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Applications in Landscape Ecology: A Simple Rule-Based Simulation Approach to Modeling Windthrow Disturbance in Forests of the Western Cascades in Oregon

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1. Preface

Acts of creation are ordinarily reserved for gods and poets, but humbler folk may circumvent this restriction if they know how. To plant a pine, for example, one need be neither god nor poet; one need only own a shovel. By virtue of this curious loophole in the rules, any clodhopper may say: Let there be a tree – and there will be one.

- Aldo Leopold

1.1 Abstract

The study of how biotic and abiotic processes function and interact within the biosphere is fundamental to the field of ecology. In particular, the field of landscape ecology focuses on the relationship between patterns and process at the landscape level. Windthrow is an important, though unfortunately under-studied agent of disturbance in the temperate coniferous forests of the Pacific Northwest. Along with wildfire, windthrow is a dominant force in shaping the structure of the region's forested landscapes, resulting in visible vegetation patterns at the landscape level. The present study involved the development of a windthrow simulation model for the Bull Run Basin in the Western Cascades of Oregon. The purpose of this model was to develop a simple rule-based representation of the process of windthrow, such that a greater understanding of windthrow can be obtained through observation of predicted windthrow in relation to variable landscape conditions. The model approximated levels and spatial distribution of windthrow observed for several periods in the landscape, demonstrating that a simple rule-based model can capture the general trends of a highly complex process. Further studies could use this methodology to develop similar rule-based models for other ecological processes, perhaps linking several models together to observe emergent behavior at the landscape level.

1.2 Acknowledgements

This research was made possible in part by a Research Experience for Undergraduates grant from the National Science Foundation.

I am indebted to Steve Garman for providing me with the guidance and opportunity to pursue the bulk of this research as an intern in the Department of Forest Science at Oregon State University. I am also indebted to David Wallin in Huxley College of the Environment, whose continuing support has presented me with many unique opportunities. I would like to thank Peter Homann and John McLaughlin for their support and advice in preparing this and other projects throughout my undergraduate career in Huxley. Annie Groeninger is to thank for the bulk of my computer programming skills.

Many thanks go to my parents, whose continuing support for my interest in science, ecology, and the outdoors has helped get me this far and will take me even further. I would like to warmly thank all my housemates - Ilsa, Katie, Amy, Kate, Cori, Cassie, Alissa – whose support, cookies, and backrubs got me through the many long hours that went into this project. I would also like to thank Jeff Davis and all my other sailing buddies at Lakewood for providing me with the opportunity to get away from the computer and out on the water.

2. Introduction

2.1 Background

Understanding the interactions between processes at the landscape level is fundamental to increasing our understanding of these processes as well as further enhancing the scientific knowledge that we bring to the management and study of landscapes. Investigating landscape processes is essential because many natural resources are managed at the landscape level, such as water, timber, wildlife, as well as a suite of other ecosystem services (Harmon et al. 2000). Many important disturbance agents also causes changes in structure and function at the landscape level, such as fire, windthrow, and insect outbreaks to name a few (Boose et al. 1994; Bradshaw & Garman 1994; Canham & Loucks 1984; Foster & Boose 1992; Garman et al. 1995; He & Mladenoff 1999; Radeloff et al. 2000). Furthermore, the landscape is a fundamental intermediate when scaling from the ecosystem level to the regional or global scale. This is especially important because regional and global scale analyses rely heavily upon principles developed at smaller spatial scales (e.g. landscapes and ecosystems) due to the difficulty of direct validation at these large scales (Waring and Running 1998). To avoid major scaling errors when moving from smaller to larger scales, it is necessary to have a thorough understanding of the spatial and temporal scale of the phenomena in question as well as the manner in which observation of these phenomena change with respect to the spatial and temporal scale at which they are viewed (Allen et al. 1984; Levin 1992).

Interactions between processes are a confounding feature of process studies because these processes cannot be fully studied in isolation from other interacting processes, even at the landscape level (Johnsen et al. 2001; Radeloff et al. 2000). Furthermore, these interactions are responsible for introducing considerable complexity into the system and are difficult to study directly. Interactions between processes are interesting because they can result in emergent behaviors at many different spatial and temporal scales. Emergent behaviors are essentially behaviors that could not be predicted merely from an understanding of each component of a given system; it is interactions of processes and their respective temporal and spatial variation that gives rise to these emergent behaviors (Garman 2001). Emergent behaviors can also serve as feedback mechanisms to the system by altering the functioning of the processes and interactions that produced them as well as other processes not previously involved (Levin 1998).

Several developments need to be made to facilitate the investigation of both processes and their resultant patterns at the landscape level (Garman et al. 1995). The most fundamental involves a paradigm shift from viewing the landscape as a patchwork wherein the pattern is the guiding principle of investigation to viewing the landscape as a network in which processes interact and vary spatially and temporally among several different types of landscape elements (Harmon et al. 2000). For example, windthrow is a process that interacts with site-level processes within a forest stand (such as tree mortality, growth, water flux, carbon flux, etc.) to produce unique changes in the structural and functional patterns of the landscape (Adler 1994; Bradshaw and Garman 1994; Sinton 1996). To reach a more complete understanding of a process and its interactions, an investigator must focus on the process that produces the patterns rather than strictly using the pattern as a basis for drawing conclusions about the process.

2.2 Windthrow

Windthrow is an important agent of disturbance in the temperate coniferous forests of the Pacific Northwest, and along with wildfire it is a dominant force in shaping the structure of the region's forested landscapes (Adler 1994; Sinton et al. 2000; Garman et al. 1995). Furthermore, as these forests have become increasingly fragmented over the last century, windthrow has become a more influential component of the region's disturbance regime because of higher levels of edge (Chen et al. 1992; Saunders et al. 1991; Sinton et al. 2000).

The process of windthrow is worthy of investigation for several reasons. First, it results in the loss of harvestable timber and thereby causes economic loss, an important concern in forests managed for timber production. Furthermore, it generates increased levels of course woody debris on the forest floor - thereby increasing potential for fire and bark beetle outbreak (Bradshaw & Garman 1994), increased levels of woody debris in streams from riparian buffers, releases understory trees to dominate forest canopy (Sinton et al. 2000), and generates heterogeneity in forest and landscape structure (Boose et al. 1994; Canham & Loucks 1984; Foster & Boose 1992). Windthrow can also interact with other agents of disturbance such as fire, bark beetles, and debris flows (Bradshaw & Garman 1994; Adler 1994; Sinton et al. 2000). Such interaction could potentially result in complex emergent behavior across the landscape over time. As human induced disturbances have increased in Pacific Northwest forests over the last century, the intensity of windthrow has appeared to increase, suggesting important implications for landscape management practices (Adler 1994; Sinton 1996; Sinton et al. 2000). Recent studies have related systems of timber harvest to levels of windthrow, revealing that certain methods of harvesting have resulted in windthrow dynamics quite different from those of a natural landscape (Coates 1997; Huggard et al. 1999).

Of all the factors involved in windthrow in the Western Cascades of Oregon, perhaps the least understood is also the most influential: the dynamics of the wind itself. Researchers have noted the importance of certain characteristics of wind flow, such as turbulence created by topographic features, which can cause greater levels damage than stronger unidirectional winds (Adler 1994). The flow of wind through a landscape is incredibly complex due to the high levels of variability of topographic structure, forest structure, and other elements that alter the direction or velocity of wind (e.g. roads, stream valleys, edges). The flow of wind is also temporally dynamic and direction, velocity and steadiness can vary significantly over time on both instantaneous and seasonal scales. Furthermore, the effect of storm winds acting on a landscape "adapted" (physiological wind hardening) to prevailing winds from a different direction is poorly understood and often ignored in assessment of windthrow risk (Foster & Boose 1992; Sinton et al 2000; Wallin 2002). Unfortunately, the difficulty of accurately measuring wind flow dynamics on small spatial scales (individual trees and small stands) over large spatial extents (landscapes) is a problem that confounds a more detailed assessment of windthrow dynamics.

However, numerous site-level characteristics can reveal information about windthrow dynamics in landscapes. A review of the literature has revealed a few major factors related to windthrow: proximity to an edge, age of the edge, topographic position in relation to wind direction (topographical exposure), soil depth and stability, physical characteristics of trees (e.g. species, age, height, diameter, etc), and physical characteristics of stands (closed/open canopy, uneven vertical structure, etc) (Adler 1994; Coates 1997; Foster & Boose 1992; Huggard et al. 1999; Lohmander & Helles 1987; Sinton et al. 2000). Of these, perhaps the most straightforward to measure in Pacific Northwest landscapes are the first three, whereby the first two can be calculated using spatial data representing timber harvesting patterns and yearly cutting records, combined with fire history data. However, we emerge upon an almost circular problem, as most natural disturbance models and reconstructions for the Pacific Northwest have focused primarily on wildfire as an agent of disturbance (Sinton et al. 2000; Wallin et al. 1996). It has already been noted that windthrow also plays an influential role in generating structural patterns of Pacific Northwest forests, and should not be ignored in reconstructing landscape histories.

While both wildfire and windthrow are dominant disturbance agents and can occur over a wide range of intensities, temporal and spatial scales, they act quite differently in shaping the post-disturbance forest structure in the Pacific Northwest (Sinton et al. 2000). Whereas fire tends to result in stands dominated by shade-intolerant Douglas fir, windthrow can result in the release and dominance of shade-tolerant species such as western hemlock and Pacific silver fir (Sinton et al. 2000). Thus incorporating windthrow dynamics into our understanding of landscape pattern will better enable us to interpret the underlying processes and interactions that generate observable patterns (e.g. species distribution, forest structure, etc).

Two mechanisms have been proposed to explain the manner in which wind causes windthrow: trees with a high degree of exposure simply blow over under strong winds, and "moderate wind speeds generate harmonic oscillations in stems, leading to failure at points of structural weakness (Hurggard et al. 1999, p. 1554)." Both mechanisms can act simultaneously in the same landscape due to variability in exposure levels between sites. In one recent study, the first mechanism was most closely associated with the downwind edges of large canopy openings due to the strong directionality of fallen stems, whereas the second mechanism was associated with relatively closed canopy stands, resulting in random orientations of windthrown stems (Huggard et al. 1999).

2.3 Purpose

The primary goal of this study is to develop a simple rule-based model of windthrow dynamics that reasonably approximates patterns of windthrow observed in real landscapes. This line of research is motivated by a desire to develop a system of rule-based models which rely on only a few general parameters, yet generate landscape level patterns similar to those found in the Western Cascades of the Pacific Northwest. Not only does this approach help researchers to better understand conceptually the behavior of the disturbance in the landscape as an agent of pattern generation, but also to target specific factors to measure in the field over large extents in an effort to better understand disturbance regimes.

3. Methods

3.1 Study Area

For purposes of this study, I used data from the Bull Run Basin in Oregon, much of which is derived from the work of Sinton (1996). This 265 km^2 watershed is located in the Mount Hood National Forest in the western Cascade Mountains of northern Oregon (Sinton 2001). Motivations for using this landscape were the availability maps for all necessary input to model, observed windthrow data from approximately 1893 – 1983, and a fairly extensive description of windthrow patterns for the landscape. Furthermore, the Bull Run Basin is located near the Columbia River Gorge, which is notable for its strong seasonal winds and severe storm events (Lawrence 1939). This landscape was first used for developing and fine-tuning the simulation model. Windthrow observed within this landscape was later used to assess the model.

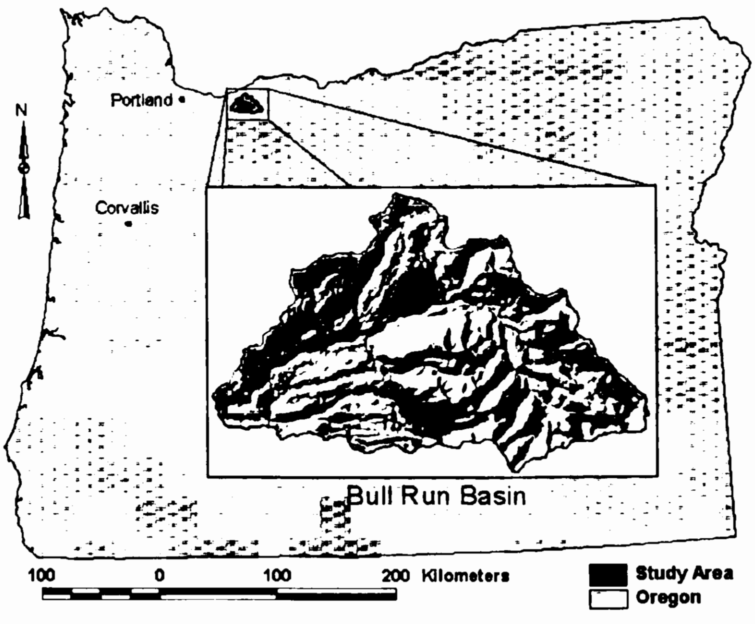

Figure 3-1. Location of the study area in northern Oregon.

3.2 Model Input

The model developed in this study (WINDMOD) relies on a series of input maps to generate a site-specific database for each cell (Figures 3-1, 3-2). The spatial resolution of all input maps was standardized to seventy-five meters by seventy-meters (0.5625 ha) to facilitate comparison with observed windthrow. Elevation and aspect were used to determine topographical exposure (Figure 3-1(a-b)). Relative elevation was calculated using a search window of eight cells directly surrounding a focal cell and depended on the proportion of neighbor cells that were of higher elevation. This proportion was divided into three classes to represent areas with low exposure, such as stream valleys, areas with moderate exposure, such as the lower slopes of ridges, and high exposure areas, such as ridge tops and upper slopes. The exposure due to aspect was determined at each time step in relation to the wind direction for that year. Areas with the same aspect as the wind direction were considered the most exposed, with exposure decreasing both clockwise and counterclockwise from the wind direction. Thus areas on an aspect opposite the wind direction were considered the most sheltered.

A generalized landcover map was derived by combining a map of permanent forest openings with a map of major water bodies and assuming that the remainder of the area was homogenous forest (data obtained from Sinton 1996). While this is a major simplification of the variability of landcover type within the study area, it simplifies the simulation of windthrow by the model. Furthermore, at the resolution used in this study, much of the area covered with vegetation was dominated by coniferous forest. Non-forest vegetation areas were classified as permanent openings (Sinton 1996).

Fire history was used to determine the initial stand age of each forested cell in the landscape. This data was derived from the work of Krusemark et al. (1996) and resampled to the resolution of the other input layers (Sinton 1996). Timber harvest history was used to determine the spatial and temporal location of clearcuts. Each of these disturbance histories was used to impose a disturbance pattern on the landscape by resetting the age of affected cells to zero. However, neither fire nor timber harvest was actually simulated within this study. Stand age was classified into an age class to simplify model processing. The model used the following age classes: 0-20 years old, 20-40, 40-80, 80-120, 120-200, and greater than 200.

A wind direction distribution for the study area was derived from the work of Sinton (1996). This distribution was based on daily mean wind speeds of over fifteen miles per hour for approximately a twenty year period. Each year of the simulation, a Uniform Random Variant (URV) was used to sample randomly from this distribution to determine that year's wind direction. This attempted to capture the variability of wind direction from year to year, thereby mimicking the real process.

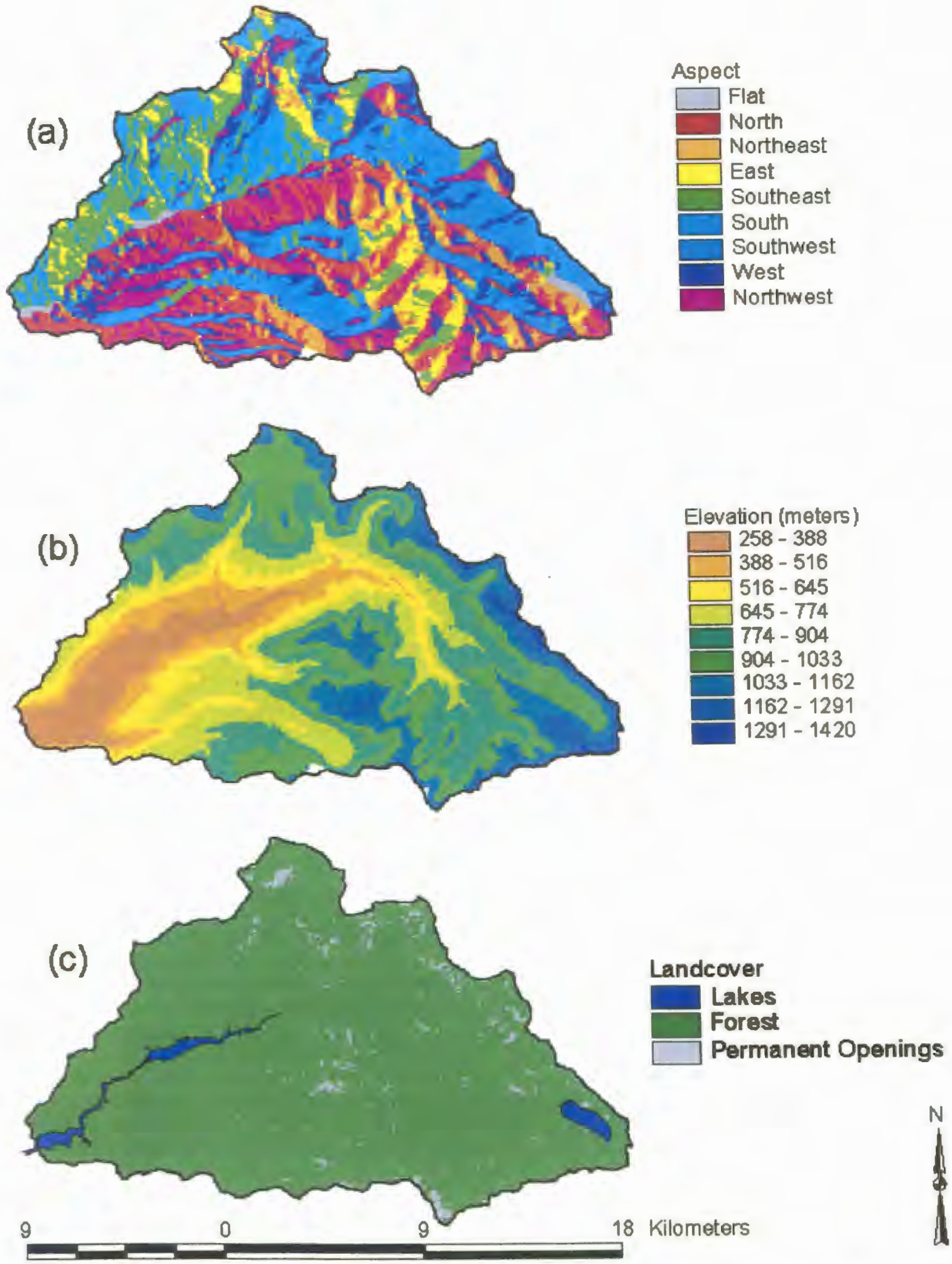

Figure 3-2. Input maps for WINDMOD (data derived from Sinton 1996). (a) Aspect. (b) Elevation is in meters above mean sea level. (c) Generalized landcover (see text for explanation).

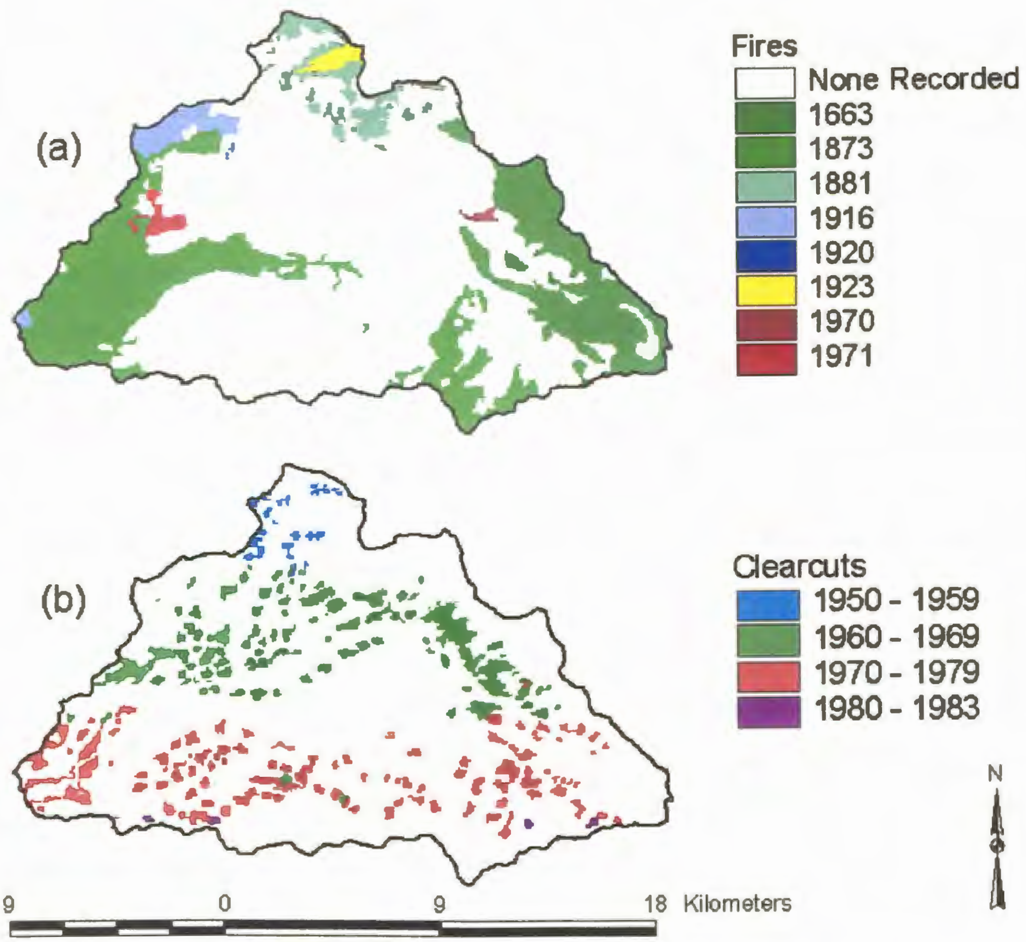

Figure 3-3. Stand Age input maps for WINDMOD. (a) Fire history (data derived from Krusemark et al. 1996). (b) Clearcut history (data derived from Sinton 1996).

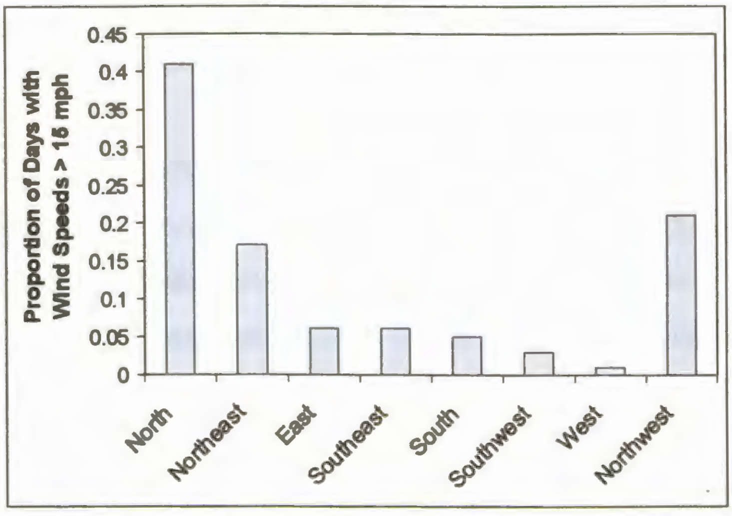

Figure 3-4. Wind direction distribution for the study area (data derived from Sinton 1996).

3.3 Modeling Procedure

WINDMOD is a cellular automata simulation model. In this type of model, the landscape is represented as a multidimensional matrix of cells. Each cell in this matrix contains information specific to its location within the landscape. The essential principle behind a cellular automata model is that the state of each cell in the landscape is dependent on the state of neighboring cells as well as its state during the previous time step (horizontal rules). A set of rules can also characterize behavior for each cell based on its unique combination of site-specific factors, such as elevation, aspect, or vegetation type (vertical rules). These rules are applied to each cell in the matrix over a specified period of time steps. A cellular automata approach is ideal for simulating windthrow because the influence of wind on a particular cell is dynamic and is altered by interaction with surrounding cells (Garman 2001). Cells downwind are exposed to wind that is in part shaped by its flow across cells upwind. Furthermore, this approach to modeling relies on simple rules rather than complex processing, thus enabling large spatial and temporal extents to be modeled in a relatively short amount of computer processing time. Even though such a model is simplistic by design, it has the potential for generating complex behavior (Garman et al. 1995).

The model was run between 1893 to 1983 to fall within the temporal extent of the observed windthrow data. The model used an annual time step to simulate windthrow. At the beginning of each year, each forested cell was evaluated to determine if it should be burnt or clearcut according to the historical data for the landscape. In such a way, the model was allowed to respond to changes in landscape structure due to patterns imposed by other disturbance regimes.

After imposing the annual disturbance pattern on the landscape, if one occurred, the model then determined windthrow probability for each undisturbed forested cell using two rule sets. The horizontal rule set used an eight cell neighborhood to determine the proportion of clearcut, fire, forest opening, and windthrow cells surrounding a focal cell (Figure 3-5). This proportion was then scaled based on the relative age differences between the focal cell and the surrounding cells. For clearcuts, fire, and previous windthrow, exponential functions were used to scale this proportion; thus cells with a large age difference were weighted exponentially higher than cells that were closer to the same age. This allowed the model to account for the higher probability of an old growth stand being blown over if it was adjacent to a new clearcut, as opposed to a young stand adjacent to a clearcut (Sinton 1996). For permanent openings, a constant was used to scale this proportion, representing the relatively constant influence of permanent edges on windthrow. Clearcuts were scaled to generate the highest probability of windthrow, whereas fires and previous windthrow were scaled to generate lower probabilities of windthrow. The neighborhood rule set also calculated the fetch distance of a directly upwind clearcut, fire, forest opening, or previous windthrow. This distance was scaled such that greater fetch distances would result in higher probabilities of windthrow. The result of the neighborhood rule set was probability of windthrow based on a particular cell's neighborhood and fetch.

The vertical rule set used topographic exposure to determine a particular cell's probability of windthrow based on its combination of relative elevation and aspect in relation to the annual wind direction. The probability for each rule set was summed to produce an overall probability of windthrow, which was then compared to a URV to determine whether or not that cell experienced windthrow during that time step. If it experienced windthrow, its age was set to zero and it was allowed to regrow. The windthrow event was then allowed to propagate to downwind cells using less stringent rule sets. This allowed the model to simulate the progression of a given windthrow event within the time step, thus attempting to mimic the actual process of windthrow in forested landscapes.

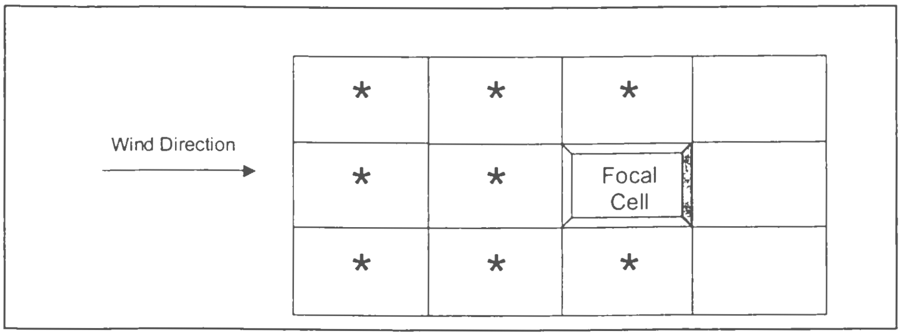

Figure 3-5. Eight cell upwind and adjacent neighborhood (*) used by horizontal rule set (see text for explanation).

3.4 Observed Windthrow

Observed windthrow for this study was derived from six discrete windthrow maps produced by Sinton (1996). The years 1900, 1910, 1921, and 1931 were considered collectively as the Pre-Harvest period for analytical purposes. For this period, the effective mapping resolution of windthrow was two hectares (Sinton 1996). For 1973 and 1983, the effective mapping resolution of windthrow was 0.5625 hectares.

3.5 Analyses

WINDMOD was run for twenty replicates in a Monte Carlo fashion to minimize the variability of predicted responses. For the Pre-Harvest period, all windthrow below two hectares in size was screened from the analysis to facilitate comparison with the observed data set. To convert the continuous predicted windthrow data into discrete time periods, all windthrow that occurred after the last period was aggregated into the current period. This facilitated comparison with the observed windthrow data.

Several responses were compared between the predicted and observed windthrow data to assess WINDMOD. The total amount of windthrow for each period was calculated, and was averaged between the replicates. A one-factor ANOVA was conducted to determine the statistical significance of differences between the observed and predicted windthrow areas, using an alpha level of 0.01. Significance values greater than 0.01 were used to indicate a non-significant difference. Windthrow rate was calculated for each period by dividing the amount of windthrow by the interval length of the periods. A patch size distribution was calculated collectively for all intervals within the predicted and observed data sets, using the frequency with which patches of each size occurred.

WINDMOD was assessed by aspect to determine if there were any correlations between the distributions of the observed and predicted data for the Pre-Harvest, 1973, and 1983 periods. Aspect was selected to demonstrate the model fit due to its significant relationship with observed windthrow within the study area (Sinton et al. 2000). The aspect distribution of the entire landscape was included to demonstrate possible relationships between the observed and predicted data. Previous clearcuts were included in the analyses for 1973 and 1983 to demonstrate possible correlations between observed and predicted windthrow and the distribution of clearcuts within the landscape.

WINDMOD was spatially assessed by intersecting predicted and observed windthrow within the landscape. Spatially explicit probability of windthrow was determined by the frequency in which the model replicates predicted windthrow for a given cell. Cells which had a frequency of over half the number of replicates were considered to be in the high probability class (>50%). Cells with lower frequency had lower probabilities of windthrow accordingly.

The model was calibrated by frequent comparisons between the observed and predicted windthrow, both quantitatively and spatially. By following this method, it was expected that the resultant accuracy assessments would not be overly biased towards the observed data set because the observed data were not used directly to parameterize the model. This approach also permitted continuous fine-tuning of the model to obtain higher levels of predictive accuracy.

4. Results

4.1 Quantitative Assessment

For much of the Pre-Harvest period, WINDMOD predicted amounts of windthrow similar to the real landscape (Figure 4-1; Table 4-1). For all Pre-Harvest years except 1931, there were no significant differences of mean windthrow area between the model and the observed data (Table 4-2). The model also produced rates of windthrow similar to the real landscape for this period, except for 1931 (Figure 4-2; Table 4-3). Although the observed windthrow represents discrete windthrow-producing storms, the calculation of a rate facilitates comparison between the model and observed data. This comparison would otherwise be hindered by the different interval lengths involved and the continuous manner in which the windthrow is simulated by the model.

The storm of 1931 is an outlier in the observed data set, having produced levels of windthrow that were similar to 1973 (Table 4-1). This is remarkable considering that by 1973 the landscape had been fragmented by over twenty years of timber harvest. It produced over twenty-five times as much windthrow as the average amount observed between 1900 and 1921. This storm could represent a rare severe windthrow event of the type that could periodically occur in an unfragmented landscape, or it could indicate the increasing precision of mapped windthrow with increasing time. If it was a severe storm and mapping precision was low, it is expected that much of the windthrow area would be classified as high windthrow severity and be located in large patches. If mapping precision was higher, it is expected that a majority of the windthrow area would be classified as low severity and be located in numerous smaller patches. Much of the windthrow area of the 1931 storm was classified by Sinton (1996) as low severity, indicating that less than twenty-five trees per hectare were uprooted. The majority of the windthrow was located in forty-seven patches between two and four hectares in size (Sinton 1996). Thus it is likely that 1931 represents both a severe storm and increased mapping precision, thereby producing higher levels of windthrow than was otherwise observed for the Pre-Harvest period.

For 1973, WINDMOD significantly over-predicted windthrow compared to the amount that actually occurred (Figure 4-1; Table 4-2). It also slightly over-predicted the rate of windthrow for this period (Figure 4-2; Table 4-3). It should be noted that the observed data for 1973 represents a single windthrow-producing storm, whereas the model simulated windthrow continuously for forty-two years. Considering that over twenty years of timber harvest occurred prior to 1973 and the relationship between timber harvest and windthrow (Chen et al. 1992; Saunders et al. 1991; Sinton et al. 2000), it is likely that significant amounts of windthrow occurred between 1932 and 1973 that were not detected and mapped. Furthermore, the observed windthrow map for 1973 was confounded by incomplete coverage of the study area, as only the southern and eastern portions of the basin were contained in the aerial photographs used to map windthrow (Sinton 1996). Much of the timber harvest prior to 1973 was concentrated in the northern and northwestern portions of the study area, further demonstrating the likelihood that windthrow was not completely mapped for this period.

For 1983, WINDMOD slightly under-predicted the amount of windthrow observed in the landscape (Figure 4-1; Table 4-1). However, mean windthrow area was not significantly different between the predicted and observed data sets (Table 4-2). The amount of windthrow for this period is below the levels predicted for 1973 due to the different time intervals involved. The model also slightly under-predicted the windthrow rate for this period (Figure 4-2; Table 4-3).

WINDMOD captured the temporal trends of windthrow rate within the landscape. For much of the Pre-Harvest period, both the model and the observed data show low rates of windthrow. The 1931 storm was well above the level of the three previous intervals and also well above predicted levels. During the Post-Harvest period, there was a significant increase in the rates of windthrow, with these rates increasing dramatically over time (Figure 4-2). It is interesting to note that a much lower rate of windthrow was observed for 1973 as opposed to 1931 even though both years experienced similar amounts of windthrow. The rate for 1973 was not much higher than the rate between 1900 and 1921. This further indicates the likelihood that significant amounts of windthrow occurred between 1931 and 1973 that were not mapped.

WINDMOD produced a patch size distribution similar to the observed data set (Figure 4-3). This is an example of a Poisson distribution, indicating high frequencies of small windthrow patches and very low frequencies of large patches. This relationship has been demonstrated for windthrow in other studies (Boose et al. 1994; Foster & Boose 1992). A trendline fitted to the predicted data set revealed a negative exponential relationship in which the Number of Patches = 116.24*Patch Size$^{-1.3355}$. This trendline was highly correlated to both the predicted and observed patch size distributions (Table 4-4). Using this equation, it was possible to extrapolate the number of patches that would be expected at a given size for a given windthrow event. Therefore, it was possible to estimate the number of patches below one hectare in size (Table 4-5). However, there is likely a lower limit to the patch size that could result from a windthrow event, equal to roughly the canopy size of a mature Douglas fir. For purposes of this study, the minimum patch size that could result from the simulation is 0.5625 hectares due to the spatial resolution of the input data. This distribution indicates that a considerable amount of windthrow likely occurred below the mapping resolution.

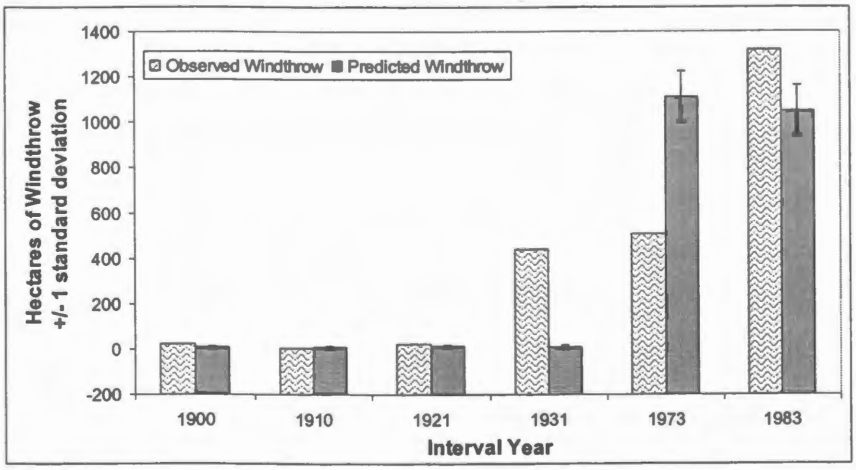

Figure 4-1. Observed and predicted windthrow area for the simulation period (1893-1983).

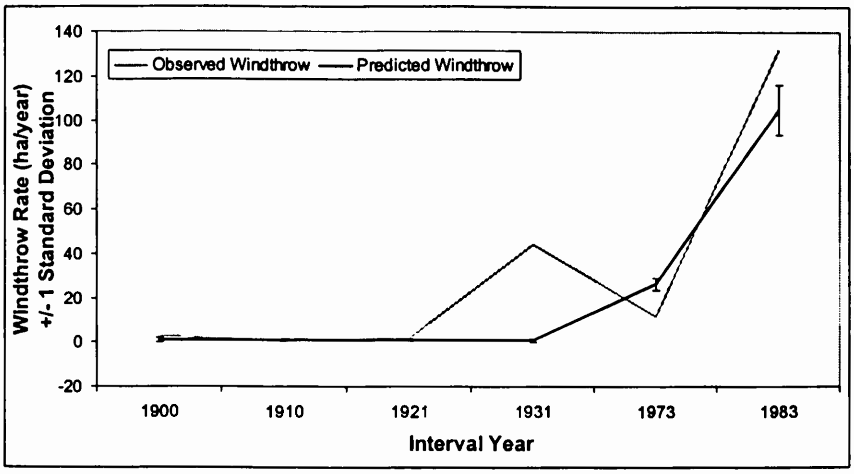

Figure 4-2. Observed and predicted windthrow rate for the simulation period (1893-1983).

Table 4-1. Descriptive statistics of windthrow area for the simulation period (1893-1983).

Interval	Mean Observed Windthrow (ha)	Mean Predicted Windthrow (ha)	Standard Deviation of Predicted Windthrow (ha)
1900	20.81	7.90	5.65
1910	4.50	9.53	4.55
1921	24.75	12.71	5.20
1931	441.56	9.96	6.37
1973	509.63	1110.57	111.45
1983	1319.62	1050.92	112.78

Table 4-2. One factor ANOVA between observed and predicted windthrow area (alpha = 0.01).

Interval	Statistical Significance	Significant Difference
1900	0.038	No
1910	0.294	No
1921	0.036	No
1931	< 0.0001	Yes
1973	< 0.0001	Yes
1983	0.031	No

Table 4-3. Descriptive statistics of windthrow rate for the simulation period (1893-1983).

Interval	Mean Observed Windthrow Rate (ha/year)	Mean Predicted Windthrow Rate (ha/year)	Standard Deviation of Predicted Windthrow Rate (ha/year)
1900	2.97	1.13	0.81
1910	0.45	0.95	0.46
1921	2.25	1.16	0.47
1931	44.16	1.00	0.64
1973	12.13	26.44	2.65
1983	131.96	105.09	11.28

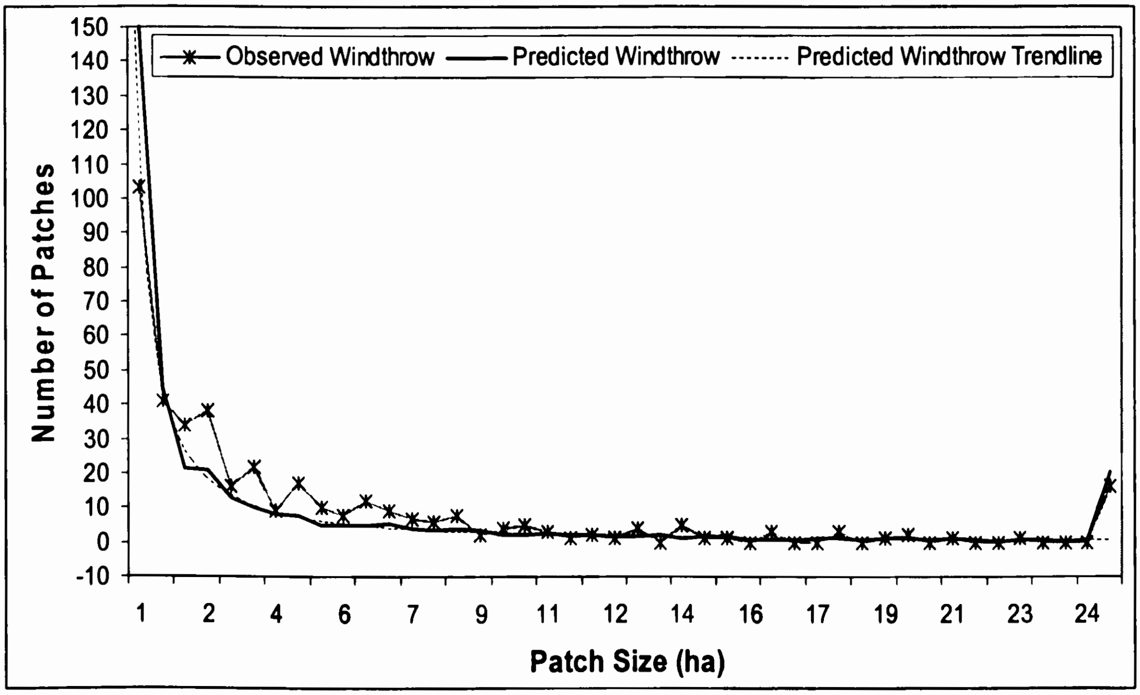

Figure 4-3. Observed and predicted patch size distribution for the simulation period (1893-1983). Predicted windthrow trendline was fitted to predicted windthrow data (Number of Patches = 116.24*Patch Size$^{-1.3355}$).

Table 4-4. Correlation matrix between number of patches and patch size for the simulation period (1893-1983).

	Observed Windthrow	Predicted Windthrow	Trendline
Observed Windthrow	1	-	-
Predicted Windthrow	0.952	1	-
Trendline	0.944	0.973	1

Table 4-5. Number of predicted windthrow patches and additional area for patches one hectare or less in size. Predicted data based on trendline (see text for explanation).

Patch Size (ha)	Predicted Number of Patches	Predicted Additional Area (ha)
1	116	116.00
0.5	293	146.67
0.25	740	185.07
0.1	2517	251.68
0.05	6352	317.58

4.2 Assessment by Aspect

For the Pre-Harvest period, WINDMOD predicted a similar proportion of windthrow on East, Southeast, and South aspects (Figure 4-4). It over-predicted windthrow on Southwest, West, and Northwest aspects, and under-predicted windthrow on North and Northeast aspects. It should be noted that this period was influenced by a sample size effect for predicted data, as only a very small amount of windthrow was predicted by the model. Thus the resultant distribution by aspect was confounded by a high level of variation due to the stochastic nature of the model. Predicted windthrow was most highly correlated with the proportion of the landscape in each aspect, indicating that it occurred somewhat well-dispersed through the landscape (Table 4-6). The distribution of observed windthrow for this period was highly correlated with the distribution of windthrow from the 1931 storm, largely due to its high proportion of area during the Pre-Harvest period. It has already been noted that the model failed to predict windthrow levels similar to what was observed in 1931, so it is not surprising that the model failed to capture the aspect distribution shown by the observed data set.

For 1973, WINDMOD predicted similar proportions of windthrow on East and Southwest aspects (Figure 4-5). However, it over-predicted windthrow on West, Northwest, and Southeast aspects and under-predicted windthrow on North and Northeast aspects. The predicted windthrow distribution by aspect was correlated with the distribution for the entire landscape, indicating that windthrow was reasonably well-distributed throughout the landscape (Table 4-7). It was also correlated with the distribution of pre-1973 clearcuts, indicating a relationship between predicted windthrow and clearcuts. This correlation was similar to the correlation between the observed windthrow distribution and the distribution of pre-1973 clearcuts.

For 1983, WINDMOD predicted similar proportions on East, South, and Northwest aspects (Figure 4-6). It under-predicted windthrow on North and Northeast aspects and over-predicted windthrow on the remaining aspects. The distribution of predicted windthrow by aspect was strongly correlated with the proportion of the landscape in each aspect (Table 4-8). It was also correlated with the distribution of pre-1983 clearcuts. Furthermore, it was more correlated with the observed distribution of windthrow than for either the Pre-Harvest or 1973 periods (Tables 4-6 to 4-8).

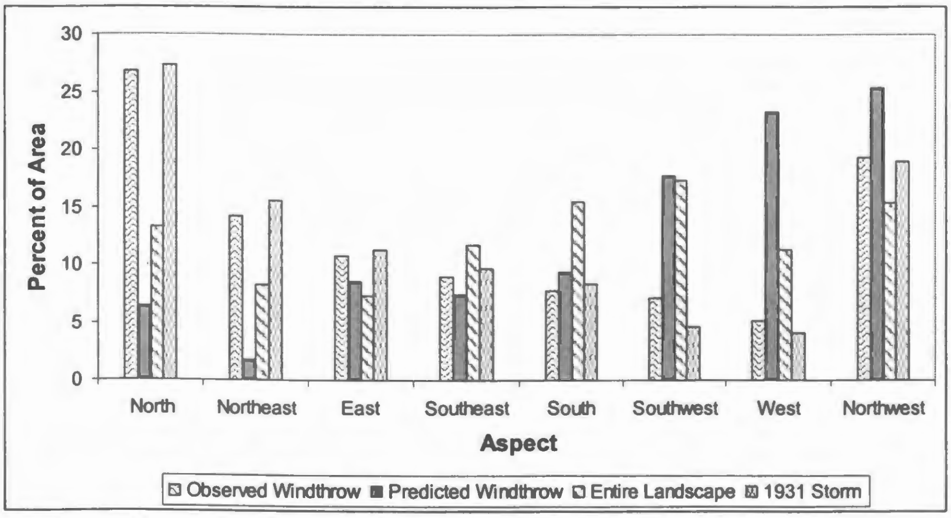

Figure 4-4. Distribution of area by aspect for the Pre-Harvest period (1893-1931). The 1931 storm demonstrates the dominance of this event in observed windthrow distribution for the Pre-Harvest period.

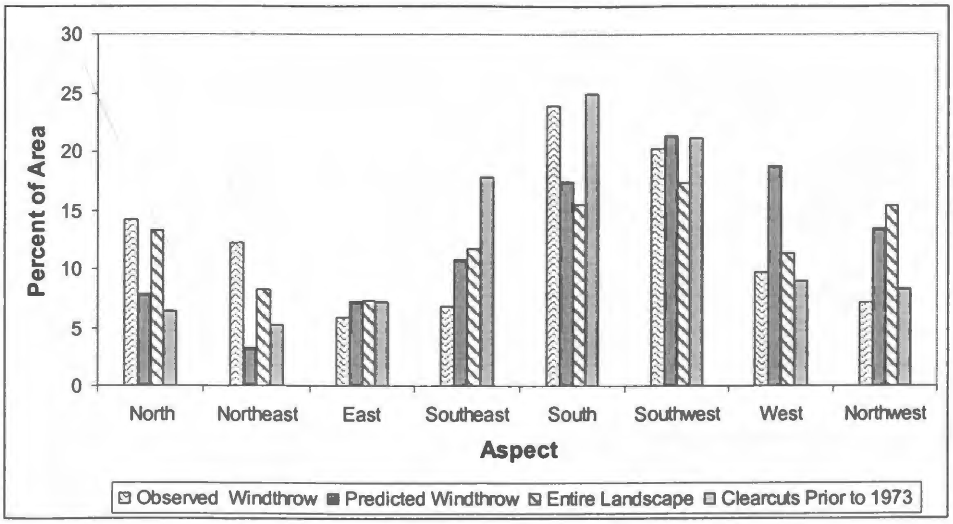

Figure 4-5. Distribution of area by aspect for 1973. Predicted data represent windthrow from 1932-1973.

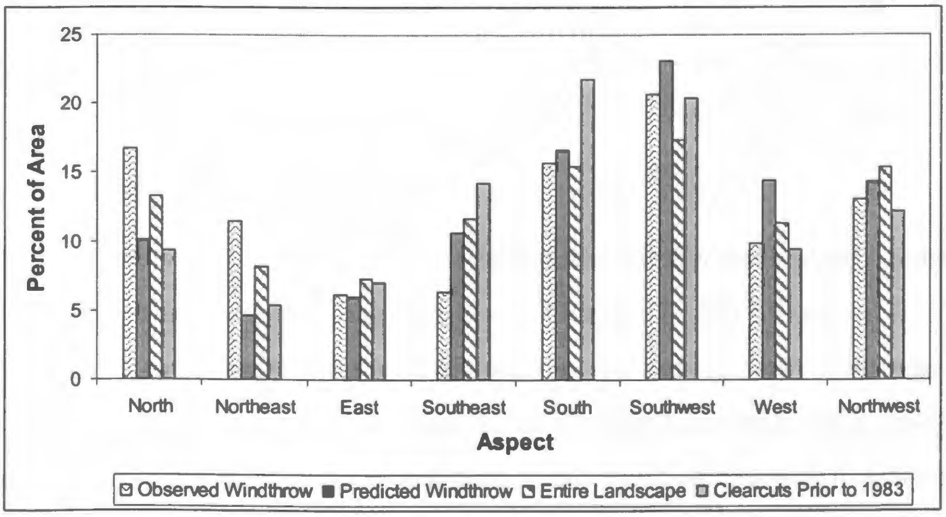

Figure 4-6. Distribution of area by aspect for 1983. Predicted data represent windthrow from 1974-1983.

Table 4-6. Correlation matrix of percent of area in each aspect for the Pre-Harvest period (1893-1931).

	Observed Windthrow	Predicted Windthrow	Entire Landscape	1931 Storm
Observed Windthrow	1	-	-	-
Predicted Windthrow	-0.194	1	-	-
Entire Landscape	0.021	0.500	1	-
1931 Storm	0.989	-0.296	-0.075	1

Table 4-7. Correlation matrix of percent of area in each aspect for 1973. Predicted data represent windthrow 1932-1973.

	Observed Windthrow	Predicted Windthrow	Entire Landscape	Clearcuts Prior to 1973
Observed Windthrow	1	-	-	-
Predicted Windthrow	0.477	1	-	-
Entire Landscape	0.605	0.743	1	-
Clearcuts Prior to 1973	0.674	0.668	0.632	1

Table 4-8. Correlation matrix of percent of area in each aspect for 1983. Predicted data represent windthrow 1974-1983.

	Observed Windthrow	Predicted Windthrow	Entire Landscape	Clearcuts Prior to 1983
Observed Windthrow	1	-	-	-
Predicted Windthrow	0.687	1	-	-
Entire Landscape	0.784	0.897	1	-
Clearcuts Prior to 1983	0.565	0.841	0.826	1

4.3 Spatial Assessment

For the Pre-Harvest period, the model predicted windthrow in small patches distributed throughout the landscape (Figure 4-7(a)). This was highly influenced by the stochastic nature of the model, as clearcut edges were absent from this period. Therefore, windthrow was somewhat randomly distributed throughout the landscape based primarily upon topographic exposure. Due to the low levels of windthrow and their highly stochastic nature, it is not surprising that there were relatively few areas with a high predicted probability of windthrow. Furthermore, spatial intersection between observed and predicted windthrow was very rare due to this fact, generating a low classification accuracy (Table 4-9). Much of the observed windthrow was generated by the 1931 storm, and it has already been noted that the model failed to predict both the levels and the distribution by aspect for this year. However, it should be noted that in the absence of a major controlling factor, such as clearcut edges, it is expected that windthrow would occur in small patches distributed throughout the landscape, as predicted by the patch size distribution (Figure 4-3).

For 1973, there were much higher amounts of predicted windthrow distributed throughout the landscape (Figure 4-7(b)). The high probability class was found most frequently around clearcuts, indicating a response to the presence of clearcut edges during this period. Due to the higher levels of observed and predicted windthrow as well as their relationship to clearcut edges, there are larger areas of spatial intersection between the predicted and observed windthrow. Thus there was a greater classification accuracy for 1973 than for the Pre-Harvest period (Table 4-9). These areas were primarily concentrated in the eastern portion of the landscape. However, it should be noted that the western and northern portions of the landscape were not completely mapped for windthrow, and it is likely that a significant amount of windthrow in these regions was undetected (Sinton 1996). Thus the predicted windthrow for this period could represent areas in which windthrow did occur, but was not detected by the mapping study. Excluding these regions from the analysis, it appears that predicted and observed windthrow fell within the similar subregions of the landscape.

For 1983, there were increasing areas of spatial intersection between observed and predicted windthrow (Figure 4-7(c)). This period demonstrated the highest classification accuracy of the periods simulated by the model (Table 4-9). In this period as in 1973, there was a close relationship between predicted windthrow and clearcut edges, as the highest probability class was found most frequently around clearcuts. Due to this sensitivity to clearcut edges, the model predicted windthrow within similar subregions of the landscape compared to the observed windthrow.

Table 4-9. Classification accuracy of WINDMOD for the simulation period (1893-1983).

Interval	Percent of Observed Windthrow Area Predicted by WINDMOD
Pre-Harvest	1.26
1973	29.25
1983	43.73

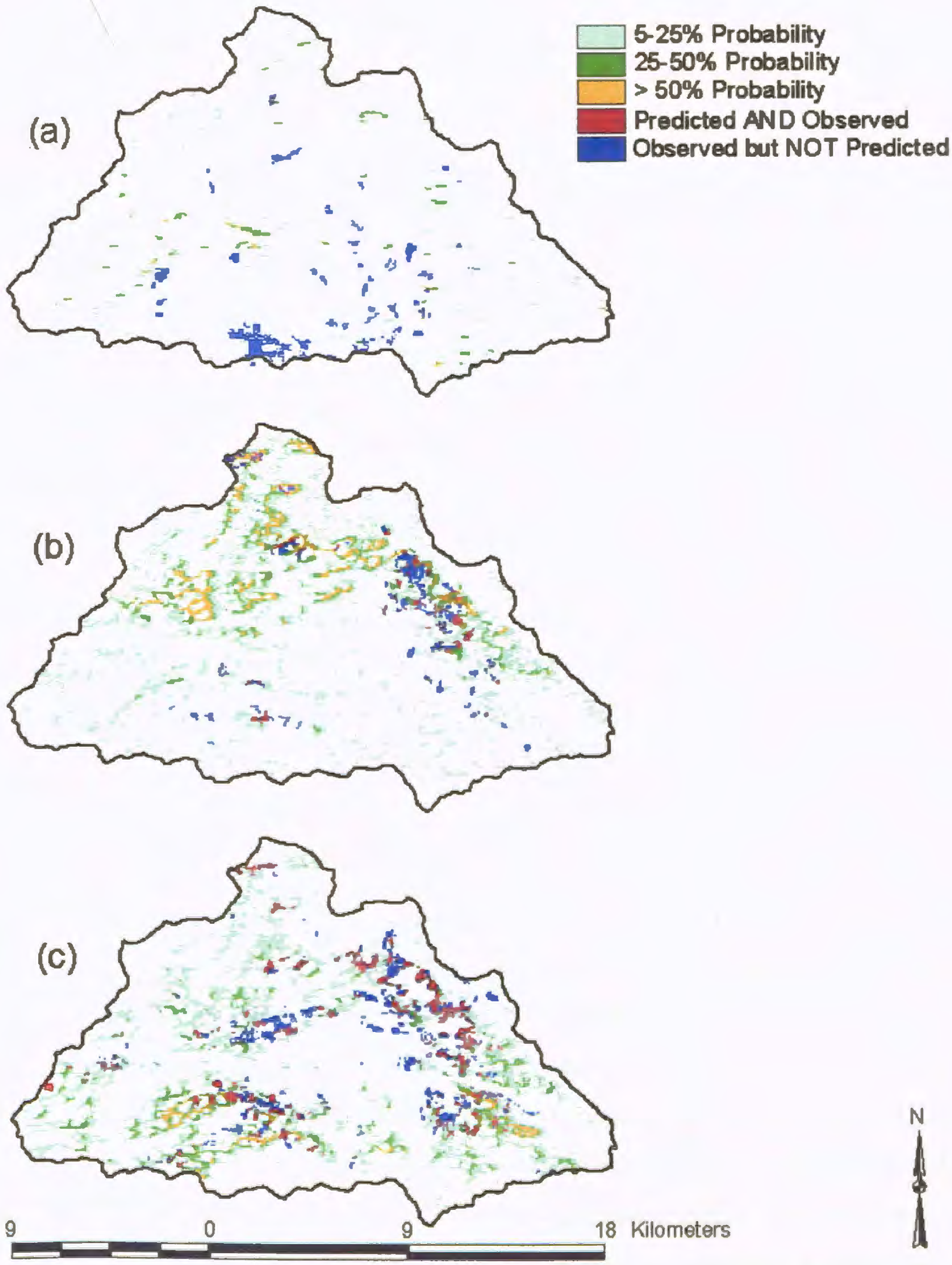

Figure 4-7. Observed and predicted windthrow maps, showing predicted windthrow by probability class, intersection between observed and predicted windthrow, and observed windthrow that did not intersect with predicted windthrow. (a) Pre-Harvest period (1893-1931). (b) 1973 storm and predicted windthrow 1932-1973. (c) 1983 storm and predicted windthrow 1974-1983.

5. Discussion

5.1 Model Assessment

WINDMOD reasonably predicted windthrow for most intervals within the simulation period. It failed to capture the levels and spatial characteristics of the windthrow that resulted from the storm of 1931. The most likely explanation for this failure is the continuous manner in which the model generates windthrow within the simulation. Windthrow is generated continuously and aggregated to form a discrete windthrow map for a period, but it does not represent a single storm event within the landscape. Thus the 1931 period most clearly demonstrates the errors in simulating an infrequent event, such as a large storm, by continuously predicting small amounts of windthrow and later aggregating them into larger patches. A real storm represents an event that could affect large areas simultaneously with a given mean return interval. However, the absence of sufficient windthrow data for extended periods of time prior to timber harvest prevents a more thorough analysis of the 1931 storm.

For most of the other Pre-Harvest intervals, WINDMOD captured the low quantities of windthrow but failed to accurately predict the spatial location of that windthrow. However, at low levels of windthrow and in the absence of a major controlling factor, it is expected that windthrow would be distributed throughout the landscape in small patches. Much of the spatial and quantitative variability of windthrow prior to 1931 was affected by the mapping resolution for this period as well as the ability to detect windthrow patches many decades after they occurred. For the Pre-Harvest period, windthrow patches were only detected if they were greater than two hectares in size. Because of this, the predicted windthrow maps were screened to remove all patches below two hectares, thus removing a considerable amount of predicted windthrow from the analysis. If the patch size distribution holds true for this period, it is expected that many more patches of windthrow would occur below two hectares in size than would occur above this size. This trend was observed in the predicted data through a comparison of the total windthrow maps with the screened maps. Therefore, it is likely that there were many actual windthrow patches distributed throughout the landscape which were not detected by the mapping study, thus causing an under-estimation of observed windthrow. The ability to detect historical windthrow decreases with time since the disturbance, further decreasing the likelihood of detecting windthrow for this period (Sinton 1996). Although the model failed to predict the spatial location of windthrow within the landscape, it is likely representative of the windthrow that could occur in the landscape prior to timber harvest. Insufficient observed windthrow data prevents a more rigorous analysis for this period.

For 1973, the model over-predicted the levels of windthrow but reasonably predicted the spatial distribution. Although the model fit was relatively poor, it did capture the general trends of windthrow location within the landscape. This period is a prime representative of the problems encountered when comparing continuous disturbance data to a discrete windthrow event. The model produced forty-two years of data, whereas the observed windthrow was only for the storm of 1973. Thus the model would be expected to over-predict windthrow when compared to a single event, especially considering the amount of timber harvest that occurred prior to 1973. Furthermore, this period likely represents an under-estimation of observed windthrow due to incomplete mapping of the study area. Therefore, it is likely that the model reasonably approximated the levels and spatial distribution of windthrow for the period between 1932 and 1973, even though a significant portion of this windthrow might not have been mapped.

For 1983, WINDMOD reasonably predicted both the levels and spatial distribution of windthrow within the landscape. This is partly due to the high correlation between both the observed and predicted windthrow and the location of clearcuts. This period clearly demonstrates the sensitivity of the model to increased levels of clearcut edge, though this sensitivity was apparently less than for the process of windthrow within the landscape. Although the classification accuracy of the model for this period is not high, it is reasonable considering the stochastic nature of both the model and the process of windthrow. Furthermore, WINDMOD predicted windthrow in similar locations of the landscape to where it was observed, thus suggesting that it was responding to similar factors as the actual process.

In the absence of major windthrow-producing storms or incongruities in the intervals used to compare windthrow, WINDMOD reasonably captured the overall trends of windthrow within the landscape. It encapsulated the temporal variability of windthrow for the simulation period, demonstrating a dramatic increase for the post-harvest periods. It also showed increasing accuracy with increasing time, signifying a similarity between observed and predicted windthrow with respect to increasing levels of clearcut edge.

5.2 Implications of Modeling Approach

The model invites numerous simulation scenarios within the study area. To further assess the accuracy of the model, it could simulate windthrow up to the present day. This predicted windthrow could then be assessed using remotely sensed data to determine the intersection between predicted and observed windthrow within the landscape. The model could also be used to examine the influence of historical management regimes. For example, salvage logging was conducted after the 1973 and 1983 storms, creating additional clearcuts (Sinton 2000). It would be possible to compare the resultant windthrow if no salvaging operations were undertaken to the levels that actually occurred.

WINDMOD could also be used to study the temporal dynamics of windthrow in the study area over greater temporal extents. It could be used to reconstruct historical levels of windthrow prior to 1900, dating back hundreds of years. This would allow researchers to incorporate the influence of windthrow into reconstructions of historical vegetation structure. It could simulate windthrow into the future, demonstrating windthrow dynamics as the existing clearcuts mature. This would allow natural resource managers to estimate the areas of high windthrow probability and plan management regimes accordingly. Although WINDMOD is unable to predict windthrow with a high spatial accuracy, it does provide a general guideline of where and how much windthrow will occur for a given time period. Because it does not rely on a return interval, it allows managers and researchers to specify a windthrow interval in which it will estimate the cumulative windthrow. While this approach does not fully capture the characteristics of rare storm events, it does reduce the overall predictive variability compared to highly stochastic models based on storm return intervals.

The model could be applied to other landscapes within the Pacific Northwest, although some calibration would be necessary. This would allow researchers to investigate the temporal and spatial dynamics of windthrow in areas where it has not been empirically studied. Such study could be especially useful for analyzing different future management scenarios on the resultant levels of windthrow. It could also help determine the spatial location of areas with a high probability of windthrow, to be used in planning future timber harvest or other management operations.

WINDMOD can also be merged with other landscape process models to investigate interactions between processes and emergent behavior. For example, it could be combined with simple models of fire and bark-beetle outbreaks to simulate landscape-level disturbances over large temporal and spatial extents. In such a way, it would be possible to observe the feedback mechanisms that exist between these interacting processes to reach a better understanding of their dynamics in real landscapes. This combined model could simulate landscape processes in a more realistic fashion than simulating each process separately, because in real landscapes no process exists exclusive of other processes. It is the interaction between processes, patterns, and time that generates the unique patterns that we observe in real landscapes. Furthermore, such a model could aid in understanding the suite of initial conditions that result in unexpected and catastrophic events.

5.3 Conclusion

This study demonstrated that it is possible to simulate windthrow using a simple rule-based model. A key feature of WINDMOD is its simplicity. It requires input data that is relatively easy to obtain. It utilizes a suite of simple calculations, facilitating fine-tuning. It is also general enough to apply to other landscapes, thereby facilitating a greater understanding of the process of windthrow in forested landscapes of the Pacific Northwest.

Simple rule-based models have considerable potential for understanding complex large-scale processes. Frequently, a few key factors control much of the spatial, temporal, and quantitative variation for a given process. For this model, clearcut edges were a controlling factor that determined much of the variation of windthrow for the study area. Similar relationships likely exist for other landscape processes. Although this simplicity prevents a high degree of predictive accuracy, it does allow for the observation of general trends that reasonably approximate the action of the real process. This simplicity also dramatically reduces the input data, calculations, and processing time required for the model. In such a way, it is possible to develop a suite of simple rule-based models for a landscape or region based on a general understanding of the process. Calibration of these models would help identify the controlling factors of the process for a given landscape, further refining the scientific understanding of landscape processes and their interactions with landscape patterns.

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