the wind (Foster and Boose 1992, Scott and Mitchell 2005). Stem response is more mechanical in character, comprising the height/diameter ratio and the brittleness of the wood (Baker et al. 2002, Scott and Mitchell 2005). The propensity for stem damage is also related to tree wind-firmness, as trees that are more windfirm, either because of root habits or soil characteristics, are more likely to break off at some point along the trunk, whereas a less windfirm tree is more likely to fall over completely, creating a "tip up" and the pit-and-mount topography so common in northern forests (Foster 1988, Heinselman 1996).

At the stand level, the position of the tree at the edge of a stand or in the interior of a stand materially influences its susceptibility to damage (Foster and Boose 1992, Pellikka and Järvenpää 2003, Schroeder 2006). Not only are trees on the edge of the stand more likely to face high winds, but frequently they have an extended canopy on the open side of the bole, creating a higher wind-loading on the tree stem.

In areas prone to wind damage, historic research on silvicultural practices emphasized identifying this susceptibility to damage and minimizing the opportunity for wind-loading on trees that have not yet experienced unimpeded wind force. Wind loading is at least partially a function of exposure to wind and wind speed, so we examined the effect of aspect and distance from the nearest lake. Wind loading increases exponentially with height of tree (Foster 1988, Gardiner et al. 2000, Ruel 2000); but topography also influences this characteristic, so we investigated elevation and slope.

Most models of potential for wind damage include species, density, and height as tree-level predictors. However, such data typically are not available over larger geographic extents, with the exception of sample-based inventory data, which are not sufficient for spatial modelling. At the landscape level, topographic positions, including aspect, slope, and distance from openings, can be the driving factors (Xi et al. 2008). The lack of sufficient plots within the damage zones reduced our opportunities to compare tree characteristics for damage susceptibility. In this paper, we limited our analysis to landscape-level factors that predispose a forest to risk of windstorm damage. Our hypothesis was that the closer to a lake, facing the storm most directly, the more exposed the topographic position, the higher the elevation, and the steeper the slope, the greater the damage potential.

Materials and methods

Comprising approximately 440,000 ha of the Superior National Forest (SNF), in northern Minnesota, USA (Figure 1), the BWCAW is located in the Quetico-Superior region of northeastern Minnesota and western Ontario. Geologically, the BWCAW occupies the lower portion of the Canadian Shield. Here glaciers of the past have exposed bedrock and formed a myriad of lakes now connected by streams and portages (Heinselman 1996). The BWCAW is a mix of forest land (72% or 317,000 ha), open water (18% or 77,000 ha), and nonforest land (10%), primarily wetlands that do not support tree cover. Hardwood (broadleaf) and softwood (conifer) forest types are equally represented; prominent tree species include paper birch (*Betula papyrifera*), quaking aspen (*Populus tremuloides*), black spruce (*Picea mariana*), jack pine (*Pinus banksiana*), and eastern white pine (*Pinus strobus*) (Moser et al. 2007). A variety of factors, including topography, species mix, history (managed and unmanaged), and individual disturbances, such as fire, weather, and animal browsing, have shaped BWCAW's forests (Frelich and Reich 1995, Heinselman 1996). The result is the mosaic of vegetation structures, species, and ages seen today. Because of its history as an important travel corridor for 19th-century fur traders, its unique ecological character, and its importance as a recreational opportunity for more than 200,000 visitors per year, the BWCAW is protected as a unit of the National Wilderness Preservation System.

Study variables

Forest blowdown data were obtained from the Minnesota Department of Natural Resources (DNR) as a 30-m blowdown damage severity map, derived from pre- and post-blowdown Landsat Thematic Mapper satellite image data and a change detection procedure (Minnesota DNR 2006). Nineteen variables were examined for effects on wind damage susceptibility within the BWCAW (Table 1). Most variables were derived from land cover, digital elevation model (DEM), or climatic datasets (Brian Sturtevant and Brian Miranda, US Forest Service, pers. comm.). The geospatial datasets were processed using various procedures in ArcGIS 8.3 (ESRI 2004) software package.

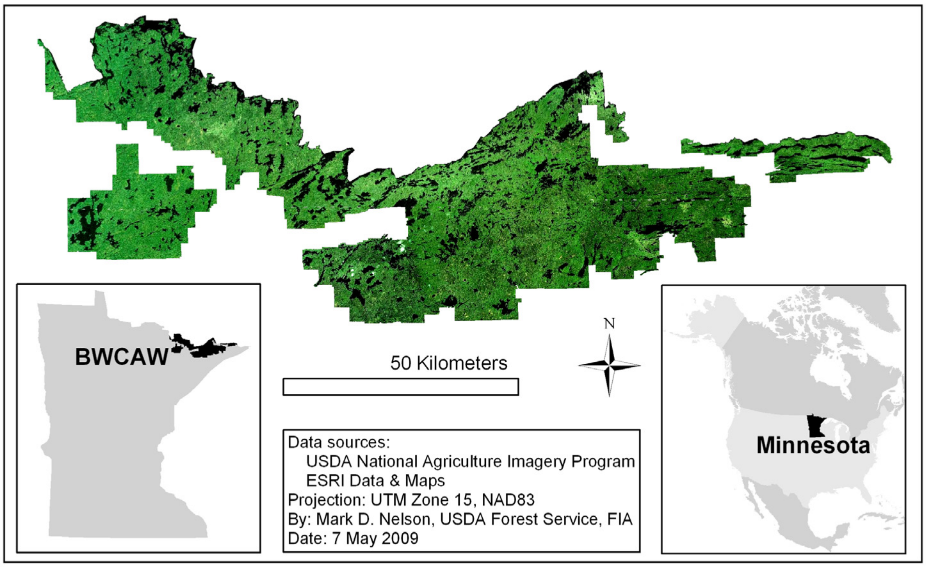

Figure 1. Natural color aerial photography, 2004, Boundary Waters Canoe Area Wilderness (BWCAW), Superior National Forest, Minnesota, USA: dark green – healthy forest, light green – blowdown damage, black – open water

Our strategy for assessing risk to wind damage was a grid-based analysis defined by randomly located points. We located one virtual plot per six hectares within the BWCAW (n = 10,000) and related pixel-based measures and layers for soils, elevation, aspect, topography, and lakes to a corresponding data layer of blowdown damage that was derived from a satellite image-based map of forest disturbance. To determine which variables were most influential, we employed a classification-tree approach. There are several reasons why this approach has become popular for land-cover classifications (Pal and Mather 2003): it is non-parametric, it can handle many data layers, either numerical or categorical, it does not require assumptions about data distributions, it is significantly less labor-intensive than other classification techniques, and it can be used efficiently for classifying large geographic extents (Homer et al. 2007, Ruefenact et al. 2008). In classification-trees, data are recursively divided into smaller groups, based on tests performed at the tree nodes. A value is assigned at the end of each tree. We used See5® software package (Rulequest Research 2004) to develop classification trees. Accuracy assessments were conducted using test data records (n = 4,906) not included in the predictive models.

The variables in Table 1 represent climatic or topographic factors that could influence susceptibility to wind damage. Topographic exposure (Wood et al. 2008) is an important factor in assessing risk of wind dam-

Table 1. Variables examined

Aspect Index	Elevation
Lake area (of nearest lake)	Lake Class (of nearest lake)
Lake distance (to nearest lake)	Lake perimeter (of nearest lake)
Land Type Association	Maximum Temperature Growing Season
Minimum Temperature Growing Season	Ownership Name
Potential Evapotranspiration August	Potential Evapotranspiration Growing Season
Potential Evapotranspiration July	Precipitation Growing Season
Relative Slope Position	Slope
Spruce Budworm Defoliation	Terrain Shape Index
Topographic Convergence Index	

age (Ruel et al. 2002). A few variables deserve further explanation. Lake variables (distance between point and lake, perimeter, edge, class) represent measures of wind "fetch" (Scott and Mitchell 2005). The distance to the lake edge can also mimic the effect of a forest edge along an open field or a clearcut harvest. Land type association is a manually interpreted collection of land surface information including topography, wetland and soil characteristics, hydrography, presettlement vegetation, bedrock type, Landsat satellite imagery, geomorphology, and local knowledge (Minnesota DNR 1999). Ownership name was the general classification of the category of owner, whether private, various state or federal government agencies, or wilderness (which is a special category of federal ownership). Spruce budworm (*Choristoneura fumiferana* Clemens) defoliation was derived from annual budworm defoliation maps produced by Minnesota DNR, indicating regions of defoliation based on aerial survey sketchmaps. Relative slope position is the position of the measuring point relative to the slope as a whole, derived from filled 30-m DEM. Terrain shape index is the local concavity or convexity, derived from a filled 30-m DEM, following a calculation from McNab (1989). Topographic convergence index is defined as percent of the upslope area relative to the slope (see US Geological Survey 2004), derived from a filled 30-m DEM. Landform index is the average vertical gradient (percent) to the topographic horizon (McNab 1993), derived from a filled 30-m DEM.

Where possible, indices were used to remove scale from the analysis. The number zero was assigned to the absolute minimum of a variable and the number one to the maximum. For aspect, we assigned the number one to the azimuth of 245° – the wind direction – and the number 0 to the azimuth 65°. For the distance-to-lake variable, an index of one was assigned to a position next to the lake and an index of zero to the maximum distance from the lake.

Results

From a management perspective, Occam's Razor applies to managing for risk: the simplest solution is the superior choice. Accordingly, we evaluated single-predictor models, then two- and three-predictor models, and finally a comprehensive model of 19 variables. Table 2 displays an example of the output from the decision tree analysis for the two-variable combination of aspect index and distance from lake. Table 3 displays our accuracy analysis for this combination of variables, obtained by comparing predicted and observed blowdown (Table 3). For this example, overall accuracy was 63.5 percent; errors of omission were 28 and 40 percent and errors of commission were 57 and 17 percent, for non-blowdown and blowdown classes, respectively.

Table 2. A segment of a decision tree from See5 model based on Aspect Index and Distance to nearest lakeshore. Model generated using GRID layers and random locations

```
Lake_dist • 0m: No-blowdown
Lake_dist > 0m:
:...Lake_dist > 569m: No-blowdown
    Lake_dist • 569m:
    :...Lake_dist > 308m: Blowdown
        Lake_dist • 308m:
        :...Lake_dist • 8m: No-blowdown
            Lake_dist > 8m:
            :...Aspect_Index > 0.25: Blowdown
                Aspect_Index • 0.25: No-blowdown
```

Table 3. Evaluation of test data for aspect index and distance to nearest lake. Classification accuracy = 63.5% using independent test data

Predicted	Actual	
	(a)	(b)
(a): No-blowdown	1073	1380
(b): Blowdown	410	2043

Table 4 displays the results for the 19-predictor (comprehensive) model and the top three results for 1-, 2- and 3-predictor models. Not surprisingly, the comprehensive model resulted in the highest overall accuracy (85.1 percent). In addition, errors of omission and commission for both non-blowdown and blowdown

Table 4. See 5 classification tree model results. Models generated from GRID layers and random locations. Classification accuracies are from confusion matrices of blowdown/no-blowdown predicted/observed. Model combinations with highest accuracy within each total number of variables (1-, 2-, and 3-variable models) are underlined

Predictor Grid Data	Overall Accuracy
<u>Land Type Association (LTA)</u>	68.8
Lake Distance (LD)	62.7
Aspect Index (AI)	59.6
<u>LD & LTA</u>	72.5
LD and Elevation	65.8
AI & LD	63.5
<u>LD, LTA, and Elevation</u>	75.7
AI & LD & LTA	72.5
LD, LTA, and Slope Position	67.9
<u>Comprehensive</u>	85.1

ranged from 14 to 16 percent. The lowest classification accuracy (59.2 percent) was for a 1-predictor model using only aspect index. The three most important variables in our analysis all represent some measure of exposure to the wind storm. Land type association (LTA) was a component of the most accurate 1-, 2-, and 3-predictor models, with overall accuracies of 68.8, 72.5 and 75.7 percent, respectively. Composed of an amalgam of topographic, edaphic, hydrological, and vegetative variables, LTA represents a comprehensive measure of exposure. Although wide-ranging in its makeup, the definition of LTA does not overlap with other variables, such as aspect, distance to lake, or elevation.

The second most important component in the 2- and 3-predictor models was distance to lake. Given the abrupt change in ecotype at the lakeside, lake distance represents the "edge effect" referred to in the literature (see Gardiner et al. 2000, Talkkari et al. 2000) and the point of maximum wind force upon a tree crown. Given the dissipative nature of intact forest canopies, wind speed at crown height is expected to diminish the greater the distance the wind must pass through the forest (Talkkari et al. 2000, Schroeder 2006). Finally, the presence of elevation in the most accurate 3-predictor model further emphasizes the importance of exposure to the wind.

Discussion and conclusions

As increased occurrence of severe weather events is one of the predicted outcomes of climate change (Dale et al. 2001), it is prudent to explore the susceptibility of forests to such weather events. Assessing the cause of wind damage is challenging because damage integrates the effects of species-, site-, stand-, or landscape-based factors (Foster 1988, Gresham et al. 1991, Xi et al. 2008). Xi et al. (2008) pointed out that understanding the patterns of disturbance in forests requires that risk factors be examined at "ecologically relevant scales." Determining the relevant scale is problematic because large-scale variation is influenced by landscape-level factors whereas smaller-scale responses are more a function of responses of individual tree stems (Lawrence et al. 1991). Predisposing factors are a logical assumption connecting wind events and wind damage. Understanding such factors aids management in making decisions. All other things being equal, exposure to wind influences susceptibility to wind damage (Schelhaas 2008). This study focused on exposure to wind, along the lines of models such as the Detailed Aspect Method of Scoring (Quine and White 1993). This study found that landscape-level factors had some relationship to actual damage. The advantage of these results is the ability to rapidly assess potential for wind damage, – irrespective of species composition – on a relative basis and prioritize potential management actions accordingly.

While the BWCAW, as a wilderness, is not "managed" for timber, the relationships between site landscape characteristics and propensity for wind damage provide valuable insights for resource managers concerned with minimizing storm impacts. The absence of active timber management within the BWCAW study area allowed for high confidence that forest canopy loss in satellite image-based maps was directly attributable to blowdown damage. Thus, effects of non-blowdown canopy disturbance were effectively controlled in this study. Additional studies are needed to assess the interaction between landscape-based factors and local effects of forest management, e.g., windthrow along edges of timber harvest.

In an excellent study of the 1999 storm's blowdown effects in the BWCAW, Rich et al. (2007) focused on tree characteristics (species, diameter, and age) as determinants of susceptibility to wind damage. Gardiner et al. (2000) and Valinger and Fridman (1997) also found similar tree-level relationships with wind damage. Foster (1988) found relationships with both tree- and landscape-level factors. Trying to separate species' susceptibility from landscape predisposition runs afoul of the potential for correlation between topographic factors and individual species' characteristics (Everham and Brokaw 1996). Nonetheless, individuals contemplating management actions should be aware that specific topographic features predispose a site to damage; managers should adjust their decisions accordingly.

While intensive (and expensive) on-the-ground measurements of damage can simultaneously evaluate tree-, stand-, and landscape-level factors, extensive or hard-to-access geographic areas can be assessed via grid-based data and geospatial analyses. The data layers employed in this study typically are available for many temperate and boreal forested ecosystems; thus our approach could be more broadly implemented. With increasing number of occurrences of wind storms and a decline in real funding for natural resource investments, geospatial analysis provides a less expensive, yet accurate, method of assessing the extent of storm impacts.

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Received 07 March 2009
Accepted 15 October 2009

ПОВРЕЖДЕНИЕ ОТ БУРИ В BOUNDARY WATERS CANOE AREA WILDERNESS (МИННЕСОТА, США): ОЦЕНКА ФАКТОРОВ РИСКА ЛАНДШАФТНОГО УРОВНЯ

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Резюме

Управление экосистемой требует понимания процессов нарушения и их влияния на лес. Одним из таких нарушений является повреждение от серьезных проявлений ветра. В идеальной модели, оценка риска повреждений от бури для засаженной деревьями экосистемы влечет за собой определение факторов на уровне дерева, древостоя и ландшафта, которые влияют на реакцию и восстановление. Данные не всегда доступны для всех трех уровней, но изобилие геопространственных наборов данных обеспечивает последовательные возможности для анализа на ландшафтном уровне. Эта статья рассматривает факторы ландшафтного уровня, которые повлияли на повреждение деревьев от бури в 1999 году в Boundary Waters Canoe Area Wilderness в северной Миннесоте, США. Геопространственный анализ проводился с использованием набора переменных данных, полученных из растительного покрова, топографических и климатических наборов данных. Тип земли, расстояние до ближайшего озера и высота над уровнем моря были наиболее значимыми факторами, влияющими на повреждение от ветра. Эти факторы выдвигают на первый план значение открытости к ветру, они как детерминанты повреждения, отражающие суровость данного шторма.

Ключевые слова: Ландшафт, буря, ветровал, риск, дикая местность, Миннесота США