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WIND DAMAGE IN MAINE FORESTS: TRENDS AND VULNERABILITY ASSESSMENT

By

Thomas Perry

B.S. Humboldt State University, 2003

A THESIS

Submitted in Partial Fulfillment of the
Requirements for the Degree of
Master of Science
(in Forestry)

The Graduate School
The University of Maine
December, 2006

Advisory Committee:

Dr. Jeremy Wilson, Associate Professor of Forest Resources, Advisor

Dr. Steve Sader, Professor of Forest Resources

Dr. Al White, Professor of Forest Ecology

WIND DAMAGE IN MAINE FORESTS:
TRENDS AND VULNERABILITY
ASSESSMENT

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Thesis Advisor: Dr. Jeremy Wilson

An Abstract of the Thesis Submitted
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The likelihood of windthrow or windsnap occurring in a forest stand includes numerous factors; however, past research suggests that these factors can be grouped into four broad categories: regional climate, topographic exposure, soil properties and stand characteristics (Mitchell, 1995). Of the three categories, stand characteristics are most commonly and easily modified through forest management. Vulnerability to wind damage in Maine may increase in the future because of three trends influencing stand conditions. One, Maine forests contain a considerable amount of balsam fir and red spruce, tree species that are considered particularly susceptible to wind damage. Two, extensive areas regenerated after the 1970's and 1980's era spruce budworm outbreak are maturing. Three, partial removals currently account for over 74 percent of the area harvested annually in the state (McWilliams et al. 2005).

Two approaches to augment our understanding of the interaction between forest management and wind damage vulnerability in Maine forests were developed.

The first approach combined information from the base of scientific wind disturbance literature with more localized information from Maine's forest resource managers. Forest resource professionals were surveyed through phone calls and professional meetings to gather information about wind damage over their careers. The second approach developed a general vulnerability to wind damage model that reflects topographic exposure (distance limited TOPEX (Ruel et al. 1997), restricted rooting depth, elevation, and stand characteristics (height, density, edge, treatment history, and species composition).

Results of the first approach reveal serious limitations in information about wind damage statewide. However, numerous patterns and trends were identified. Damage differs by storm type and storms impact the state on a continuum of storm intensity, frequency, and scale. Numerous factors influence the damage potential of these wind events on forests. These factors include topographic exposure, soil conditions and stand characteristics. Damaging storms appear to originate from the southwest most frequently and impact softwoods more severely than hardwoods. Frequent low-intensity winds tend to eliminate softwoods from hardwood dominated stands.

The general vulnerability to wind damage model is based on Mitchell's (1998) conceptual windthrow triangle and is built from eight component variables describing stand, soil, and topographic characteristics. The model is built and calibrated from composite variables which combine the component variables into distinct site and stand components. The model was tested on a 40,800 hectare forest area in northern Maine with spatially explicit wind damage records. To avoid problems with spatial autocorrelation ten random samples were drawn from the study area and evaluated individually with a Mann-Whitney non-parametric comparison of means test (alpha 0.05). Results from the ten samples were pooled, and a one sample comparison of means t-test was used to analyze the consistency of the results from the ten individual samples (alpha 0.05).

The final model identifies significant and consistent differences between damaged and undamaged areas (p-value 0.000). When evaluated individually, not all model components were significantly different (e.g., density, edge, exposure and species composition). Variables describing thinning, stand height, and elevation had the greatest differences between means of the populations of damaged and undamaged stands in the study area. The general model developed proved useful on the study area and by design should be transferable to diverse regions throughout the state.

ACKNOWLEDGEMENTS

First, and foremost, I would like to thank Dr. Jeremy Wilson for all his help, both with the project and as a mentor in general. I cannot say enough about my experience working with him; and, my completion of this thesis would not have been possible without his help and support. I would also like to thank my committee members, Dr. Steve Sader and Dr. Al White, for their insights and direction. I wish to acknowledge the Windthrow Research Group of the University of British Columbia and Dr. Jean Claude Ruel, University Laval, for providing versions of the exposure modeling software. I would also like to thank the forest managers of Maine for their interest and willingness to help with this project. Finally, it is my pleasure to thank the friends I have made here, who all have made this experience wonderfully memorable.

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Introduction:

Wind influences all of the world's forests. It may cause damage to individual trees, remove whole trees from stands or destroy stands entirely. Damage trends and patterns from wind disturbance rely on the interaction of many complex factors. Differences in storm type, season, landscape position, forest type, and differing stand conditions within the same forest type are examples of factors that will influence the damage resulting from wind disturbance. The pervasive nature of this disturbance makes it a universal concern for forest managers. Potential loss to wind damage is a risk inherent to the management of all forests. Vulnerability to wind damage in Maine may increase in the future because of three trends currently influencing stand conditions. One, Maine forests contain a considerable amount of balsam fir and red spruce, tree species that are considered particularly susceptible to wind damage. Two, extensive areas regenerated after the 1970's and 1980's era spruce budworm outbreak are maturing. Three, partial removals currently account for over 74 percent of the area harvested annually in the state (McWilliams et al. 2005).

Given these trends, and the importance of forest industry to Maine's economy, study of this topic is warranted. Little work has been done exploring wind damage in Maine's managed forests. This thesis should help to fill a void in Maine's forest research.

The thesis has two distinct chapters. The first chapter examines critical wind damage factors in the scientific literature and matches these phenomena with examples of local damage trends. By surveying resource managers in the state, decades of information about storms and their subsequent damage are recorded. The chapter considers the potential interactions between these factors and across spatial scales.

The second chapter builds and evaluates a risk assessment index model within a GIS framework. The model is based on variables identified in the first chapter and is calibrated with information from the literature and resource manager surveys. A comparison of means analysis indicates that the model identifies significant difference between damaged and undamaged areas. The potential value this type of general modeling may have for resource managers trying to minimize crop tree loss under changing landscape conditions is discussed.

1.1 Chapter One Introduction:

Wind is a complex disturbance agent that impacts all of the world's forests. The influences of wind on forest development and change are complex and incorporate factors across both temporal and spatial scales. Wind may be considered the dominant abiotic disturbance agent in forest types with an extended fire return interval, and many of Maine's forests fit this description.

Extensive blowdown in Maine has been described after wind events during the late 18th, 19th, and 20th centuries. Boose et. al. (2001) reported eight hurricanes with wind speeds in excess of 112 mph making landfall in New England since European settlement (1620). Five of these storms tracked through the state of Maine, the storm tracks were not identical and impacted different areas. Timber loss from this type of occurrence can be astronomical depending on the landscape condition, as evidenced by the devastating 2005 hurricane season. Preliminary estimates of the combined damage of hurricanes Katrina and Rita to southern forests are sobering: 15-19 billion of board feet of predominantly softwood timber down or damaged, affecting over five million acres of the forest land base in Alabama, Louisiana and Mississippi (Bosworth, 2005).

Chronic more localized and often less intense events impact forests throughout the northeastern United States on a yearly basis. Although these events are less dramatic than hurricanes, this endemic damage can aggregate to substantial losses to the resource base. In fact, managers from three large Maine forest landholdings acknowledge having year-round harvest crews solely dedicated to salvage logging following tree damage and mortality caused by these less intense but frequent storms (confidential personal communications, 2005). In these events, wind speeds are relatively mild; as a result the vulnerability of stands plays a more critical role in determining the probability of damage.

Over the past two decades dramatic shifts in harvesting practices have occurred in Maine (MFS, 1997-2004). Clearcutting, used extensively during and after the latest spruce budworm infestation, which occurred from the early 1970's to the mid 1980's, has declined while partial harvesting has increased dramatically (Figure 1.1). Forest policy changes have instituted constrictive regulations on clearcut size, and partial harvesting (including shelterwood cuts) has become the industry standard harvesting technique, accounting for 94.7% of the state's silvicultural activities in 2004 (MFS, 2005). As a result of this change in harvesting, the total land area harvested has doubled since 1988 to maintain relatively consistent levels of volume removed. Considerably less wood per acre is removed under the partial harvesting regime. This trend in harvesting patterns has the potential to result in a landscape increasingly susceptible to wind damage.

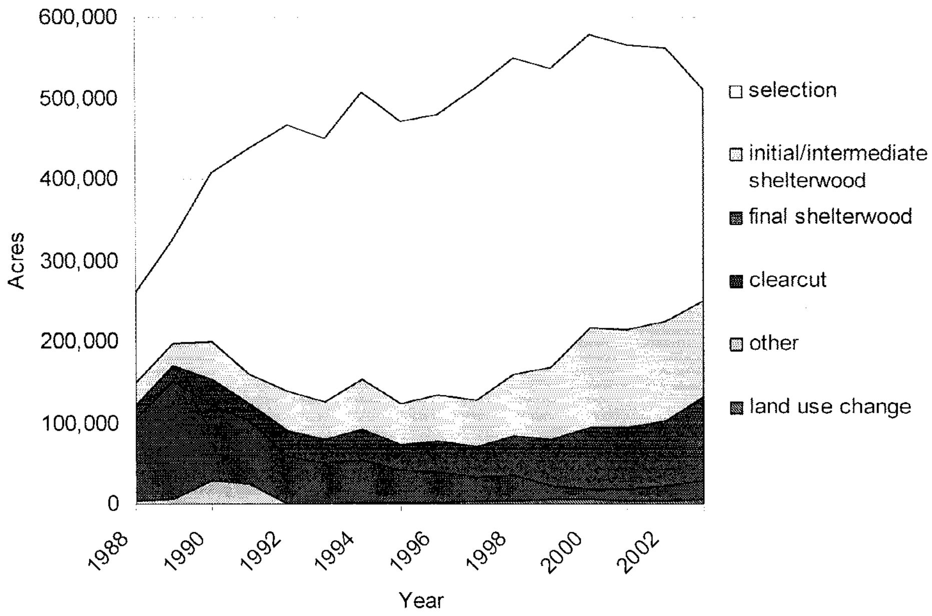


Figure 1.1: Use of different harvest techniques in Maine forests (MFS 1997-2004). With the exception of clearcutting, the remaining silvicultural prescriptions identified in the figure should be interpreted generally, viewed more as harvest practices, as opposed to following traditional silvicultural treatments.

There is a void in research and literature regarding wind damage in Maine's forests. An era of diameter limit cutting, 1920s-1960s, systematically removed the most windfirm trees from resident stands (Seymour, 1992; Sokol et al., 2004), led to a widespread increase in windthrow damage potential. This contributed to the general perception that Maine's dominant commercial species (spruce and fir) are vulnerable to wind damage. Currently little is known about the extent of both catastrophic and endemic wind damage in Maine; trends in wind damage patterns have not been evaluated. The contribution of wind disturbance to non-timber values in Maine's forests has not been quantified. Implications of current harvesting techniques on future vulnerability to wind damage have not been assessed.

The goal of this chapter is to combine information from the scientific wind disturbance literature with more localized information from Maine's forest resource managers in an attempt to further our understanding of this complex disturbance, and to fill some of these gaps in the knowledge base. Specifically, the chapter reviews literature on types of wind damage impacting Maine forests and provides examples from the collective memory of managers and institutional records of large land owners in the state. Site and stand factors, including silvicultural treatments, considered important to wind damage are critically examined. Wind disturbance is also examined at two spatial scales, the stand scale and the landscape scale. The discussion of scale addresses the high degree of variability inherent to the interaction of the complex factors associated with wind damage.

1.2 Methods:

Initial data collection for the project began in the spring of 2005. Contact letters were sent out to representatives of private industrial and non-industrial landowners, state forest management agencies, and non-profit groups involved in forest management as the initial step in a focused survey of resource professionals. The primary goal of the land manager surveys was to begin a cursory analysis of the patterns and variations in wind disturbance events in the northern portion of the state (chapter one), and to use this information to develop a general model assessing the vulnerability of stands to future wind damage (chapter two). Isolating potential trends in frequency, location, and structural conditions of disturbed stands was also a goal of the study. A detailed literature review was conducted to augment and evaluate information obtained through the survey process. The litereature review utilized several literature databases: Agricola, CABdirect Forestry abstracts, Ecology Abstracts, JSTOR, and Web of Science were all queried through the University of Maine's Fogler Library.

Resource professionals with experience throughout Maine were interviewed about both catastrophic and chronic wind damage encountered in the field or through professional interactions over the past fifty years. Surveys involved preliminary screening for contribution potential with a letter and then follow up phone calls and professional meetings. Queries of forest resource professionals focused on date, extent and location of significant blowdown events and estimates of chronic wind disturbance encountered on company or agency lands. Records documenting wind damage event location and repeated patterns or regional hotspots of blowdown activity were pursued. Questions about these events focused on a few key variables of interest including soil depth and drainage, stand history, and topography and exposure. Essentially any information surrounding the "what, where and when" of significant blowdown events was considered of value to the study.

Surveys also investigated the potential existence of data or information regarding wind damage and specific company's management practices in an attempt to quantify winds impact in the state. For example, the amount of annual harvest attributed to blowdown, the size of blowdown required to trigger a salvage operation in an unroaded area, recording of blowdown in cruises or active monitoring with aerial surveys are all practices that could vary between managers and provide valuable clues to the nature of this disturbance in Maine's forests. Questions were oriented towards establishing patterns and commonalities between reported observations. Queries about susceptible stand characteristics or site conditions were asked consistently. Several field visits were conducted and focused on recent storm events and areas considered significant by the surveyed professionals. Specific locations and company references are not provided in this chapter as a condition of confidentiality for the participants.

The original contact list was generated from membership lists for the Society of American Foresters and contacts recommended by faculty at the University of Maine, School of Forest Resources. Contacts were initially made with managers and upper level administrators requesting further contact recommendations for regional foresters and land managers. Retired forest professionals, and managers employed prior to recent ownership changes were also contacted to cover as long of a time period in the institutional and personnel memory bank as possible. Fifty-five individuals, representing sixteen private landowners and three state agencies, were contacted, The number of actively engaged respondents was reduced to thirty-six following preliminary screening.

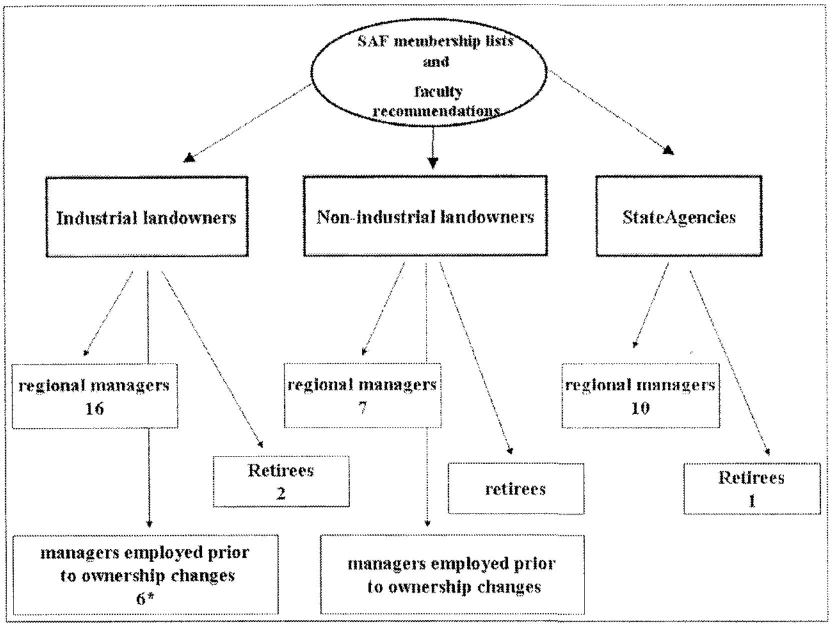


Figure 1.2: Survey Contact Network Pathway. Numbers indicate the number of actively engaged participants in each category. The six managers surveyed in the "industrial landowner – prior to ownership change" category are also included in the "industrial landowners - regional managers" category if they are still employed.

1.3 Results:

1.3.1 Damage Types:

Wind has the capacity to damage individual trees in several ways. Subtle damage in the form of wind stress (a reduction in tree vigor from wind induced crown or root damage) is common on windy sites. However, this type of subtle wind damage may not contribute as significantly to forest development and change as more intense wind damage in the forms of windthrow and windsnap. This type of damage may be a primary catalyst for forest development in Maine. For this paper, windthrow is defined as the blowing over of the entire tree with the root wad, while windsnap is defined as wind breakage of the main tree stem at some point above the ground surface. Understanding how wind disturbance occurs and its effects on the forest are crucial to understanding a large part of the dynamics of Maine's spruce fir forest.

Windthrow can also be differentiated by the manner in which the wind throws or snaps the tree. Static windthrow occurs when a gust of wind has sufficient strength and duration to push the tree over. Dynamic windthrow occurs when wind gusts induce stem sway, if the gusts of wind are synchronous with the stem sway, the sway will increase until the tree blows over (Smith and Watts, 1987). Dynamic windthrow is caused by turbulence, which can be generated from winds with dramatically slower peak wind speeds than those needed for static wind throw; subsequently, this type of windthrow is the most common in gap-forming windthrow events. Static windthrow is fairly uncommon, requiring immense wind speeds; it is therefore restricted to more extreme events (Blackburn et. al., 1988). Static windthrow and the extreme events which facilitate it often result in large areas of blowdown. This type of catastrophic disturbance is often stand replacing, and occurs less frequently than lower wind speed driven dynamic windthrow in Maine's forests.

Mitchell (1998) classifies damaging winds in two categories, catastrophic winds and endemic winds. Catastrophic winds are very high speed winds with infrequent or long return periods, the damage from these storms has a higher proportion of windsnap than windthrow. Endemic winds, by contrast, are peak winds with a relatively frequent and short return interval. Endemic wind damage is characterized by a higher proportion of stems windthrown than windsnapped. The frequency of these endemic winds allows for the prediction of future damage in all forests and mitigation of future damage in managed stands.

This dichotomous classification of wind events seems limiting in Maine. Managers reported numerous types of wind events impacting the forests of Maine along gradients of both frequency and intensity (Figure 1.3 and Table 1.1). Catastrophic winds impacting large acres of land are relatively infrequent. As mentioned earlier, Boose et al. (2001) depicts five hurricanes with winds in excess of 112 mph tracking through Maine since 1620. Powerful region wide storms are differentiated from hurricanes and occur more frequently with less intense canopy disturbance. Catastrophic damage from convective straight line winds and downbursts also affect the forests of Maine on an annual basis. Larger storms of this type occur less frequently than smaller storms but records of their occurrence were collected from several landowners.

Table 1.1 should be considered an incomplete record of more memorable wind events, a sample of storm types that have impacted the state. Many wind events are not recorded for a number of factors. Timber cruises performed by interviewed companies do not actively record blowdown. Cruises are generally limited to prism sweeps and tallies of merchantable timber only. This means locating wind damaged areas depends on the event occurring near a road, in areas being harvested or adjacent to these areas. Occasionally aerial surveys may be conducted as part of a companies overall management strategy. These aerial surveys have the potential to lead to blowdown salvage operations.

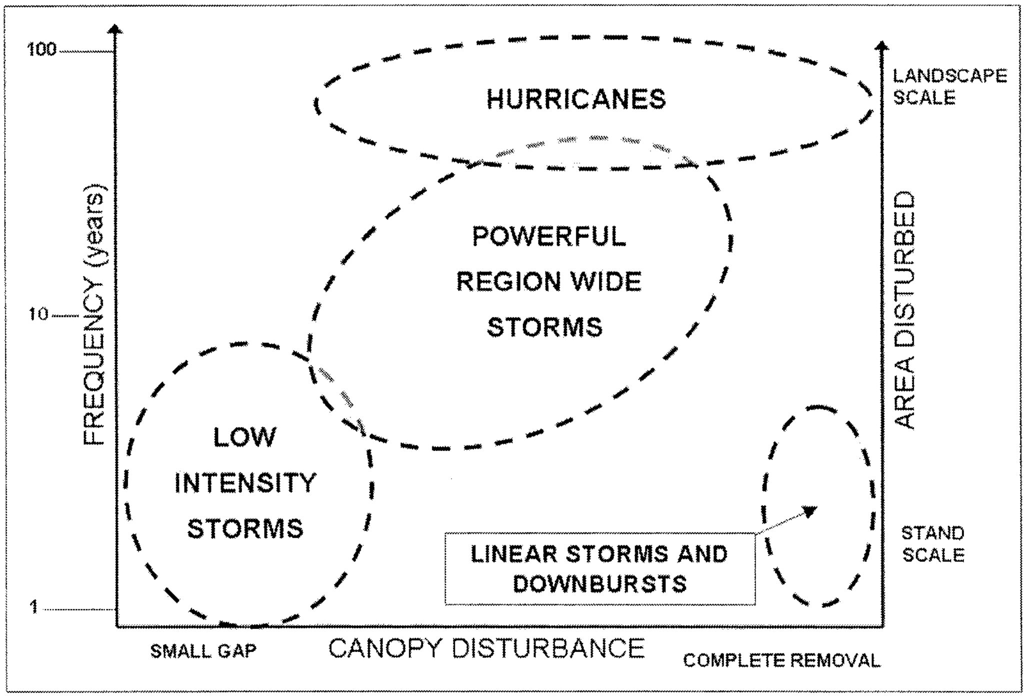


Figure 1.3: A Continuum of the Storm Types Affecting Maine Forests and Their Damage Patterns. Storm types impacts Maine forests along gradients of frequency, intensity, and spatial scale.

Table 1.1: Record of Specific Events Damaging Maine Forests. This record is built from interviews with managers from eight distinct ownerships. Wind types: SW, sustained wind; SW-HURR, hurricane; CSL, convective straight-line winds; DB, convective downbursts. This table exemplifies the limited information available surrounding wind damage in Maine's managed forests.

year	date	windtype	general location	acres	volume
1953		CSL	Allagash Watershed		
1955		CSL	Round Pond		
1964		CSL	Eagle Lake		
1965		CSL	5-Finger Brook, Allagash Watershed		
1966		CSL	Eagle Lake		
1972		SW	T11 R9		2,500 cords
1973	Fall	CSL	T13 R5		
1974		SW	T2 R10	80	
1975		CSL	T12 R6		
1976		SW	Sebago Lake		
1978		CSL	T9 R8 to T9 R7		25,000 cords
1979	6-Oct	SW			8mmbf
1980	25-Oct	SW	T8 R12	6000	
1985		CSL	Telos Area		
1987		CSL	T10 R15		
1991	16-Aug	SW-HURR			
1995	31-Oct	CDB	Ross Lake to Long Lake		1,000,000 cords
1995	31-Oct	CDB	T4 R11		
1995	31-Oct	CDB	T8 R10		
1995	31-Oct	CDB	T8 R9		
1995	31-Oct	CDB	T10 R8		
1995		CSL	T10 R8		
1997		SW	T7 R10		
1998		SW	T11 R16		
1999	5-Jul	CDB	Long A Township		
2001	Nov	SW	T4 Indian Purchase		15 cords per acre
2002	Feb	SW	T13 R8		
2003		SW	T13 R8		
2003	Nov	SW	Telos Area		
2003	Dec	SW	T4 R11		
2004	Aug	CSL	T4 R12		
2005	25-Jun	CDB	Lincoln to Mattawamkeag		1000 cords
2005	2-Aug	CDB	Myra Corner	20	

1.3.2 Damage Records:

1.3.2.1 Linear storms and downbursts:

Managers consistently cited several storm types as common damaging agents to the forest resource. Tornado like linear events, identified by the random and twisted array of blown over stems and straight line events equivalent to small scale derechos with stems laid down in one direction have been recorded throughout the Maine forest land base. Downbursts, when wind plunges straight down into a stand, can also be associated with these catastrophic events, resulting in stems laid out radially from the center of the disturbed area. Damage from convective storm cells, these stand replacing events are documented across six ownerships around Portage Lake, the Allagash watershed, throughout Aroostook County and in areas of western Maine. The July fourth 1999 storm systems that struck Minnesota and the Boundary Waters Canoe Area reached Maine on July fifth, and caused intense damage in the western mountains of the state. In the memory of one survey respondent all the linear damage he encountered after this storm stopped after reaching the shores of large lakes. Another respondent feels this type of damage has been occurring more often in the last five years than the previous two decades. In general this respondent feels gusts associated with other storm types have become stronger and more sustained recently as well.

During the 2005 summer field season a convective system producing microbursts with estimated wind speeds between eighty and ninety miles per hour tracked from Olamon (Greenbush Township) to Myra (T32MD) on the 2nd of August. Damage from this storm was patchy and intense. Significant damage to a stand of white pine occurred along the Studmill Road at Myra Corner. The stand, originating in 1940 and thinned from below in 2003, was decimated (Figure 1.4).

Figure 1.4: Damage to a Pine Stand from a Convective Storm on August 2nd 2005 in T32MD. Downbursts produced patchy but intense disturbance, destroying the majority of this white pine stand.

A similar series of organized storms impacted Northern Penobscot County on the 25th of June 2005. Again, damage was severe but sporadic, and was reported from East Millinocket to Mattawamkeag. The patchy nature of these disturbances does not diminish their potential impact to the landscape. A similar storm, the October 31st 1995 Beetle Mountain Blowdown, caused over 3,200 acres of catastrophic damage based on Maine Forest Service aerial surveys.

1.3.2.2 Region-wide windstorms:

Windstorms impacting large contiguous areas are also prominent in the industrial wind disturbance record. These large storms often have varying intensities of damage potentially from variations in site and stand conditions across the damaged landscape. For example 60,000 acres were damaged in December of 1983 when a snow storm was followed with strong winds. Damage estimated for this event suggests ten percent of the stems were lost throughout the entire area. Frequently, events of this magnitude happen in the late fall and early spring when soils are often saturated and strong fronts move through the region. Depending on the depth of frozen soil, this period of heightened susceptibility attributed to soil saturation may extend from fall through spring.

1.3.2.3 Hurricanes:

Hurricanes have affected the forests of Maine, although not as frequently as other coastal states. Hurricanes can still cause extensive forest damage even if they do not make landfall or track directly into Maine's forest production region. Managers cite Hurricanes Carol, Edna, Hazel, and Bob as storms that caused considerable damage in Maine. The impact of this type of storm is similar to the sustained wind events described earlier. However, hurricanes tend to impact a larger area at one time. Wind speed dictates the degree of canopy removal. Winds from Hurricane Bob were responsible for the loss of over 1,000,000 cords of wood across one ownership. This storm occurred on August 16th 1991; aspen and the more dominant crown classes of pine on the ownership suffered the most damage.

1.3.2.4 Low intensity storms (endemic damage):

The first complete sample of Maine under the new FIA protocol (1999-2003) found seven plots coded as wind damaged. This number of plots represents 41,466 acres of timberland, of a potential 16.9 million acres of forested timberland. This provides a very low estimate of the amount of timberland affected by wind, suggesting that less than 0.05 percent of the state's timberland is damaged annually. To be recorded under this protocol damaged areas must be greater than one acre in size and twenty-five percent or more of the stand must have been damaged (snapped or thrown) (Laustsen, 2006). It is not clear how long a period of windthrow damage these FIA assessments are picking up. Furthermore, any salvage operations in the stand prior to re-measurement would make it difficult to detect wind damage.

The recent shift to partial harvesting in Maine has brought changes to post-harvest wind damage patterns. Managers have stated that blowdown in residual stands following partial harvests is higher than the blowdown experienced along edges of clearcut blocks. This phenomenon is exemplified by a storm that occurred on October 6th 1979. The storm impacted stands that had been salvaged from spruce budworm damage in western Aroostook County. Mature spruce trees greater than twelve inches in diameter were left standing. Virtually all the residual spruce was lost resulting in eight million board feet being salvaged. In some areas such as the Telos region, which is considered a "hotspot" for blowdown activity, managers are pushing for a shift back to clearcutting since the loss to the residual stands is so high in this area following partial harvests. Soils are cited as critical to post harvest stand stability by the regions managers. The shallow rooted spruce-fir stands of the Telos display a higher susceptibility to post-harvest windthrow than mixed wood stands on deeper soils.

Estimates range from one-half to one cord per acre for endemic loss in stands that have been partially harvested or thinned from below (managers from two ownerships). Leaving emergents is discouraged because they are extremely susceptible under saturated soil conditions common in the spring. Seasonal differences worth noting are the switch from damage by windsnap as opposed to windthrow; the former occurring during the winter months when root systems are frozen into the soil.

Blowdowns whose salvage is economically viable have a greater likelihood of being recorded or recollected. However, even salvage operations do not guarantee a record of the damaging event. Salvage volumes are not separable from planned harvest volume in mill records, transportation records and harvest records. The likelihood of a manager remembering an event hinges on the events intensity and uniqueness, and the individual managers themselves.

Generally salvage operations are not conducted unless the blowdown is large enough to be economical. The minimum area required for economic viability is inversely proportional to the severity of the damage; however, a minimum area of five acres is standard for partial stand damage resulting from endemic winds. Often minor damage will be ignored by managers unless it is easily accessible, such as alongside a road or in a recent harvest unit.

1.3.2.5 Regional “hotspots”:

Certain areas of the state may be more prone to wind disturbances than others due to numerous potential factors. These areas are referred to as regional “hotspots” for blowdown activity. Large geographic features, Mount Katahdin for example, and the excessively shallow and rocky soils of the Telos region create a scenario where large scale disturbance from wind storms may be more probable. Large blowdowns have occurred in this area. Approximately 5000 acres blew down in and around Baxter State Park in November 1974 preceding the 1977 Baxter Park Fire (Small, 2004). In 1980, 6000 acres were blown over in the Telos region. Other areas considered to be “hotspots” subject to frequent wind damage are the Allagash watershed, particularly around Eagle Lake and the northern portion of Chamberlain Lake, the Haynesville Township and the area directly north of Oakfield.

1.3.3 Precipitating Factors to Wind Damage:

Windthrow is affected by numerous factors; climate, topography, physical and biological stand attributes, soil characteristics and silviculture all play a role in the dynamics of wind disturbance (Ruel 1995). To simplify the relationships of these interacting factors, Mitchell (1995 and 1998) advocates grouping the factors into three categories, exposure, soils, and stand characteristics, to form the conceptual ‘windthrow triangle model’.

1.3.3.1 Exposure:

Exposure, the first leg of the windthrow triangle, is primarily dependent on topography, although neighboring stands and past management within a stand can contribute to this category. Wind speed is an important variable in windthrow; however, wind speed fluctuates and gusts are often more damaging than sustained wind. Gusts, pulses of wind stronger than the mean wind speed and occurring in seemingly random directions, are a result of turbulence from the interaction of the wind with topographic features and varied forest cover (Ruel, 1995). This turbulence is generated through the interaction of surface obstructions and air flow (Gloyne, 1968). Patterns of turbulence are unique to the type of topographic feature encountered and the part of the feature the wind initially contacts. Hutte (1968) has detected different definable patterns of turbulence and areas most susceptible to damage on round hills, mountain ridges, valleys, and shoulders of larger hills and mountains. Turbulence in valleys is exceptionally dynamic and is ultimately determined by the direction the wind enters each individual valley.

Ridges and hills are notorious for generating wind turbulence. The topographic features do not need to be massive in order to induce major changes in air flow, although wind speed, frequency, and duration are known to increase with elevation (Bair, 1992). Ranges of hills or gentle ridges only a few hundred feet high are large enough to generate lee waves, an acceleration of surface wind on the lee slopes of such features (Gloyne, 1968). Valleys and notches can serve as funnels accelerating the wind as can long open features such as bodies of water or expansive fields.

Wind consistently increases in speed upslope, and turbulent eddies and vortices form as the wind rushes over the top or around the sides of a topographic feature. The wind is separated from the surface at these points and is most damaging just downwind where it plunges downward and 'reattaches' to the surface (Hutte, 1968). This phenomenon makes lee slopes of ridges and mountains especially susceptible to wind damage and results in a higher proportion of windthrow on windward slopes and windsnap on leeward slopes (Maccurrach, 1991).

Generally, topographical influences on forests are estimated with reference to the direction of the prevailing winds or regular storm tracks. Conifers may develop structural resistance to these prevailing winds in the form of tension wood on their windward side if exposed to these winds throughout their development. Winds coming from the opposite direction as the prevailing winds may be especially damaging even at low speeds and in topographic locations protected from the leeward wind direction. Failure in this direction may be exacerbated from compression failures on the leeward side of trees suffered in previous storms, leaving the tree with little capacity in tension strength on the leeward side (Mergen, 1954). Variations in localized wind intensity and direction is likely to be a function of storm type (Canham, 2001), causing the reliance on topography as the sole predictor of wind damage to be inadequate.

Wind direction plays an important role in patterns of damage. The interaction between surface wind and topographic features creates eddies and lee waves, phenomena which can impact slopes protected from the dominant wind direction. Separate convective straight line wind events have resulted in damage being concentrated on opposite sides of the exposure gradient. Two similar storms (traveling from the southwest to the northeast, and causing damage in the form of swaths of blowdown approximately 500' in width and between fifteen and thirty miles in length) damaged forests in western Aroostook County, one in 1987 and one in 2004. The 1987 storm left a track of damage from Ross to Long Lake with the worst impact on the windward ridges. The 2004 event tracked from T12R14 and T11R14 through to T12R10 with the worst impact concentrated on the leeward slopes. Records for these two storms came from the same manager and reflect damage on one ownership.

Patterns of storm direction may be discerned from downed trees. Turbulent wind damage from downbursts may cause trees to blow down in any direction but generally trees will be blown over in the direction of the dominant storm winds of an individual event (Franji and Lugo, 1991; Huggard et al, 1999; O'Cinneide, 1975).

Table 1.2: Storm Types and the Direction of Storm Origin in Aroostook and Northern Piscataquis Counties. Wind types: SW, sustained wind; CSL, convective straight-line winds; CDB, convective downbursts.

Date	Wind Type	Direction
1972	SW	NE
1974	SW	NW
1987	CSL	SW
1995	CDB	SSW
2001	SW	NE
2002	SW	NW
2004	CSL	SW

Of the seven storms listed in Table 1.2, all but two have a westerly component, and three of the seven have a southerly component. This corroborates with tree fall data from Baxter State Park. Data from 114 CFI plots were obtained, that recorded species, diameter and direction of fall for 279 blown down trees. Tree counts were totaled by degree sections of a circle to detect the direction associated with the most tree fall. Sections of both 90 and 180 degrees were tested. Both perspectives show southwest winds producing the most treefalls. The direction of wind origin was assumed to be the opposite of the direction of fall for this analysis; results are displayed in the two following figures.

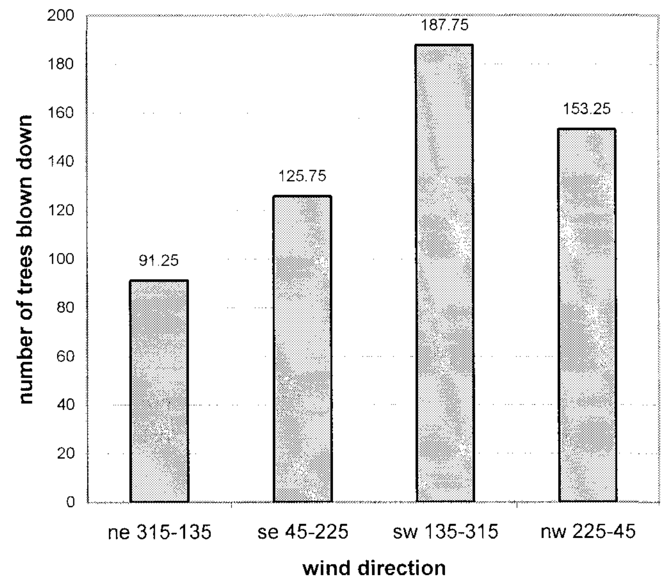


Figure 1.5: Number of Trees Blown Down by Wind Direction in the Scientific Forest Management Area, Baxter State Park. Tree falls were grouped into hemispheres, or 180 degree sections. The midpoint of each section and the corresponding directional degrees are listed as the wind direction.

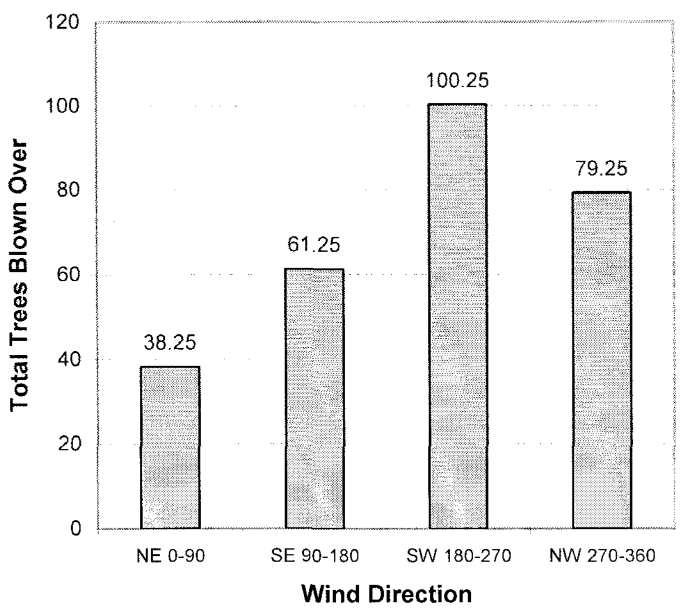


Figure 1.6: Number of Trees Blown Down by Wind Direction in the Scientific Forest Management Area, Baxter State Park. Tree falls were grouped into quadrants, or 90 degree sections. The midpoint of each section and the corresponding directional degrees are listed as the wind direction.

1.3.3.2 Soils:

Forest soils are also a major component in understanding a stand's susceptibility to wind damage. Soil aeration, ease of soil penetration by roots, and moisture holding capacity all affect the pattern of root development. Generally, loose drier soils facilitate deeper rooting and allow root systems to spread further than shallow clayey soils (Mergen, 1954). Shallow soils which saturate easily, like those commonly found in the spruce flat forest type, are increasingly prone to windthrow when saturated. The mass of soil which roots adhere to for anchorage becomes so wet it no longer adheres to itself, and the tree loses a substantial portion of its basal mass, crucial for resistance to windthrow (Day 1950). To compound the problem on wet soils, the rocking of the root plate can pump mud out from under the tree further reducing its stability (Maccurach, 1991).

Mitchell (1995) categorizes wind damage hazard by soil depth, on soils deeper than 0.8m (32inches) wind hazard is low and wind hazard is high on soils shallower than 0.3m (12 inches). Moderate hazard falls between these two thresholds. The majority of the soils in the state of Maine are very shallow with the water table very close to the surface. The deepest well drained soils in Maine are often hardwood dominated while the shallower poorly drained soils are usually dominated by spruce and fir. Soil depth, specifically the depth to the water table, was cited regularly by managers as an environmental factor which appears to correlate strongly with the occurrence of wind damage

Soil texture can also play a role in wind disturbance. In a study of the sub-alpine zone along Kancamagus Pass and Wildcat Mountain in New Hampshire, Rizzo and Harrington (1988) found that stress induced by root damage from wind may be compounded by coarse soil texture and the presence of sharp edged rocks in the soil. Roots move under windy conditions and suffer damage from soil abrasion consisting of the loss of fine root hairs, and the destruction of conductive tissues. Damage to the roots resulted in decreased vigor, evidenced by reduced crown density and size. The reduction in crown density actually reduces the individual windthrow risk of root damaged trees, since there is less surface area to intercept the force of the wind.

However, the reduced vigor and physically damaged roots increased tree susceptibility to secondary disturbance agents including fungal rots.

1.3.4 Stand Level Factors:

Seven stand attributes have been consistently identified as determining factors in wind damage. These attributes are height to diameter ratio, stand height, tree spacing, species composition, prevalence of fungal pathogens manifested as either stem or root rots, recent stand harvest, and recently exposed edges (Savill, 1983; Lekes and Dandul, 2000). Survey respondents consistently cited three stand characteristics that they believed increase a stand's vulnerability to wind damage in Maine, reinforcing consistency of findings in the literature. Specifically managers cited stands with a component of mature balsam fir, thinning or recent stand entry, and edges or remnant patches as being prone to wind damage.

1.3.4.1 Fungal Pathogens:

Fungal rots are a significant component of several crucial stand characteristics in Mitchell's windthrow triangle. Stand density and structure are also critical stand level factors which contribute to a stand's wind susceptibility, and provide opportunities to potentially mitigate winds damaging effects.

Alexander (1964) found that of all wind-caused tree mortality in western spruce fir forests, one third of thrown trees were weakened by butt and root rots. All trees killed by stemsnap had various stages of trunk rot at the point of breakage. Root support may often be compromised prior to stem support, and a lesser degree of stump-level decay would be expected in uprooted trees than in trees with stem breakage (Whitney et. al. 2002). Windthrow may further compound the spread of decay fungi and future wind damage by creating infection courts on residual stems from collision and abrasion from falling trees. Logging damage associated with partial harvesting induces the same types of damage to residual trees and may also damage the root systems of these individual trees, creating more sites for potential fungal infection. *Inonotus tomentosus, Armillaria ostoyae, Scytinostroma galactinum,* and *C. puteana* were the most commonly found stem and root decay fungi in studies of eastern spruce fir forests (Whitney et. al. 2002). The prevalence of these and other decay fungi decreases as elevation increases (Worrall and Harrington, 1988).

Rates of root rot in naturally regenerated, even aged, spruce fir stands can be exceptionally high. Whitney (1989) explored rates of root rot in this type of boreal spruce fir forests of eastern Ontario. This study found that in forty year old stands root rot was highest in balsam fir, intermediate in black spruce and least in white spruce. The author found that in naturally regenerated boreal spruce-fir stands 76% of balsam fir trees were infected with some type of decay fungus by age 40, increasing to 96% by the time the stand reached age 120. The number of black spruce trees infected ranged from 56% at age 40 to 89% at age 120. White spruce suffered slightly less damage from decay fungi initially with 39% of the trees affected at age 40, but by age 120 92% were infected. Red spruce has been considered slightly less resistant to rot than white spruce but it is susceptible. The percentage of trees infected with decay fungi, and the amount of decay in the butt and root system increases over time with stand age, making older stands increasingly susceptible to wind damage. The high degree of rot in firs, particularly butt rot, makes them more prone to windsnap than other species (Veblen et. al., 2001).

The role of stem and root rot in windthrow and windsnap was reinforced by Whitney et al (2002) in a study examining blowdown and strip cutting of black spruce. Working in black spruce forests over 100 years old, the authors found that the majority of windthrown trees in leave strips had pre-existing fungal decay, while virtually all windthrown trees in uncut stands had pre-existing fungal decay. These findings suggest that mortality from wind disturbance in black spruce forests is primarily root rot driven. By reviewing uprooted trees in old growth stands Jonsson and Dynesius (1993) found a correlation between the number of trees blown down and wind intensity, suggesting that trees predisposed to windthrow by rot may accumulate during years of mild wind events, resulting in more blowdown than expected when damaging winds occur. This accumulation results in periodic times of high disturbance which should not be interpreted as the sole result of catastrophic winds.

1.3.4.2 Canopy Structure:

The structure of the forest, and in particular the canopy, plays a vital role in wind disturbance because canopy structure effects turbulence. Canopy-induced turbulence is an extremely complex and highly variable phenomenon; it increases with wind speed and canopy roughness (Savill 1983; Bull and Reynolds, 1968). Increased turbulence from canopy roughness results in faster and more powerful downward transfer of wind energy into the forest and onto individual trees (Bull and Reynolds, 1968). These downward gusts are the cause of maximum wind loading on individual trees, not the mean wind speed (Gardiner et. al., 1997). Live trees are more likely to be windthrown because wind gusts will exert a greater pressure on live tree boles than on trees without live crowns.

Stand density is directly linked to canopy roughness and consequently stand density alters the susceptibility of stands to wind damage. Dense stands are resistant to wind damage as an entity, a direct result of stem density and crown closure. Dense stands generally have a closed, more uniform canopy which reduces stand-generated turbulence. Support from neighboring trees and interlocking root systems decrease the amount of individual stem sway and dissipates wind energy through numerous stems (Smith and Watts, 1987; Blackburn et. al., 1988; Maccurrach, 1991; Mitchell, 1995; Whitney et. al., 2002). Stands with more open canopies generate more within stand turbulence from canopy roughness and allow more wind to penetrate the stand in general.

1.3.4.3 Spacing:

Stand density also affects individual tree susceptibility to wind damage and silvicultural activities may change susceptibility of trees to wind damage. Spacing through pre-commercial thinning (PCT) and commercial thinning (thinning) are silvicultural tools which potentially both increases and decrease wind damage risks within stands. Stands are more vulnerable to windthrow following thinning for two reasons. First, the increase in spacing created by thinning creates more canopy roughness, which subsequently increases the turbulence of the wind moving through the canopy.. Increased turbulence and wind penetration results in reduced tree stability. In addition, alignment of gust and tree sway frequencies is more likely, causing more stand windthrow and windsnap (Blackburn et. al., 1988; Maccurrach, 1991). Second, high initial stand density produces unfavorable H/D ratios (Wilson and Oliver 2000). This is less of a problem if stand density remains high; however thinning removes the support of neighboring stems dramatically, increasing stand vulnerability.

Stands are very susceptible to windthrow following thinning. This period of susceptibility, may last from a few years to over a decade, and is relieved as crown closure occurs in the stand and stems and roots become more windfirm (Lohmander and Helles, 1987). The increased vulnerability following thinning diminishes as crown closure occurs in the stand and stems and roots become more windfirm. However, increased spacing also allows for better root development and more carbohydrate allocation to diameter growth increasing a trees resistance to wind damage (Ruel et al, 2003; and Telewski, 1995). The primary benefit associated with thinning regarding windthrow is the decrease of the height-diameter (H/D) ratio resulting from reduced competition and allocation of carbohydrates to diameter growth. Younger stands respond better to thinning and are generally more resistant to wind damage. Bending stress that is not strong enough to cause structural damage can stimulate cambial growth in the bole and roots, allowing development of windfirmness in trees (Mergen, 1954).

There is debate if thinning pattern (thinning from above, below, or crown thinning), defined by the d/D ratio, has a significant effect on the residual stands windfirmness. The d/D ratio is a quantitative description of the structural effects of thinning treatments; the ratio compares the average diameter of removed trees 'd' to the average diameter of the stand before treatment 'D' (Smith et al, 1997).

Emergent and dominant crown classes are likely to be the most windfirm in stands of moderate density since they have been exposed to the most wind stress and have access to the most growth resources (Mitchell, 1995). Thinning from above (d/D ratio greater than one) involves removing dominants which have already demonstrated windfirmness. Thinning from above removes trees with the most wind resistance, leaving a stand of susceptible stems (Ruel, 95); however, the residual stand may have more uniform canopy height, potentially reducing turbulence.

In single cohort stands, dominants exhibit a faster growth rate, and thinning from below (d/D ratio less than one) favors these faster growing trees. Dominants close the canopy faster than intermediate trees following thinning and dominants have faster rates of diameter growth than other crown classes, increasing their stability (Oliver and Larson, 1996). Crown thinning (d/D ratio greater than one), which focuses on the optimum spacing of individual trees, often leaving co-dominants, may result in more stand damage than other thinning patterns. Studies of Engelmann spruce have shown co-dominant trees suffering more crown breakage than dominants, the same was found true for silver fir (Savill 1983).

Regardless of the d/D ratio utilized in the thinning regime, the increased spacing will increase the turbulence in the stand until crown closure occurs. Lohmander and Helles (1987) argued that no significant difference between windthrow rate and thinning pattern were evident. Gardiner (1997) also obtained similar results and determined wind velocity over the canopy depends on stand density and not on the pattern of thinning. Thinning very dense stands can result in large losses to windsnap and windthrow because trees grown in dense stands have been relatively sheltered from wind stress. Older stands are best left at high densities so wind energy may be dissipated throughout the stand by numerous stems.

Spacing, either through initial planting or PCT, may be the best option for reducing future wind damage in stands. Spacing trees exposes them to wind early enough to stimulate root and cambial growth and develop favorable H/D ratios before the onset of competition (Wilson and Baker, 2001; Wilson and Oliver, 2000). For this reason PCT may be a more effective tool to increase windfirmness than commercial thinning. Stands with wide initial spacing have been shown to be the most effective at dissipating wind energy without support from neighboring trees. Early spacing of spruce and then allowing canopy closure without subsequent thinning resulted in the most windfirmness of all thinning regimes in three experiments of spruce stands in the Czech Republic (Slodicak, 1995). Spaced stands will be the least affected by the creation of edges from adjacent management activities (Gardiner et. al., 1997).

1.3.4.4 Edge and Clearcutting:

Edges are formed from clearcutting blocks of forest, road building, or stand replacing disturbances like wildfire. These edges create large turbulent eddies that impact the stand at a distance between 10 and 15 times the height of the edge trees (Papesch, 1974; Savill, 1983). Less damage is associated with clearcutting, compared to thinning, since the unit boundaries (edges) are the only areas with increased susceptibility to damage (Alexander, 1964). The majority of wind damage along the boundary occurs during the first severe windstorm following the harvest, the boundary tends to stabilize after this initial loss (Alexander, 1964). Natural or inherent edges are also found in forested landscapes. These edges occur as a result of major changes in the substrate or local landforms. Rock outcroppings and lakes create this type of natural edge. Inherent edges are not as susceptible as induced edges (edges created by management) since trees occupying these inherent edges have developed under more wind stress than trees in closed forests and it is inferred that these trees will have undergone structural development similar to trees in spaced stands.

Damage along unit boundaries is dependent on the boundary location with respect to the direction of prevailing winds, topography, stand and soil conditions, and the shape of the harvest unit. Windthrow following clearcutting increases with the distance cut in the direction of the prevailing winds (Ruel, 1995). Narrow width leave strips in strip cutting as opposed to large block clearcuts increase the potential of windthrow in adjacent stands, whereas strip cutting creates more edges in the residual forest than more square harvest units.

Alexander (1964) provides several recommendations for locating boundary units to mitigate wind damage following clearcutting. Larger units provide managers with more flexibility in boundary placement. This flexibility allows boundaries to be located in areas with less wind damage potential. Alexander recommends that boundaries should avoid areas with: exceptionally shallow and poorly drained soils, and high incidence of root and butt rot. Desired boundary areas include stands of young immature trees or poorly stocked stands because trees in poorly stocked stands are open grown and are generally more likely to be windfirm. Placement of the leeward, or downwind boundary, is the most critical. This boundary will absorb the most direct force from prevailing winds which may accelerate across the harvested area.

1.3.4.5 Partial Harvesting:

Unlike clearcutting, partial harvesting and selection must consider factors influencing the windfirmness of individual trees to mitigate wind damage. The intensity of the removal and leave tree selection are critical to control wind-induced damage in the residual stand. In stands with open and multilayered canopy structure individual trees have continuous exposure to growth resources and wind stress, increasing the likeliness of windfirmness in individuals of all crown classes (Mitchell, 1995). This type of stand provides managers with the most flexibility as crown class will be less of a determinant for windfirmness than in denser stands where individual wind resistance is low (Mitchell, 1995).

Partial harvests of spruce-fir forests (Figure 1.7) have come under criticism in the past, and the spruce-fir forests of Maine have a stigma of being prone to high wind damage following partial harvesting. However, harvesting practices which ignore foreseeable wind risk may be more to blame than physiological traits of red spruce. McLintock (1954) noted that extensive wind damage was occurring following poor and uncontrolled spruce harvests in New Hampshire. These partial harvests were conducted on a diameter limit protocol and had effects similar to thinning from above. The larger trees exhibiting windfirmness were removed leaving stems which previously depended on the shelter and mutual support of neighboring trees. As a result McLintock cautioned against removing more than 25% of the merchantable basal area in spruce fir stands to minimize loss to wind; however, the majority of leave trees in McLintock's study were mature fir with a high incidence of butt and root rot. Other studies have indicated that, when care is taken in selecting residual stems to anticipate potential wind disturbance, losses to the residual stand can be greatly decreased. Losses of only five percent of residual merchantable timber have been recorded for partial harvests removing over 70% of the original volume in upland spruce-fir stands in New Brunswick (Kelly and Place, 1950).

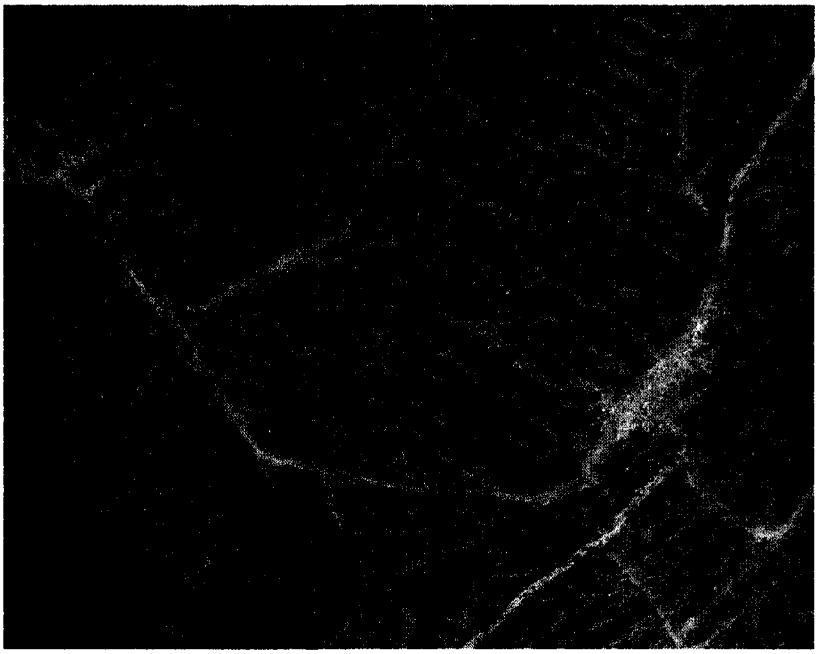


Figure 1.7: Pattern associated with partial harvesting using boom mounted feeler bunchers and grapple skidders. This pattern is ubiquitous across the forests of Maine in many more recent aerial photographs and illustrates the potential for extensive wind damage following stand entry.

1.4 Wind as a Disturbance Agent:

While wind damage can be mitigated and reduced in intensively managed stands it is important to recognize the role this disturbance plays in less manipulated forests. Influences of wind disturbance should be considered across spatial scales.

1.4.1 Wind Disturbance at the Stand Scale:

The impacts of wind vary between tree species and depend on some variables not captured in the windthrow triangle. Windthrow drives gap dynamics and facilitates regeneration. Windthrow may release advance regeneration or favor intolerant and mid-tolerant species. Windthrow also affects the soil via mixing and can create the 'pit and mound' topography characteristic of wind disturbed ecosystems (Ruel, 1995). Pioneer species may be maintained within older forests by windthrow because several types of substrate and moisture conditions are available with the exposure of soil and creation of pits and mounds, providing a range of regeneration niches favoring different species (Jonsson and Dynesius, 1993). Wind contributes to nutrient cycling through foliar decomposition of windthrown trees and wind throw is also the dominant contributor of coarse woody debris, a crucial part of the forest ecosystem (Ulanova, 2000). Windsnap influences forest development in an almost identical nature with the exception of the soil disturbance inherent to the lifting of the root wad.

Individual tree species have different susceptibility to windthrow. Inter-specific variations in susceptibility decreases as storm intensity increases, but at lower storm intensities this variation plays a key role in forest succession, and developing more windfirm stands over time. *Populus sp.* for example is known to reproduce from root sprouts, these stem sprouts maintain root connections allowing them to effectively distribute wind energy and avoid being thrown or snapped (Veblen et. al., 2001).

Trends of species susceptibility were often identified in manager interviews. Softwoods are consistently cited as more vulnerable to blowdown than hardwoods. Managers' rating of species places balsam-fir as the most likely to blow over followed by red and white spruce. Northern white cedar is also cited as vulnerable but less emphasis is placed on it as a commercial species. White pine is considered fairly resistant to blow down in comparison with these other conifers. Hardwoods are generally considered less vulnerable than conifers in general. One manager indicated that in his experience big tooth aspen appeared more prone to blowdown than the other hardwoods managed in the ownership. Data obtained from the scientific management area of Baxter State Park provides examples of these trends, illustrated in the following figures. Trends displayed in these figures are discussed further in section 1.4.2.

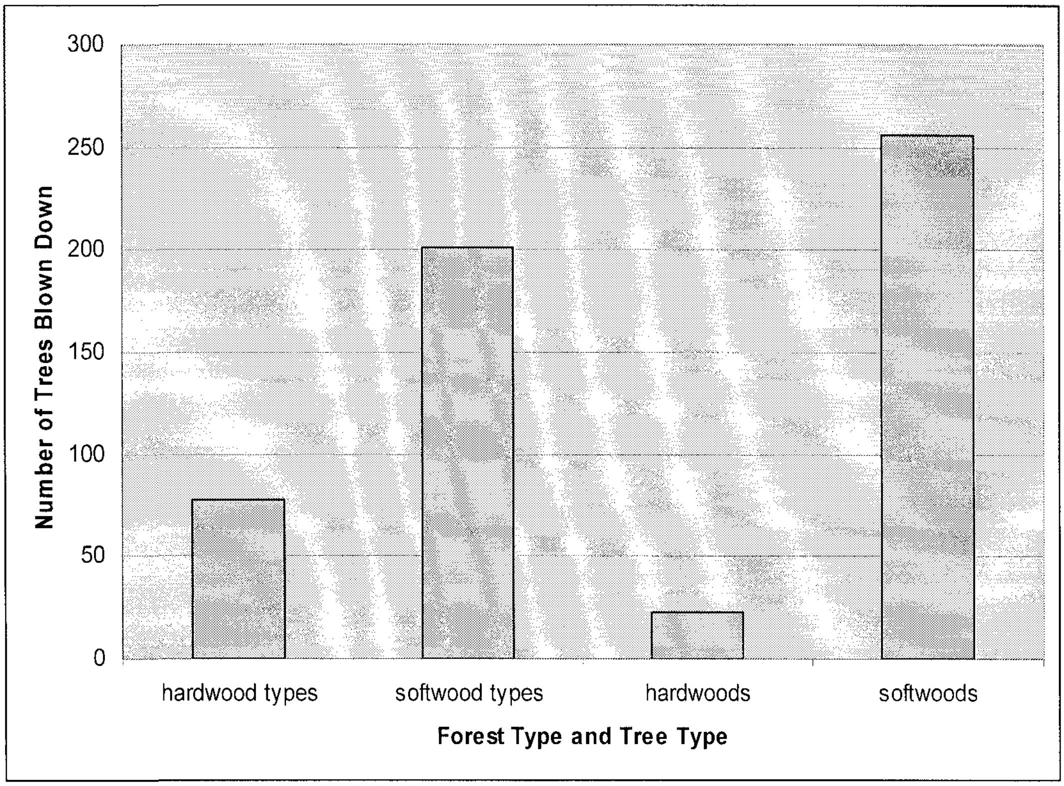


Figure 1.8: Number of Trees Blown Down Displayed by Broad Classification of FVS Forest Types and by Broad Classification of Tree Types in the Scientific Forest Management Area, Baxter State Park.

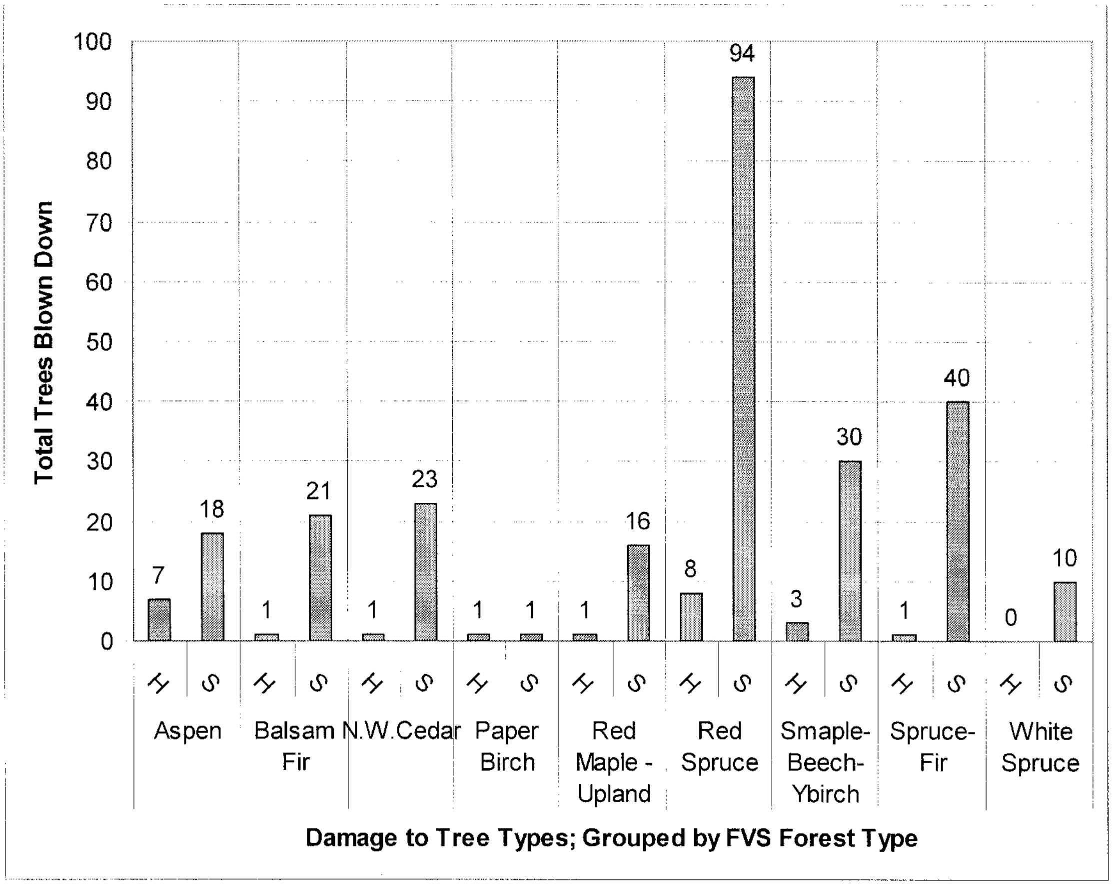


Figure 1.9: Number of Trees Blown Down Grouped by Tree Type within FVS Forest Types in the Scientific Forest Management Area, Baxter State Park. This table illustrates the disproportionate number of conifers blowing down compared to hardwoods. The increased vulnerability of softwoods may lead to the slow exclusion of larger softwoods from hardwood dominated stands.

Probability of windthrow is also directly linked to tree size. Canham et. al. (2001) studied interspecific differences in wind susceptibility of tree species in the Adirondacks. Red spruce showed the highest rates of windthrow across virtually all levels of storm severity, while yellow birch and sugar maple had the lowest rates of windthrow for intermediate sized stems. Shade tolerance was correlated with windthrow under extreme wind speeds for small stems (10 cm DBH): the most shade tolerant species (beech, hemlock, and sugar maple) had the lowest rates of windthrow while the most intolerant species (red maple, black cherry and yellow birch) had much higher rates of windthrow. The same trends were not evident in larger stems (70cm DBH) where red maple and yellow birch were two of the more resistant species. The authors suggested both red maple and yellow birch survive intense windstorms by sloughing large canopy branches, which presumably reduces the wind load on the stem. It should be noted that the stands sampled in this study did not have a balsam-fir component, a species considered more susceptible to windthrow than red spruce. In direct comparisons of the spruce and fir genera, Lohmander and Helles (1987) found fir to be more susceptible to windthrow than spruce of the same height; the windthrow risk between the two genera was estimated to be the same when spruce is approximately four meters taller than fir in the same stand.

1.4.2 Wind Disturbance at the Landscape Scale:

While numerous factors are involved in wind disturbance at the stand level a regional wind disturbance trend can be identified. The impacts of the three components of the windthrow triangle: exposure, soils, and stand characteristics, become more acute at higher elevations where winds are consistently stronger and more frequent. Wind disturbance increases, and acts increasingly as a primary disturbance agent as elevation increases.

At lower elevations in areas not prone to major wind damage, individual wind caused gaps will tend to be smaller in size. Individual tree falls may be more common than multi-tree gaps. In these lower elevation forests, gaps will maintain high species diversity. Spruce has shown preference for seedling establishment on decaying logs and windthrow mounds, while intolerants like birch are more common in pits and the bare soil of the root plate (Ulanova, 2000). Windthrow gaps will also provide pine with light and germination media. Shade tolerant species present in the understory will be released; this process is fundamental to the spruce-fir ecosystem. The high rate of windthrow of fir from rot is compensated by the prolific fir regeneration in the understory. Spruce tends to be more windfirm than fir, but advance regeneration often has a much higher proportion of fir than spruce. However, unlike release from complete overstory removal following a severe spruce budworm or spruce beetle outbreak, spruce and fir growth responses do not differ significantly in small to moderate windthrow gaps. These qualities allow both spruce and fir continued codominance of the forest under a pattern of fine-scale wind disturbance (Veblen et. al., 1991).

At slightly higher elevations in Maine soil drainage improves, and combined with exploitive harvesting, hardwoods become increasingly dominant on these sites. Hardwoods utilize a strategy of avoidance to maintain their dominance on these sites. Damaging winds tend to be strongest through out the period of the year when deciduous trees have shed their leaves, which greatly reduces the force of wind on the trees. Snow loading can decrease the wind speed needed to throw or snap trees in the winter. More force is exerted upon trees and their resistance is exceeded from the added weight and canopy density from snow in conifer crowns. Deciduous trees are again at an advantage because they have a much smaller crown area for winter snow to adhere (Peltola et. al., 1997). The ability to withstand wind damage ensures hardwoods are in dominant canopy position and are the largest contributor to the local seed bank and regenerating cohorts.

The hardwood zone tapers off as soil depth decreases further up the elevation gradient and wind processes become increasingly important. Individual species susceptibility to windthrow increases as species reach the limits of their elevation defined range; consequently, with the exception of birch, hardwoods tend to be absent from spruce slopes. Studies by Worrall and Harrington (1988) in Crawford Notch, New Hampshire found gap size from chronic wind stress, and windsnap or windthrow increased strongly with elevation, accounting from over 60% of the gap area at 764 m (2521 ft) to almost 85% of the gap area at 1130 m (3729 ft). Gap formation led to subsequent mortality from chronic wind stress and windthrow in gap edge trees. This trend was confirmed on Camel's Hump in Vermont by Perkins and Klein (1992). Perkins and Klein also found that the gaps at these higher elevations expanded in directions coincident with the prevailing wind and crown exposure was the most important factor related with stress caused from wind induced canopy damage. This finding provides insight into the role wind stress plays at the elevation extremes of Maine forests.

Balsam fir commonly dominates the highest elevations below tree line in the mountains of the northeast. Wind stress at these higher elevations may be directly responsible for the decline in vigor of balsam fir and the creation of fir waves (Sprugel, 1976). Fir waves are progressions of fir regeneration, growth, decline and mortality; a high proportion of standing dead stems illustrates that the phenomenon is not simply migrating blowdown (Reiners and Lang, 1979). However, the cause of mortality in these stands is likely to be from the compounded effects of wind driven stresses. Fir waves are commonly found on exposed faces, and the waves travel downwind. Although fir waves are not completely understood, high wind speed, rime ice formation, winter desiccation, and summer cooling stresses are probable factors that are all dependent on or enhanced by wind (Sprugel, 1976).

Figures referenced in the last section from the Baxter Park data show a regional phenomenon in which larger softwoods may be slowly excluded from hardwood dominated forest types resulting in a shift from mixed wood to hardwood stands. Wind driven softwood exclusion has also been witnessed in the Deboullie Reserve (T15 R9) a Bureau of Parks and Lands Township. The Deboullie blowdown event in the fall of 2004 created dispersed blowdown in numerous stand types. Although the majority of damage hit hardwood and mixed wood stands. The heaviest damaged areas were salvaged mechanically, trails followed the path of the heaviest damage. In August of 2005, a walkthrough of the impacted but unsalvaged area was conducted.

Walkthroughs through several hardwood and mixed wood stands displayed the same trend detected in the data from Baxter State Park's SFMA.. Damage in these areas was restricted to conifers. No incidence of hardwood blowdown was encountered. This trend of exclusion of softwoods from the canopy is also supported by managers rating conifer susceptibility higher to that of hardwoods.

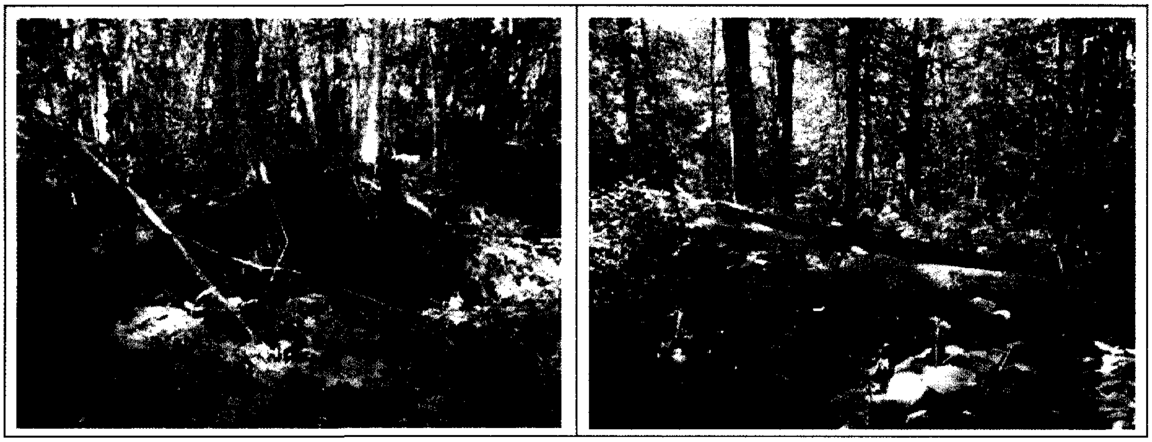


Figure 1.10: Selective Removal of Softwoods from a Hardwood Dominated Stand Due to a Wind Event.

1.5 Conclusion:

The importance of wind in Maine forests should not be underestimated. A multitude of variables influences the amount, the type, and the outcome of wind disturbance in the various subtypes of Maine's diverse forests. The importance of wind will not diminish in the future; in fact, it is likely to increase. At this time definitive, localized effects of global climate change are primarily speculative; however, increased global temperature and increased atmospheric turbulence, is almost certain. Years of hard frost have been shown to restrict uprooting (Jonsson and Dynesius, 1993). The combination of shallower frosts, more frequent strong winds, and heavier snow loads from wetter snow has the potential to drastically increase the rate of windthrow in Maine forests. Increases in the mean gap size from increased windthrow and windsnap will change forest micro-climate. Presumably, more healthy trees, prone to windthrow rather than windsnap would also blow down. This would increase the amount of exposed bare mineral soil suitable for colonization. Increases in light, diverse soil substrate, and average gap size have the potential to increase the proportion of intolerant conifers and hardwoods in Maine forests. Wind will continue to profoundly impact Maine's forests making an understanding of this disturbance invaluable.

Wind damage to forests in Maine is a continual consideration for forest managers across the region. The importance of wind damage is likely to increase in the future as large areas of the state regenerated during the spruce budworm outbreak of the 1970's and 80's continue to mature. In addition, the vast majority of harvesting in the state utilizes partial harvesting techniques. Partial harvesting currently accounts for 95% of the silvicultural activity in the state (McWilliams et al, 2005). The increase in vulnerability following partial removal of forest stands has been addressed in this chapter. The scale of impact from this harvesting should not be overlooked. Estimates put the annual acreage harvested under partial harvesting close to double the acreage when clearcutting was the dominant silvicultural prescription, from 250,000 acres/year to an average of 562,000 acre/year currently (McWilliams et al, 2005).

Hurricanes and tropical depressions have impacted the forests of Maine in the past. While these storms events may be infrequent they have the potential to substantially impact the regions forests. Initial damage estimates to the Louisiana forest production sector from Hurricane Katrina are immense; 612 million dollars, representing over three billion board feet of timber, or twice the annual harvest were lost (Olivier, 2005). If current landscape trends in Maine continue, maturation of post-budworm spruce fir stands and an increased reliance on partial harvesting, a large proportion of the Maine landscape could be in a highly vulnerable state to a similar storm.

As discussed in this chapter, there is a relatively small amount of research surrounding wind disturbance in Maine. Institutional record keeping has not been diligent about recording detailed information about wind storms that have occurred. However, a substantial portion of wind research from other areas appears to be applicable to Maine forests. The research in this chapter has also identified trends of softwood exclusion and gradients of storm types important to the state's forest resource.

As landscape trends continue to become increasingly complex managers will need tools and techniques to help them manage the growing wind damage threat. The following chapter describes the process of developing an index model to assess stand vulnerability to wind damage. This type of model may prove to be a valuable tool for assessing potential threat's to the states forest resource.

2.1 Chapter Two Introduction:

Numerous factors, some of which cannot be controlled, are continually interacting with the forest resource, introducing risk to management, and making consistent predictable management outcomes uncertain (Birot and Gollier, 2001; Wilson and Baker, 2001). This uncertainty includes product markets and non-market forest values. Forest managers must balance societal needs and values in an environment that includes factors over which they exert limited control. Included in these factors are threats or hazards, factors or phenomena with the potential to damage forests, such as windstorms and wildfire. Effective management requires tools to assess the potential damage, or risk, from such hazards (Gadow, 2000). Gardiner and Quine (2000) describe risk management as a four step process, of which risk assessment is an integral component. This stepwise process involves identification of risk, assessment of risk, assessment of management alternatives, and implementation of informed decisions. The first chapter of this thesis introduced wind as a hazard that introduces risk to forest management in Maine. Chapter two will detail an approach developed to assess this risk across a forested landscape in northern Maine.

Understanding windthrow risk throughout the landscape can provide insights into natural vegetation patterns and habitat types. Risk evaluation can be used to help predict how current forests may change without harvesting, and subsequent impacts to forest health associated with this change. Management options associated with high hazard potentials may be excluded from alternative plans intending to decrease risk (Gadow, 2000). Risk evaluation can help managers evaluate where to locate plantations, determine which silvicultural prescriptions and regeneration strategies are appropriate, and what species composition or rotation length is desirable for individual sites. Predicting damage, or potential for damage, provides the opportunity for impacts to be considered during prescription development allowing for the revision of management objectives or the incorporation of mitigative actions into management plans (Mitchell, 1998).

As discussed in chapter one, the likelihood of wind damage occurring in a forest stand includes numerous factors; however, past research suggests that these factors can be grouped into four broad categories. These categories are: regional climate, topographic exposure, soil properties and stand characteristics (Mitchell, 1995). Of these categories, stand characteristics are most commonly and easily modified through forest management. A prevalence of spruce and fir, current harvesting trends (reflecting a strong public aversion to clearcutting), and legacy issues associated with a 1970s and 80s budworm outbreak may increase future landscape vulnerability to wind damage in Maine.

To augment our understanding of the interaction between forest management and wind damage vulnerability, this project developed a generalized wind damage model that reflects topographic exposure (distance limited TOPEX (Ruel et al. 1997)), soil conditions (rooting depth), and stand characteristics (density, edge, height, species composition and treatment history). Results from similar modeling projects in British Columbia suggest these risk factors are consistent in varied locations; suggesting general models may be portable, useful in other landscapes than the ones for which they were developed (Lanquaye-Opoku and Mitchell, 2005). This model was calibrated using information from published literature and experiences of regional managers. The model was then evaluated using a 40,800 ha area of managed forest in northern Maine.

Modeling and assessing windthrow risk has been done in numerous parts of the world. These models can be grouped into three categories: observational, empirical, and mechanical or mechanistic. Mechanical models calculate critical wind speeds for species-specific tree failure and the probability of these critical winds occurring at a given location. This type of model's use is limited to uniform single-species stands (Lanquaye-Opoku and Mitchell, 2005). Empirical models are best suited for areas with complex, heterogeneous stand structure and composition (Mitchell et al, 2001, and Lanquaye-Opoku and Mitchell, 2005), like the forests of Maine. The empirical approach often utilizes regression models relating wind damage to physical stand components. Generally, the models produce a probability value rating, or index, of the potential for damage based on the stand's suite of environmental conditions. Empirical index modeling of spatial phenomena is enhanced with geographic information systems (GIS), which allows for the integration of spatially explicit model parameters.

Logistic regression is a commonly used tool for evaluating these models and isolating highly correlated component variables (Mitchell et al., 2001; Lanquaye-Opoku and Mitchell, 2005). Rather than using logistic regression, this project produced a generalized model, retaining variables that would not be statistically significant in a logistic regression analysis. This approach is unique because it attempts to create a model that is applicable regionally, and is not limited to the landscape where it was developed.

The intensity, duration, and frequency of wind events are critical factors in determining the influence wind will have as a forest disturbance. Mitchell (1998) classifies damaging winds in two categories, catastrophic winds and endemic winds, which are expanded upon in the first chapter. Damage from endemic winds is more strongly influenced by site conditions than damage from catastrophic winds (Miller, 1985). This characteristic makes endemic wind damage more predictable and, therefore, more manageable than catastrophic windthrow (Miller, 1985; Gardiner and Quine, 2000; Mitchell et al., 2001). Focusing modeling and management efforts on stand vulnerability to endemic winds should allow managers to reduce endemic wind damage (Elie and Ruel, 2005) and provide the ability to infer damage intensity from catastrophic events across the landscape.

The null hypothesis this project tests is that a vulnerability index model generated from the current literature base and experience of regional land managers will not be able to differentiate between a wind damaged and an undamaged stand in a managed landscape. Specifically, differences in index values cannot be detected for component or composite variables believed to influence the likelihood of windthrow in forest stands between categorical populations of stands that have either recorded blowdown or no blowdown during the last fifteen years. Testing of the model was done with a comparison of means analysis, comparing index values produced by the model between historical, spatially explicit records of windthrow presence or absence in a forest landowner GIS database.

2.2 Methods:

This phase of the project seeks to develop a general model of wind damage vulnerability based on literature and regional experiences discussed in chapter one. Data coverage was available for a 40,400 ha study area of managed forestland in five townships north of Baxter State Park. Damage from several wind events has been recorded across the study area. The study area is characterized by low hills drained by small creeks, The elevation ranges from 189 meters (624 feet) to 668 meters (2204 feet) with three-quarters of the landscape below 340 meters (1100 feet). Several areas of poorly drained soils create wetlands, which occupy four percent of the study area. The remaining land area is forested, mostly by larger mature timber. Thirty-eight percent of the forests are considered to be sawtimber size, fifty-five percent are in pole size timber; the remaining forests, five percent of the land area are sapling size (one percent) and seedling size (four percent). Forests range in species composition from softwoods to hardwoods; however, no one type dominates the study area. Approximately thirty-four percent of the forest area was harvested with silvicultural prescriptions leaving mature residuals in the decade preceding the most recently recorded damaging wind event, 2001.

Five environmental parameters (topographic exposure, rooting depth, elevation, stand structure and composition, stand history) will be used to generate a spatially explicit vulnerability index value. As a conceptual model of the relationship between these interacting factors Mitchell (1995 and 1998) advocates grouping the factors into three broad categories, exposure, soils, and stand characteristics, to form a conceptual "windthrow triangle" (Figure 2.1). These broad parameters have all been associated with wind damage in forestry literature and in the surveys of Maine forest managers conducted during the first half of this project.

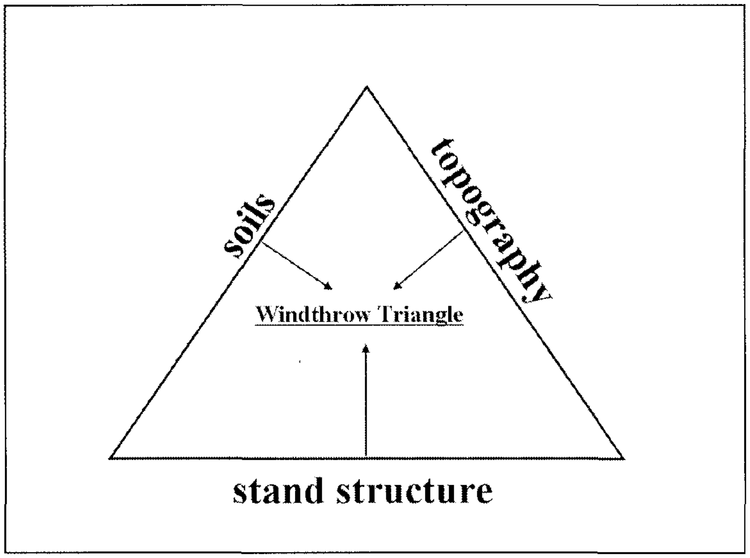


Figure 2.1: The Conceptual Windthrow Triangle; Adopted from Mitchell (1998).

A static index of wind vulnerability could be generated from elevation, rooting depth and topographic exposure without the incorporation of any stand attributes. This would be a static wind risk assessment because these site factors would not be expected to change. However, managers have the greatest ability to influence stand variables through manipulating both stand structure and species composition. These changes in structure and species composition can be manifested at the stand scale, through silvicultural treatments, and at the landscape scale, through intentional location of unique treatments. Incorporating stand variables into the model provides opportunities to assess changes in vulnerability through time, and incorporate a dynamic component to the vulnerability index. Stand variables are used in wind models from other regions (Lekes and Dandul, 2000; Mitchell et al., 2001; Lanquaye-Opoku and Mitchell, 2005).

The composite risk index generated for the model consists of five components. Individual stands receive separate index values corresponding to their species composition, height, and density prior to the most recent treatment defined as either harvest entry or wind damage event. A variable quantifying the proportion of the stand categorized as edge is included, and a binary thinning variable is incorporated into the stand component of the model. Similar modeling projects divide model components in the same way, describing site risk as permanent as opposed to static and stand risk as temporary, as opposed to dynamic (Lekes and Dandul, 2000; Wilson, 2004). For this project data for all model parameters were available digitally allowing the model to be run in a GIS (Table 2.1).

Table 2.1: Model Parameters and Their Corresponding Data Sources

Model Parameter:	Generated From:	Original Source:
Topographic exposure	30 meter DEMs Distance Limited Topex Software	Maine Office of GIS Windthrow Research Group, UBC
Rooting Depth	Depth to groundwater raster, and soil polygons and NRCS data	ME CFRU, USDA NRCS
Stand Attributes	Access queries of database to generate raster layers	Forest Landowner GIS Database
Elevation	30 meter DEMs	Maine Office of GIS

Model construction involved two steps, creating separate site and stand raster layers, and then combining these two rasters to create the cumulative vulnerability model. Stand variables were rasterized from Arc shapefiles. The elevation and topographic exposure variables were originally in raster format and did not have to be rasterized. The depth to groundwater portion of the soil depth variable was originally in raster format; the second portion of the soil depth variable was rasterized from an Arc shapefile. Construction of the data layers was completed for the entire study area.

The stand scale, as delineated by the spatial database of forest stands, defined the scale of the model. This is the finest scale feasible because it is the resolution describing the forest structure and composition, as well as the resolution at which wind damage is recorded. Stands in the database ranged from a minimum of 0.4 hectares to a maximum of 145 hectares; however, 75% of the stands in the study area are ten hectares or less. Rasters built from the data within the spatial database are created at this scale with Arc's *feature to raster* tool. Within-stand variation of site variables, which could detect the exact locations of wind damage within the stand, cannot be tested in the model evaluation process. All site variables are processed before analysis to obtain the mean value corresponding to the stand in the database that encompasses them. This results in an overall loss of precision for the analysis of site variables (Figure 2.2).

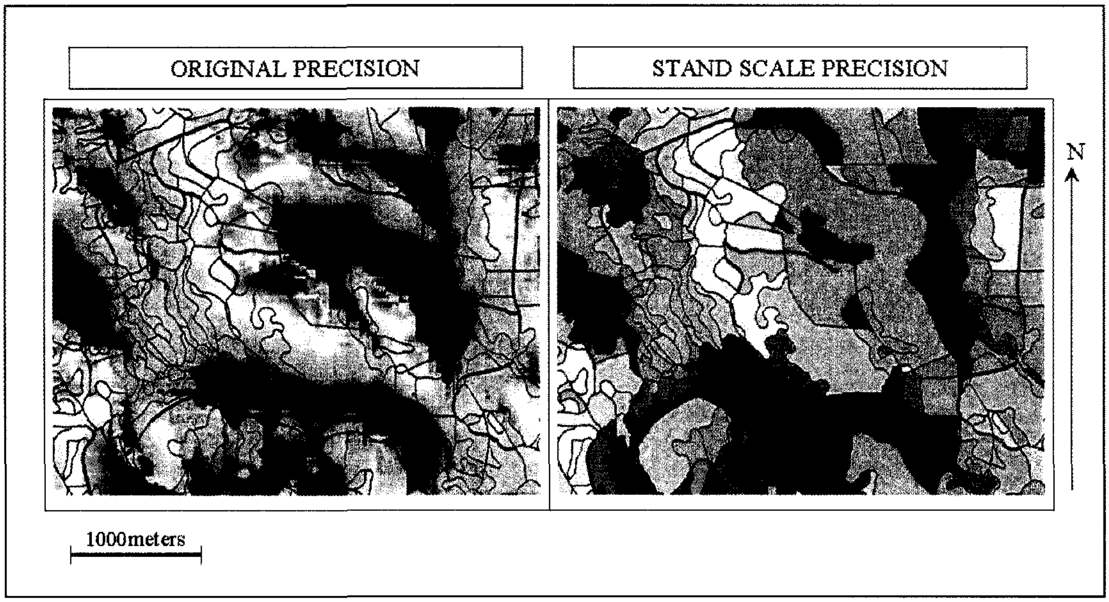


Figure 2.2: Example of the Loss of Data Precision from Obtaining the Mean Stand Value. This figure displays data from a topographic exposure grid, modeling exposure to the southwest. Stand boundaries are displayed in black.

In the initial stages of model development, variables were indexed on a five class scale. The five-class scheme was initially pursued because of its ease of interpretation for practitioners and classification schemes for wind risk have been used in other modeling projects. Lekes and Dandul (2000) devised a ranking scheme for their wind damage risk classification ranging between one and nine, corresponding to low and high risk. Wilson (2004) developed a vulnerability assessment for Douglas-fir stands in the Pacific Northwest based on a scale between one and three. Several classification methods for breaking data into classes were tested: Jenks natural breaks (Jenks and Caspall, 1971), equal intervals, and breaks along standard deviations. However, forcing the continuous variables into discreet classes proved ineffective at capturing critical values in the original data. The classification resulted in an overall loss of resolution of the variables of interest.

Subsequently, individual variables were indexed between zero and one, and combined additively to integrate the variables into the vulnerability model. This indexing procedure retained the distribution of the original variables. The second standard deviations of the mean were located and used as the endpoints of the indices. Data points outside the endpoints assume the same index value as the new endpoints. The rationale for this procedure is the majority of the landscape represented by the variables occupies the space between the new endpoints. Using the adjusted endpoints, rather than the actual minimum and maximum data points, enhanced the variation in the vast bulk of the distribution, potentially increasing the sensitivity of the model to critical differences in variable data values (Figure 2. 3).

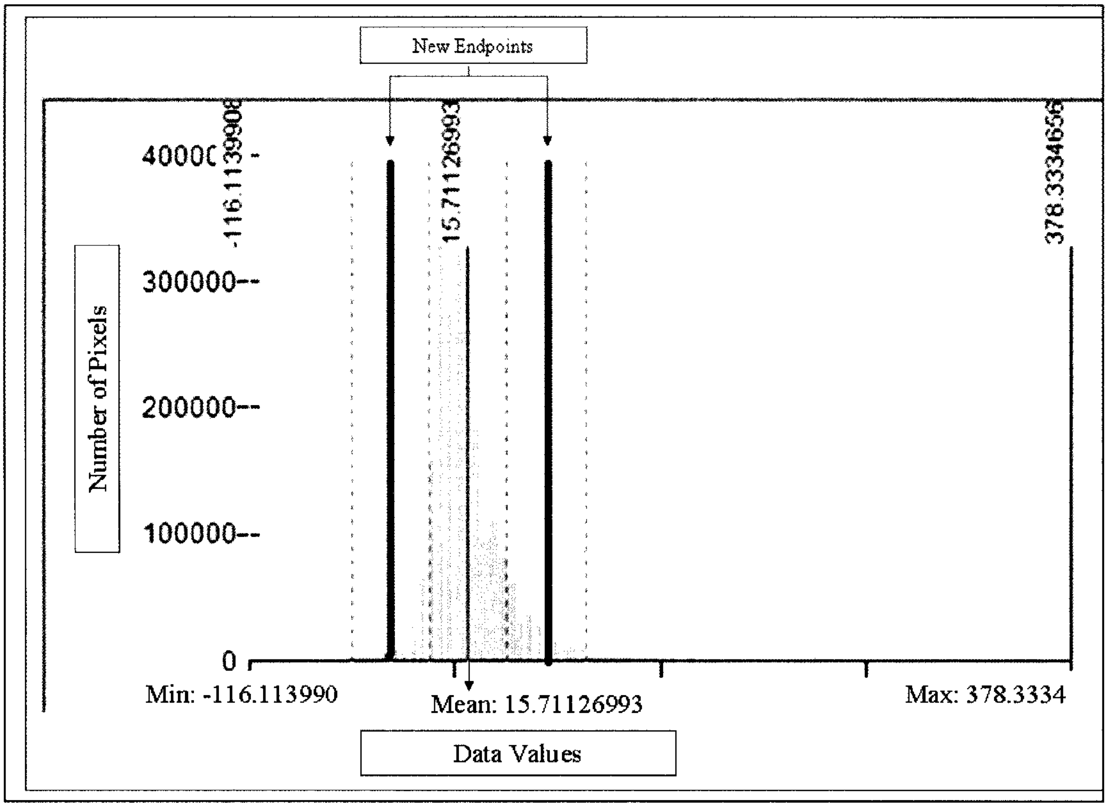


Figure 2.3: Example of Data Consolidation to Enhance the Center of the Data Distribution. The data from an exposure grid are shown displaying the full data range and the new endpoints, two standard deviations from the mean.

2.2.1 Site - Elevation:

Elevation is incorporated into the site component of the model. Elevation values from a 30-meter resolution digital elevation model (DEM) of the study were recalculated into an index between zero and one. Elevation had statistically significant correlation with wind damage in cut-block edge vulnerability modeling by Mitchell et al. (2001). Studies by Worrall and Harrington (1988) in Crawford Notch, New Hampshire found gap size from chronic wind stress, and windsnap or windthrow increased strongly with elevation, accounting from over 60% of the gap area at 764 m (2521 ft) to almost 85% of the gap area at 1130 m (3729 ft). Gap formation led to subsequent mortality from chronic wind stress and windthrow in gap edge trees. This trend was confirmed on Camel's Hump in Vermont by Perkins and Klein (1992). These trends are driven by surface friction acting counter to the force of the wind. Wind speed will increase locally with elevation because surface friction will decrease (Bair, 1992).

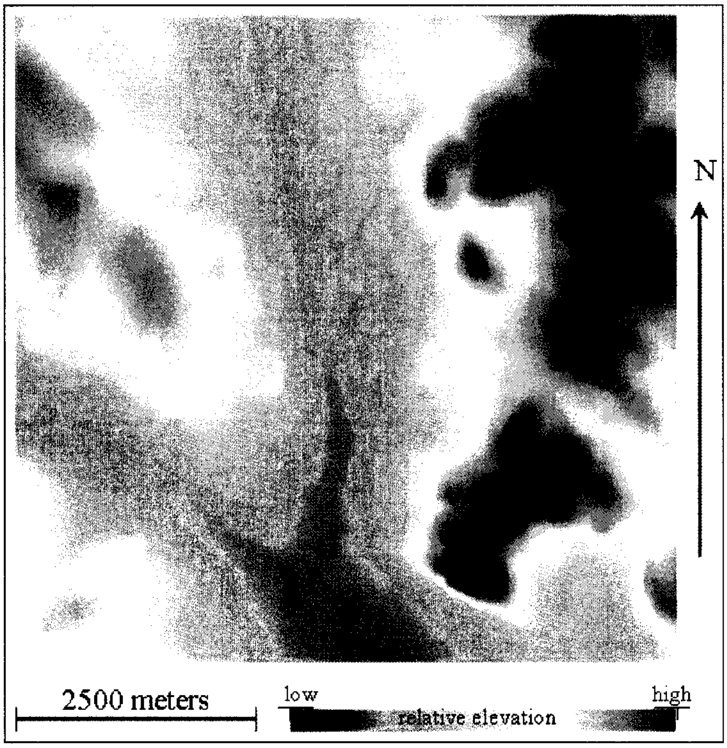


Figure 2.4: A Section of the Digital Elevation Model Providing Elevation Data for the Study Area.

2.2.2 Site - Exposure:

Topographic exposure is a critical variable in assessing stand vulnerability. Several indices have been created to describe relative topographic exposure or topographic protection. Distance-limited Topex was chosen for this project because of its relatively easy calculation and strong correlation to wind tunnel simulation (Ruel et al., 1997). The TOPEX wind exposure index has been used for some time in assessing windthrow risk in Great Britain (Miller, 1985) and the importance of topographic exposure in modeling windthrow risk has been demonstrated in other areas with forest based economies. "This variable accounts for over 77% of the British (wind) hazard rating system's total score (Ruel et al., 2002)".

Topographic exposure rasters were generated from a 30 meter digital elevation model using a software program developed and provided by The Windthrow Research Group, University of British Columbia, Vancouver, Canada. The exposure model calculates an index of exposure that is the summation of the maximum (positive) and minimum (negative) angles to the skyline within a user specified distance (Figure 2.5 and Figure 2.6). The index can be calculated in the eight cardinal directions and weighted according to user preferences; or, it can produce an index of exposure without directional weights.

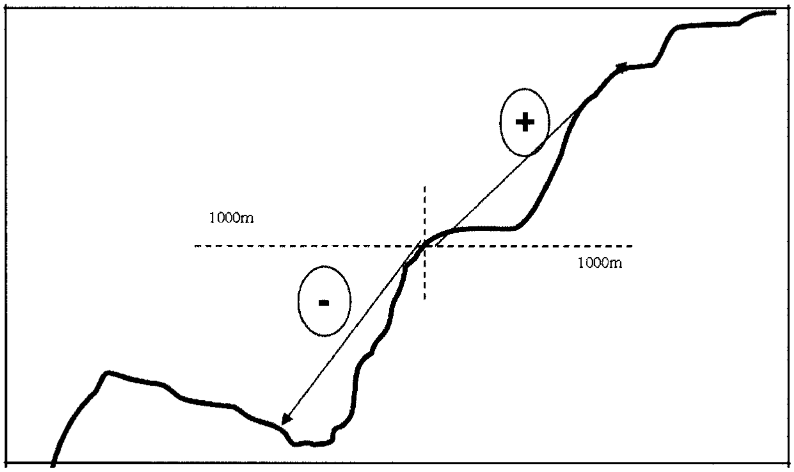
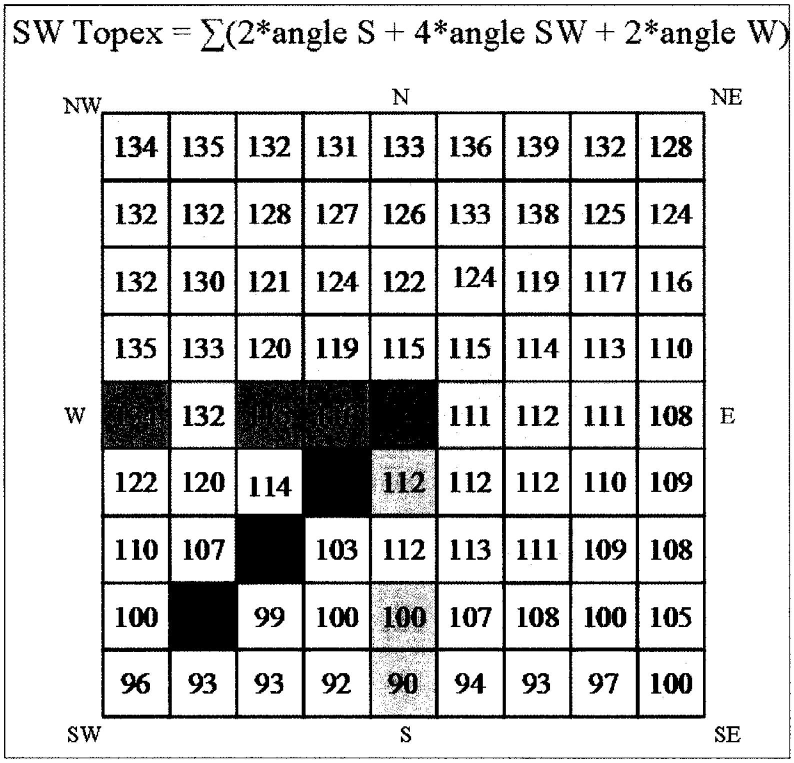


Figure 2.5: Positive and Negative Skyline Angle. Topex sums the skyline angles with directional weights in up to eight directions and a user specified limiting distance.



SW Topex = $\sum(2*\text{angle S} + 4*\text{angle SW} + 2*\text{angle W})$

134	135	132	131	133	136	139	132	128
132	132	128	127	126	133	138	125	124
132	130	121	124	122	124	119	117	116
135	133	120	119	115	115	114	113	110
[illegible]	132	[illegible]	[illegible]		111	112	111	108
122	120	114		112	112	112	110	109
110	107		103	112	113	111	109	108
100		99	100	100	107	108	100	105
96	93	93	92	90	94	93	97	100

Figure 2.6: Topex Calculation from a Hypothetical Height Grid. This grid simulates the calculation for exposure to the southwest from an elevation grid. Cell numbers represent elevation values for each grid cell, or pixel. The fuchsia cell in the center of the grid is the cell the for which the index will be calculated. The yellow cells represent the point of the maximum or minimum skyline angle in the user specified directions. User weights are specified in the equation at the top of the figure.

Ten exposure grids were produced for this project (Figure 2.7). These exposure grid values were indexed between zero and one. Eight grids represent topographic exposure in the eight cardinal directions with a limiting distance of 1000 meters, the remaining two grids represent exposure without directional weighting with a limiting distance of 1000 meters and 1500 meters respectively. Modeling by Lekes and Dandul (2000) utilized exposure data for the eight cardinal directions only.

Inclusion of the un-weighted grids may be beneficial because it identifies consistently exposed areas.

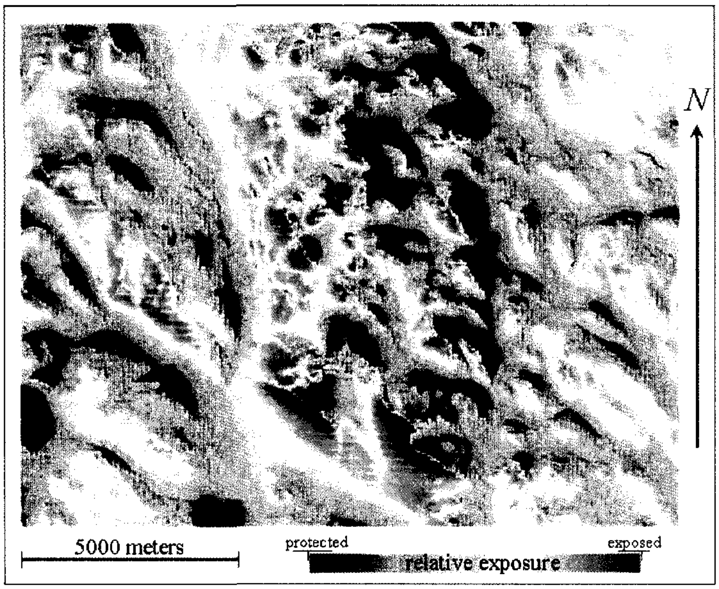


Figure 2.7: Topographic Exposure Grid Modeling Exposure to Southwest Winds

2.2.3 Site - Soils:

Forest soils represent a major component in understanding the inherent site susceptibility associated with forest stands. Soil aeration, ease of soil penetration by roots (rooting depth), and moisture holding capacity all affect the pattern of root development. Generally, loose drier soils facilitate deeper rooting and spread root systems further than shallow clayey soils (Mergen, 1954). Soil data is a critical component in several empirical wind vulnerability models already developed (Lekes and Dandul, 2000; Wilson, 2000; Mitchell et al., 2001)

Shallow soils, which limit rooting depth and saturate easily, like those commonly found in the spruce flat forest type of Maine, are increasingly prone to windthrow when saturated. The mass of soil that roots adhere to for anchorage becomes so wet it no longer adheres to itself, and the tree loses a substantial portion of its basal mass, crucial for resistance to windthrow (Day 1950). To compound the problem on wet soils, the rocking of the root plate can pump mud out from under the tree, further reducing its stability (Maccurach, 1991).

Depth to groundwater was consistently cited by Maine forestland managers as crucial to predicting the likelihood of blowdown in stands. Depth to groundwater data from the Maine Cooperative Forestry Research Unit was combined with rooting depth data from the US Department of Agriculture Natural Resources Conservation Service (NRCS) to create a restricted rooting depth variable. NRCS data consisted of two components. The first component was a soil polygon shapefile, with a minimum mapping unit of 40 acres, containing soil series names and numbers. The soils polygons were delineated from vegetation type maps and are not directly from an intensive soil survey. The second component was NRCS datasheets of soil attributes associated with the series and numbers in the shapefiles. The attribute table for this shapefile was appended with a new column, rooting depth. Data were entered manually into this column from the NRCS soil series description datasheets. The NRCS data provided a range, minimum and maximum values, for the rooting depth of each soil series. The midpoint of this range was entered into the shapefile as the restricted rooting depth. A raster of this variable was created from the shapefile following data entry (Figure 2.8). This restricted depth raster was combined with the CFRU's depth to groundwater raster (Figure 2.9). The combination process selected the minimum value at each point creating the composite restricted rooting depth raster used in the model (Figure 2.10).

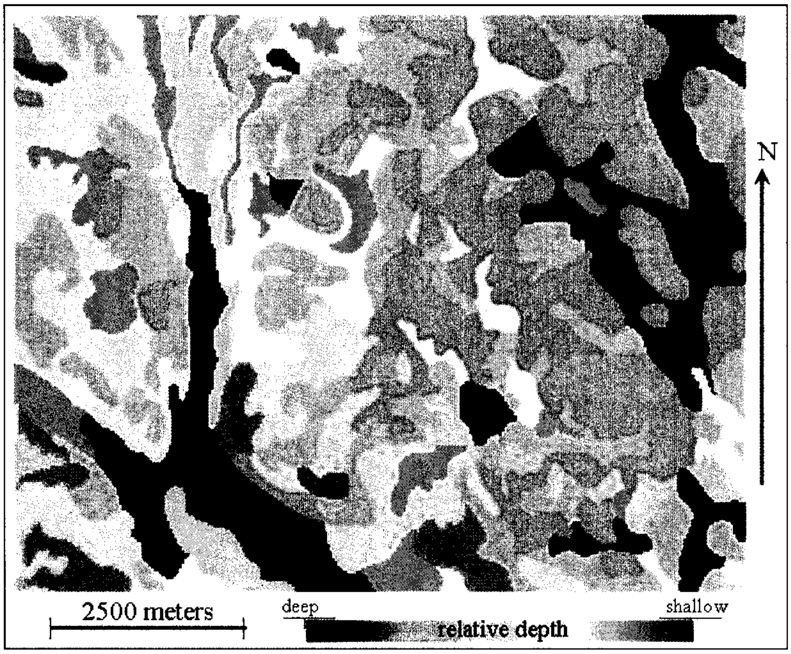


Figure 2.8: Restricted Rooting Depth Grid Produced from NRCS Data.

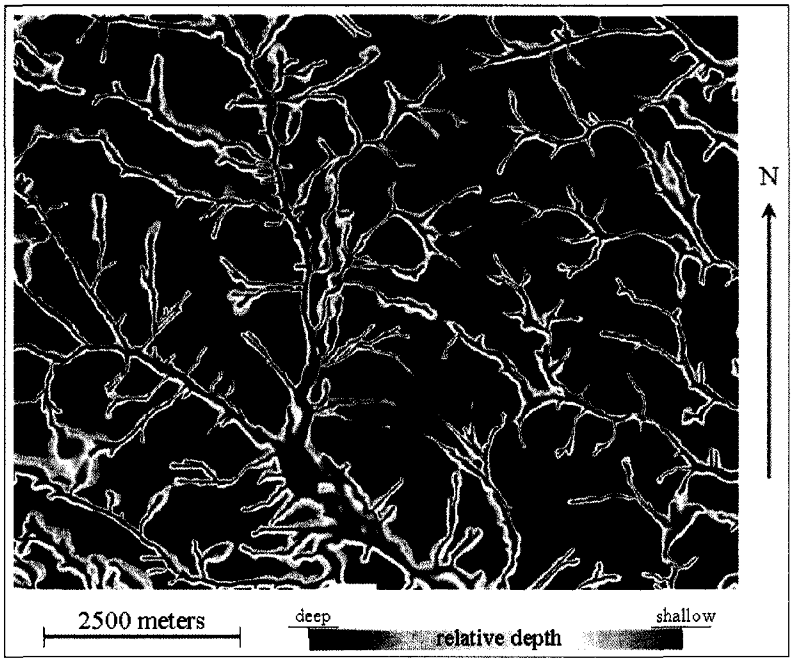


Figure 2.9: Depth to Groundwater Grid from the Maine Cooperative Forestry Research Unit (2006).

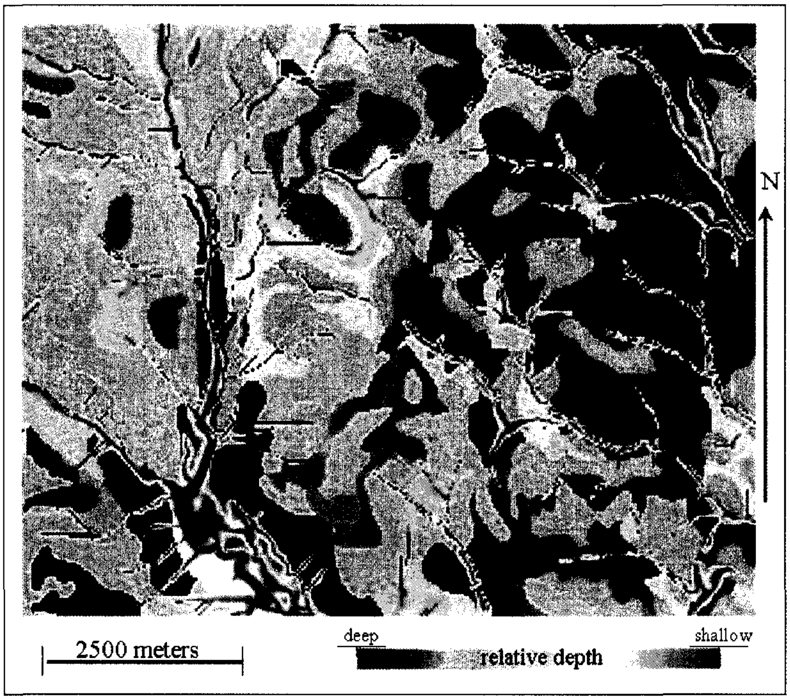


Figure 2.10: Composite Restricted Rooting Depth Grid. This grid is generated by selecting the minimum value, or the shallower value, of the two input grids.

2.2.4 Stand - Composition and Characteristics:

Variables describing stand composition and characteristics were extracted from the forest landowner GIS database, which contains stand level information to a minimum size of one acre. Stand composition is recorded under a three variable scheme (Table 2.2). These three variables are: (1) a 4-class species type code is used to define the proportions of hardwood and softwood in the stand; (2) a four class height code is used to define heights along a gradient of saplings to sawtimber; (3) a four class density code defines crown closure of the overstory. Dominant species are also recorded for the overstory.

Table 2.2: Three Variable Stand Type Scheme. Sixty-four unique stand type combinations are possible with the stand-typing scheme illustrated in the table.

Species Type Code	Height Code	Density Code
H: > 75% hardwoods	1: seedlings	A: 100-75% crown closure
S: > 75% softwoods	2: saplings	B: 75-50% crown closure
HS: > 50% hardwoods	3: pole size timber	C: 50-25% crown closure
SH: > 50% softwoods	4: sawlog timber	D: 25-0% crown closure

The database also consistently records stand history into the mid 1980's; history fields include stand damage by wind storms and previous harvest entries. The history records include the year of the event, and the event type or silvicultural prescription. An iterative network of Microsoft Access™ queries was developed and used to isolate prior stand entry, wind damage events and to create a vulnerability index based on tree type and the presence or absence of balsam fir (species risk index).

During the initial development of the model, a more complex index was created incorporating all of the variables mentioned above, height density, species classification, and balsam fir presence. The index was built on several assumptions and the result was an index with similar values for drastically different stands and a lack of interpretability for risk evaluation. For the final version of the model individual indices were created for the species composition, height, and density of the mapped stands.

The species risk index assigns ranks for the four potential forest types (H=0.3; S=0.7; HS=0.45; SH=0.55). The forest type rank is combined additively with an adjustment factor for the presence of balsam fir in the overstory; high rates of root rot predispose fir to wind damage, and are discussed in detail in chapter one. The balsam fir adjustment considers the relative abundance of balsam fir in the overstory The database lists the three most dominant species in the overstory and the balsam fir adjustment (0.3) is divided by the rank of overstory species dominance (1, 2, or 3) it occupies in each stand. The maximum adjustment for the presence of balsam fir is 0.3; this adjustment indicates balsam fir is the primary species in the overstory. The minimum adjustment for the presence of balsam fir is 0.1, indicating balsam fir is the tertiary overstory species. After adjusting the stand type index for the presence of balsam fir, the maximum risk value is 1.0, for softwood stands dominated by balsam fir. Hardwood stands with no Balsam fir in the overstory have the lowest risk index value for forested areas, 0.3. Sites with no trees present are assigned a value of 0.

Stand risk index values were appended to the attribute tables of the database shapefiles, then rasterized to produce the stand composition risk grid (Figure 2.11).

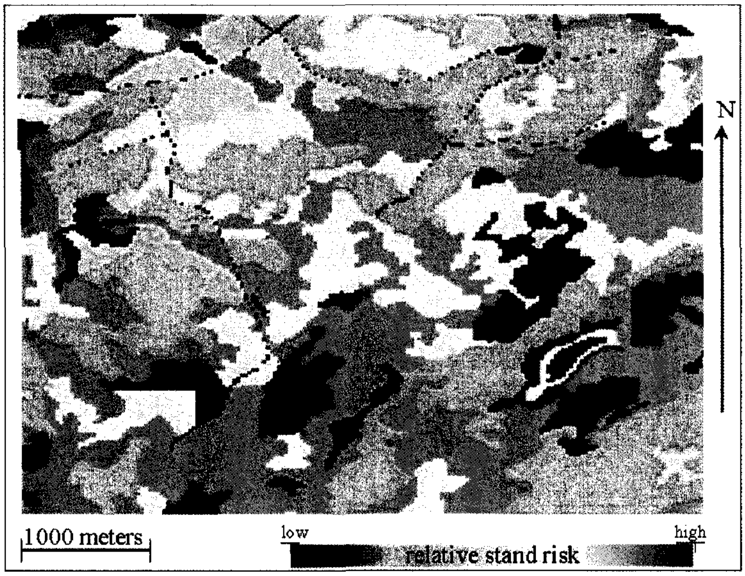


Figure 2.11: Portion of the Species Composition Risk Grid. Grid values display the combination of forest type and overstory presence, or absence, of balsam fir.

2.2.5 Stand - Thinning:

Stands are more vulnerable to windthrow following thinning, or partial removals, for two reasons. First, the increase in spacing resulting from thinning creates more canopy roughness, which in turn increases turbulence of the wind at the canopy level. Increased turbulence and wind penetration results in reduced tree stability. In addition, since support from neighboring trees is diminished, alignment of gust and tree sway frequencies is more likely, causing more stand windthrow and windsnap (Blackburn et. al., 1988; Maccurrach, 1991). Second, high initial stand density produces unfavorable H:D ratios (Wilson and Oliver 2000). This is less of a problem if stand density remains high; however, thinning removes the support of neighboring stems, dramatically increasing stand vulnerability. This period of vulnerability may last from a few years to over a decade. It is diminished as crown closure occurs in the stand and stems and roots become more windfirm.

As mentioned in chapter one, Lohmander and Helles (1987) argued that no significant differences between windthrow rate and thinning pattern were evident when windthrow was examined across different thinning regimes. Gardiner (1997) also obtained similar results and determined wind velocity over the canopy depends on stand density and not on the pattern of thinning.

The forest stand database provided for the project specifies silvicultural treatment on a stand by stand basis. A preliminary analysis was conducted to determine the structure of the thinning index variable. A proportional analysis was performed on the wind damage database to detect trends between prior silvicultural treatment and wind damage. This analysis was conducted to evaluate the possibility of a more refined thinning variable. Thinning grids differentiating silvicultural treatments were produced, and wind damage locations were overlaid onto these grids. Pixels in each treatment type were summed and separated by blowdown occurrence to determine the proportion of stands blowing down by treatment and the proportion of blowdown represented by each treatment (Table 2.3)

Table 2.3: Proportion of Stands Blown Down Relative to Silvicultural Treatment.

Silvicultural Prescription	Percent Blowdown by Treatment	Percent of Total Blowdown
no treatment	0.38	7.90
crown thin	2.33	0.32
group selection	96.67	3.24
low thin	0.00	0.00
Other	0.00	0.00
Spacing	0.00	0.00
Selection	17.26	88.12
strip cut	0.00	0.00
shelterwood removal	4.12	6.54
selection thin	0.00	0.00
shelterwood prep.	0.00	0.00
shelterwood reserves	89.11	1.77

Results from this analysis show only 0.38% of the recorded blowdown occurred in unthinned stands. Both group selection and shelterwood with reserve systems appear highly vulnerable; however, they comprise only a small percentage of the total harvested area. Conversely, selection appears less vulnerable but the majority of land impacted has been harvested under this regime. While selection is a distinct silvicultural prescription it may result in highly varied post-harvest structures. In addition, selection has been used interchangeably with selective harvesting in the profession. Selective harvesting does not follow specific silvicultural guidance and is best described as a partial harvest. After considering inconsistent reporting in the literature and these data trends, it was determined that a binary variable would best capture risk associated with stand entry from thinning and partial harvesting for the model.

A binary index raster of stand treatments was created from the records of stand entry in the landowner database (Figure 2.12). All prior entries that involved incomplete removal of the overstory, and occurred in the decade preceding the most recent wind event (2001) were classified as thinned. Clearcuts and uncut stands were classified as unthinned. Thinned stands were assigned a value of one and unthinned stands a value of zero.

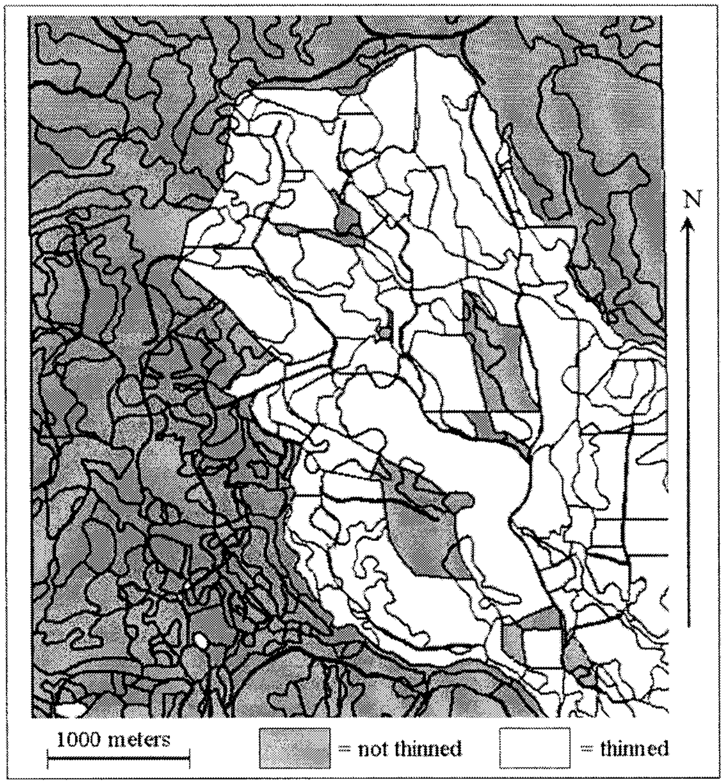


Figure 2.12: Binary Thinning Grid. Stand boundaries are shown in black.

2.2.6 Stand - Edge:

Edges are formed from clearcutting blocks of forest, road building, or stand replacing disturbances like wildfire and catastrophic blowdowns. Less damage is associated with clearcutting, compared to thinning, since the unit boundaries (edges) are the only areas with increased susceptibility to damage (Alexander, 1964). These edges create large turbulent eddies that impact the stand at a distance between 10 and 15 times the height of the edge trees (Papesch, 1974; Savill, 1983).The majority of wind damage along the boundary occurs during the first severe windstorm following the harvest, the boundary tends to stabilize after this initial loss (Alexander, 1964).

Natural, or inherent, edges are also found in forested landscapes. These edges occur as a result of major changes in the substrate or local landforms. Rock outcroppings and lakes create this type of natural edge. Inherent edges are not as susceptible as induced edges (edges created by management) since trees occupying these inherent edges have developed under more windstress than trees in closed forests and it is inferred that these trees will have undergone structural development similar to trees in spaced stands..

For this project edge is defined as the portion of the stand that is occupied by a boundary two height classes taller than an adjacent stand; inherent edges found in the landscape were not included in the development of this variable. An indexed edge grid, describing the proportion of stand area classified as edge, was produced from stand height data. Production of this data layer was a multi-step procedure.

First a raster of stand height was produced and processed with the Topex software program (the same program used for determining exposure based on elevation data) with a limiting distance of 30 meters, or one pixel, and no directional weights. This identified all height class differences. Positive values indicated edges of shorter stands, and negative values indicated edges of taller stands (Figure 2.13).

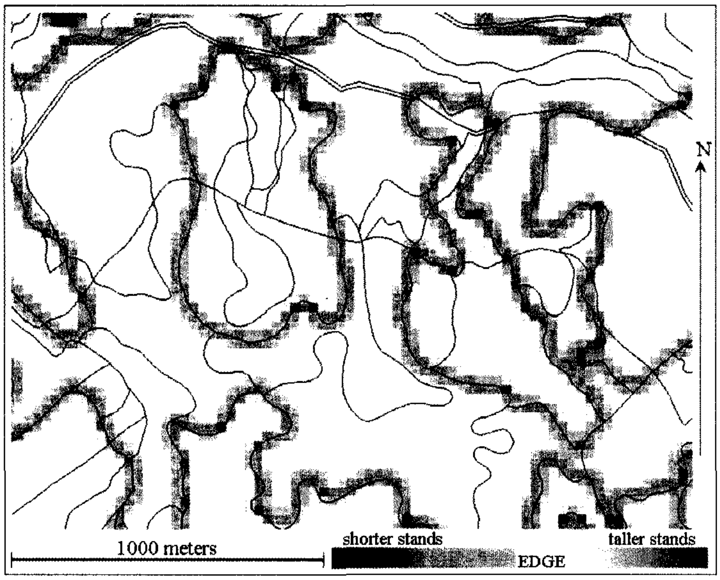


Figure 2.13: Topex Generated Grid of Stand Edges. The center of the image shows two taller stands in the middle of an area of shorter forests stands, stand boundaries are delineated in black.

The same grid of stand heights was also analyzed with Arc9's zonal statistics range tool. Range statistics defined all edges classified by the height differences between the two adjacent stands. This raster was recoded to display only edges two height classes or greater. The Topex-generated edge raster and range-statistics raster were combined to identify the edges of the taller stands (negative topex scores) when the height difference between adjacent stands was greater than two height classes (range statistic greater than two). This raster stored all pixels representing edges as "one" and all non-edge pixels as "zero". The zonal statistics tool was used to calculate the percentage of edge within the individual stands. Stands delineated in the GIS database were used as zones; and the mean of all pixels was calculated for each stand. This statistic was used directly as the proportion of the stand classified as edge, as defined above (Figure 2.14).

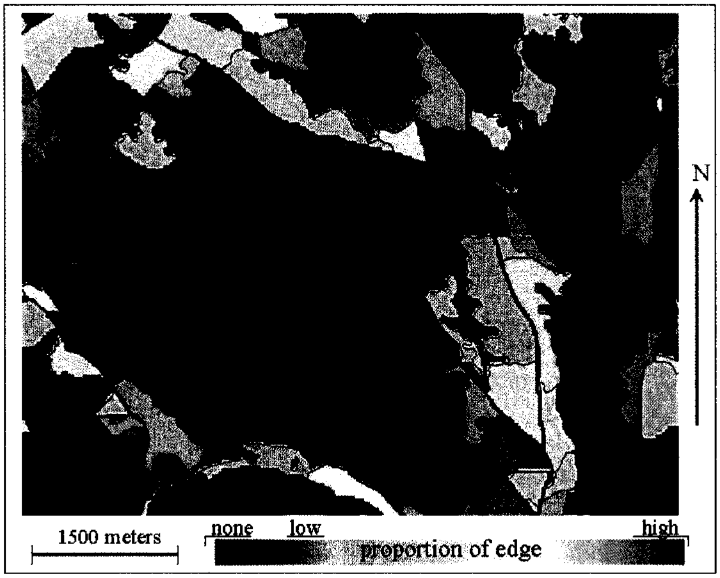


Figure 2.14: Proportion of Stand Categorized as Edge; a Positive, Between Stand Difference of Two Height Classes.

2.2.7 Stand – Height:

A grid of stand heights was built directly from the landowner database. The stand type height code was rasterized, creating a raster with five potential data values (0-non-forest; and 1 through 4 representing the height classes found in Table 2.2). The values were divided by four, the maximum value to create the desired index range, between zero and one.

2.2.8 Stand – Density:

The density grid captures the overstory density of the stands in the study area. Access queries determined the height and density of the most dominant or two most dominant species in each stand, if more than one species were present. Queries assigned values corresponding to the original alphabetical density codes of the most dominant overstory species. Density of the primary overstory species was collected and modified if the secondary species was also in the same canopy strata. If the secondary species was not in the same strata then only the density of the primary species was recorded. The density variable was modified if the secondary species was denser than the primary species. The density index was created by dividing the density values by the maximum possible value, three (Table 2.4).

Table 2.4: Density Codes and Their Index Values.

Density Code	Value		Density Code	Value
A	0.333		C	1.000
AB	0.333		CA	0.750
AC	0.333		CB	0.833
AD	0.333		CC	1.000
AA	0.333		CD	1.000
B	0.667		D	1.000
BA	0.500		DA	0.750
BB	0.583		DB	0.833
BC	0.667		DC	1.000
BD	0.667		DD	1.000

2.2.9 Cumulative Risk:

The cumulative risk grid is composed in two stages. In the first stage individual site and stand components are combined to form separate composite stand and composite site grids. The three site variable grids are combined additively and the five stand variable grids are combined additively to form a composite stand grid (Figure 2.15) and a composite site grid (Figure 2.16).

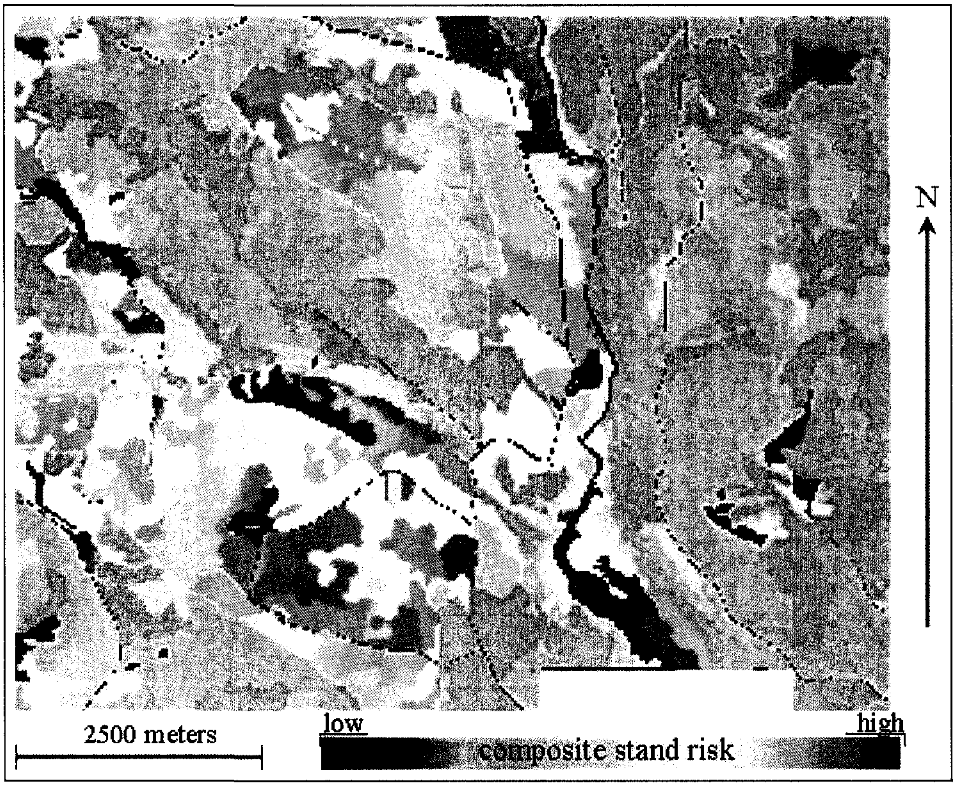


Figure 2.15: The Composite Stand Grid for a Portion of the Study Area.

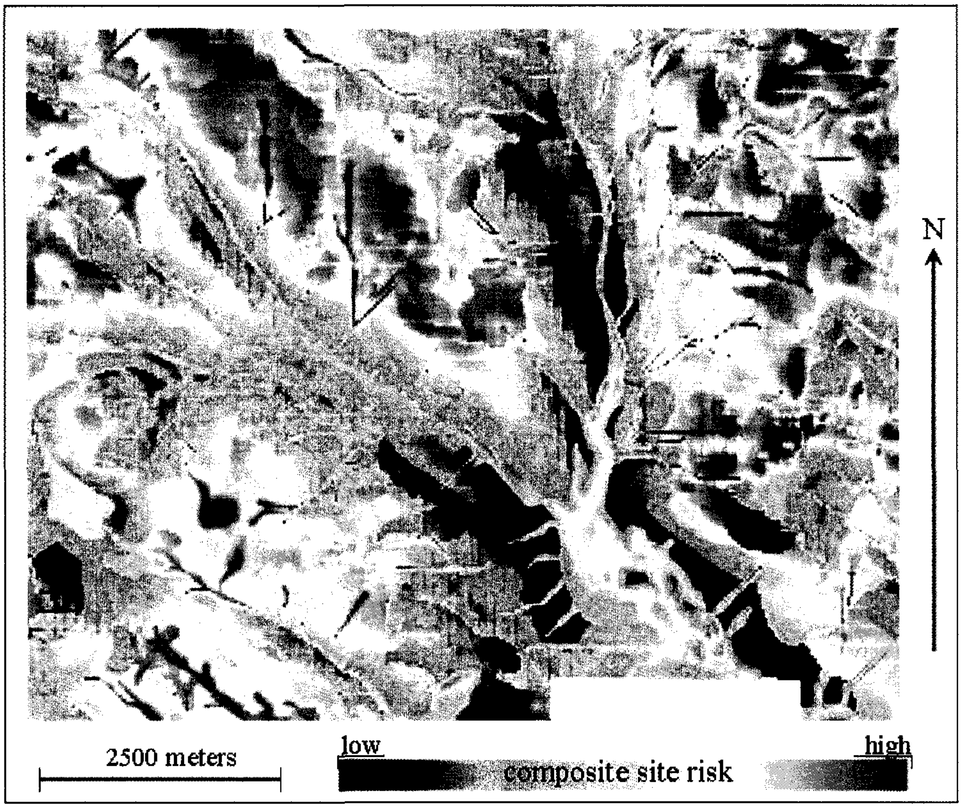


Figure 2.16: The Composite Site Grid for a Portion of the Study Area. The exposure input variable for this example models exposure to the southwest.

The second stage combines the composite site risk grid and composite stand risk grid additively to form a cumulative windthrow risk grid combining both the site and stand risk factors (Figures 2.17 and 2.18). All input grids have been indexed between zero and one and this index range is maintained through both combination phases. Ten separate grids are produced, one for each direction of exposure grid (eight cardinal directions and two without directional weighting). All grid combinations were performed with the single output map algebra tool in Arc9's spatial analyst toolbox.

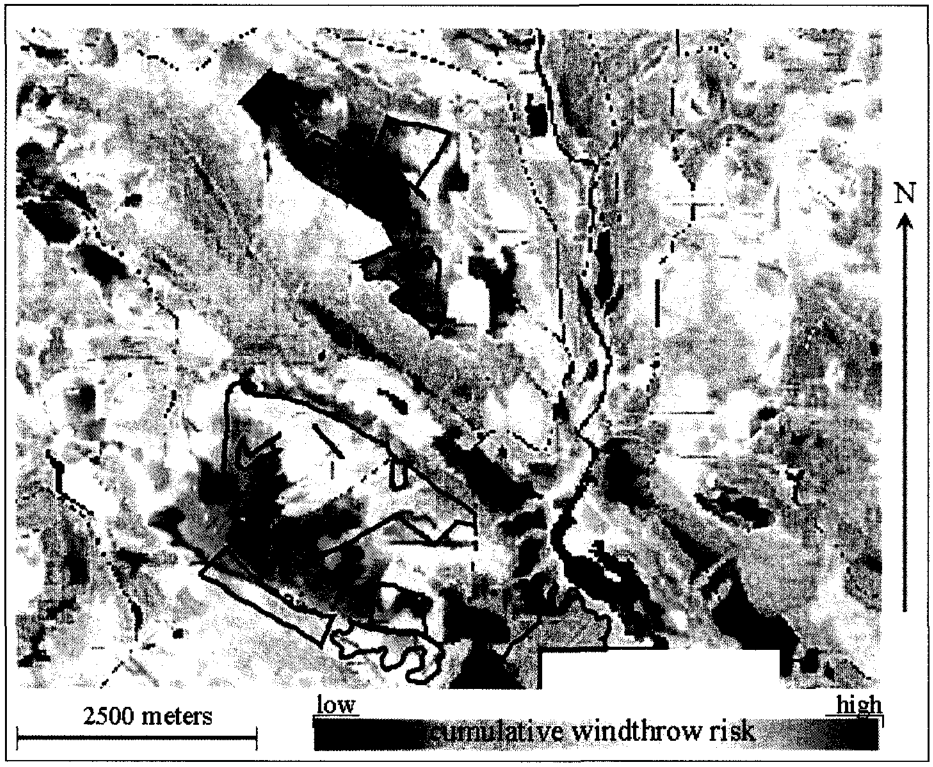


Figure 2.17: Cumulative Windthrow Risk Grid for a Portion of the Study Area. The exposure input variable for this example models exposure to the southwest. Locations of actual wind damage are outlined in black.

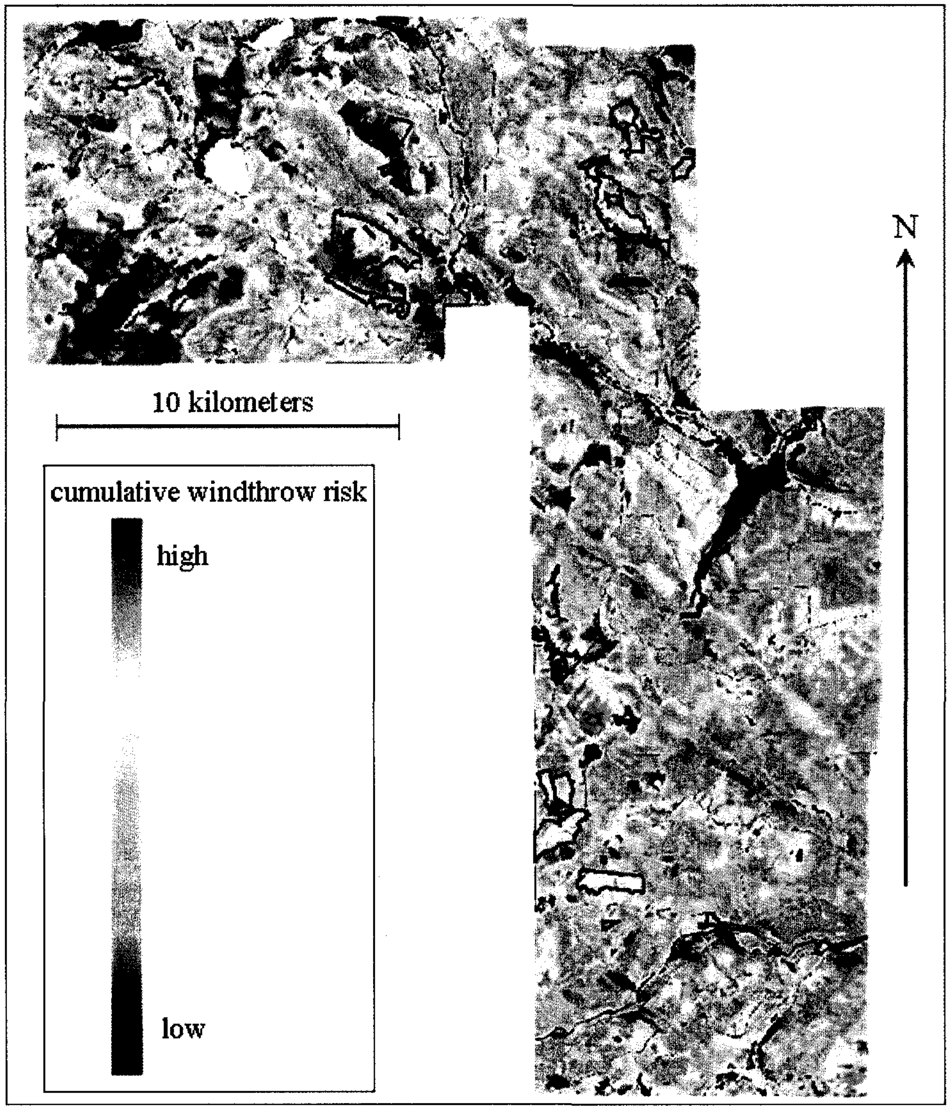


Figure 2.18: Cumulative Windthrow for the Entire Study Area. The exposure input variable for this example models exposure to the southwest. Locations of actual wind damage are outlined in black.

2.3 Model Evaluation:

An analysis of all polygons in samples with a high degree of adjacency is inappropriate because of spatial autocorrelation inherent to this type of data. Spatial autocorrelation can be found in all ecological data and describes the degree to which data or variables correlate with each other in space. This correlation can cause problems statistically since ecological variables are not truly randomly distributed in the landscape (Legendre, 1993). ArcGIS© software provides a spatial statistics tool set to explore the degree of auto correlation in spatial data. Moran's I tests were conducted on all stand variables. Strong autocorrelation was found for all the stand variables in the model. All tests satisfied an alpha of 0.01, suggesting that there is less than a one percent chance that the probability that the clustered pattern in the data is random. The analysis is not available for raster data although both soils and elevation are inherently autocorrelated. Almost any variable sampled across geographic space will be non-random (Legendre, 1993).

To avoid problems associated with spatial autocorrelation, the wind damage vulnerability model was analyzed with a comparison of means from a random sample of polygons within the study area. Random samples of polygons were developed using Hawth's Analysis tools, an add-in available for ARCGIS. To ensure that the random samples did not include adjacent polygons, random points were selected with a 420 meter minimum distance between points. This was the minimum between-point distance that produced a limited amount of adjacent stand selection. To ensure consistent results, ten separate random samples of polygons were drawn from the study area. These ten samples are analyzed individually and the results pooled to measure consistency between the samples. All model variables were analyzed in this manner. This includes all the individual model components, the grouped variable site and stand components, and the cumulative risk grid. Approximately 560 polygons are sampled in each random iteration, accounting for roughly fourteen percent of the study area in each sample. The sample size criterion was based on maximizing area sampled with a minimum of adjacent stands.

The vulnerability variables were analyzed individually to detect differences between the means of the two populations, polygons with a record of blowdown and polygons with no blowdown record. The analysis uses either a two sample t-test or a Mann-Whitney test to detect differences between the population means. Mann-Whitney was chosen as the default test, because this non-parametric test is justified in all situations where the t-test is applicable and in situations where the assumptions of the 2-sample t-test are not met (Zar, 1984).

Tests used an alpha of 0.05 to test the null hypothesis, the means between the two populations are equal: H_0: $\mu1 = \mu2$. Results from the analysis of the ten samples were tested for consistency with a t-test. Significant results from the Mann-Whitney tests were coded as either one, positive correlation with the model, or negative one, negative correlation with the model. Non-significant results were coded as a zero.

The t-test was applied if significance was not detected, but a close to significant p-value was obtained (alpha <0.10 and >0.05) from the Mann-Whitney tests, and a significant result would change the results of the subsequent consistency analysis. To assess the applicability of the 2-sample t-test, the residuals were examined diagnostically to ensure data met the model's assumptions that "both samples come at random from normal populations with equal variances" (Zar, 1984).

The consistency analysis utilized a one sample t-test. The t-test procedure tested for statistically significant differences between the responses of the individual model variables across the ten samples. A mean statistically not equal to zero indicated consistent significance, reflecting either positive or negative difference between means. Tests used an alpha of 0.05 to test the null hypothesis that the means between the two populations are equal: H_0: $\mu 1 = \mu 2$.

2.4 Results and Discussion:

Several model variables were found to have statistically significant differences between the two populations (blowdown and non-blowdown). However, not all statistically significant differences were in the direction expected. Positive difference is used to describe statistically significant differences between populations in the direction expected, based on assumptions from preliminary model research. Negative difference refers to statistically significant differences between populations in the opposite direction expected based, on assumptions from preliminary model research.

Table 2.5 shows the difference between the means and the index ranges of the individual variables. Table 2.6 displays p-values from the ten randomly sampled test populations for all the individual component variables. Table 2.7 displays p-values from the ten randomly sampled test populations for all the composite variables created from the individual components in Table 2.6. "stand_cmltv" is the composite stand variable created from the stand component variables. The 10 site grids are comprised of all site components and are identified by the topographic exposure input variable. The ten "cmltv_" grids are the combination of the composite stand and site variables, identified by the topographic exposure input variable. The tables have been color coded for ease of interpretation.

Table 2.5: Difference Between the Means of Wind Damaged and Not Damaged Polygons. Colored cells indicate statistically significant differences between population means. Orange represents negative difference between means and yellow represents positive difference between means.

	Difference Between Population Means	Index Range of Both Populations	The Difference's Proportion of the Range	Range of Wind Damage Population
soil depth	-9.30	100.00	0.09	100.00
topex_north	-5.45	92.96	0.06	90.38
topex_ne	-4.55	98.74	0.05	87.11
topex_nw	-2.98	98.90	0.03	93.56
topex_east	-1.98	99.60	0.02	97.98
species	-1.35	100.00	0.01	80.43
density	-1.19	100.00	0.01	69.59
topex_1000	-0.64	81.65	0.01	76.57
topex_1500	-0.31	83.84	0.00	78.14
topex_se	0.72	99.49	0.01	86.71
topex_west	1.01	99.15	0.01	98.08
site_north	1.03	69.34	0.01	50.39
site_ne	1.39	70.07	0.02	49.03
site_nw	1.82	63.38	0.03	57.27
site_east	2.26	68.15	0.03	49.54
edge	2.32	100.00	0.02	50.77
site_1000	2.69	66.61	0.04	54.24
site_1500	2.80	65.26	0.04	52.95
topex_south	2.92	89.87	0.03	87.46
site_se	3.15	74.18	0.04	50.44
site_west	3.19	67.18	0.05	60.56
topex_sw	3.52	97.37	0.04	95.71
site_south	3.86	77.40	0.05	53.05
site_sw	4.05	70.78	0.06	60.68
cmltv_north	8.23	62.90	0.13	36.25
cmltv_ne	8.40	65.16	0.13	33.16
cmltv_nw	8.64	61.64	0.14	40.77
cmltv_east	8.84	63.89	0.14	32.25
cmltv_1000	9.05	61.63	0.15	35.95
cmltv_1500	9.11	61.55	0.15	36.39
cmltv_se	9.29	62.24	0.15	34.34
cmltv_west	9.32	64.68	0.14	43.73
cmltv_south	9.65	64.17	0.15	38.50
cmltv_sw	9.75	64.68	0.15	42.00
height	11.41	100.00	0.11	34.78
stand_cmltv	15.46	87.52	0.18	62.95
elevation	17.87	99.83	0.18	98.81
thinning	74.28	100.00	0.74	100.00

Table 2.6: P-Values for Individual Model Component Variables Listed by Randomly Sampled Test Population Number. Uncolored cells are non significant, yellow cells are significant (alpha = 0.05) and indicate a positive difference between the population means, green values are significant with an alpha of 0.10 and and indicate a positive difference between the population means. Orange cells are statistically significant (alpha=0.05) and indicate a negative difference between the population means, purple cells indicate a negative difference between the population means at an alpha of 0.10. The two sample t-test was used on normal variables with p-values less than 0.10 and greater than 0.05 if a significant result would change the result of the consistency analysis.

	RANDOMLY SAMPLED TEST POPULATION NUMBER									
VARIABLES	1	2	3	4	5	6	7	8	9	10
Density	0.693	0.602	0.141	0.307	0.184	0.311	0.945	0.491	0.190	0.193
Edge	0.969	0.739	[illegible]	[illegible]	[illegible]	0.354	0.576	[illegible]	[illegible]	0.366
Height	0.000	0.022	0.000	0.001	0.000	0.137	0.003	0.002	0.002	0.009
species	0.338	0.294	[illegible]	0.825	0.867	0.787	0.960	0.243	0.460	0.182
thinning	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
elevation	0.001	0.002	0.001	0.001	0.000	0.003	0.007	0.001	0.000	0.001
soil depth	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.240	0.101	[illegible]	[illegible]	[illegible]
topex_1500	0.302	0.720	[illegible]	0.873	0.744	0.531	0.852	0.165	0.146	0.577
topex_1000	0.388	0.705	0.050	0.929	0.629	0.676	0.907	0.188	0.172	0.555
topex_north	0.805	[illegible]	0.737	0.262	[illegible]	0.092	0.449	0.488	[illegible]	0.110
topex_ne	0.919	[illegible]	0.321	0.154	[illegible]	0.146	0.922	0.875	[illegible]	0.199
topex_east	0.852	0.164	0.269	0.302	0.459	0.265	0.924	0.613	0.181	0.439
topex_se	0.792	0.279	0.247	0.926	0.665	0.717	0.759	0.371	0.372	0.353
topex_south	0.199	0.438	0.259	0.646	0.214	0.119	0.766	0.155	0.900	0.911
topex_sw	0.093	[illegible]	0.510	0.220	0.278	0.014	0.791	0.197	0.764	0.748
topex_west	0.536	0.335	0.727	0.426	0.550	0.143	0.309	0.891	0.525	0.825
topex_nw	0.647	0.337	0.265	0.504	[illegible]	0.532	0.153	0.498	[illegible]	0.263

Table 2.7: Table 2.4.2: P-Values for Composite Variables Listed by Randomly Sampled Test Population Number. Uncolored cells are non significant, yellow cells are significant and indicate a positive difference between the population means, green values are significant with an alpha of 0.10 and indicate a positive difference between the population means.

	RANDOMLY SAMPLED TEST POPULATION NUMBER									
VARIABLES	1	2	3	4	5	6	7	8	9	10
stand_cmltv	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
site_1500	0.423	0.666	[redacted]	0.311	0.040	0.019	0.180	0.026	0.793	0.397
site_1000	0.450	0.677	[redacted]	0.336	0.040	0.022	0.222	0.028	0.818	0.419
site_north	0.759	0.890	0.214	0.558	0.438	0.319	0.599	0.288	0.968	0.559
site_ne	0.817	0.769	0.101	0.723	0.306	0.306	0.455	0.166	0.968	0.443
site_east	0.941	0.890	0.037	0.324	0.038	0.187	0.252	[redacted]	0.523	0.279
site_se	0.348	0.402	0.040	0.147	0.002	0.032	0.146	0.023	0.150	0.143
site_south	[redacted]	0.157	0.118	0.190	0.002	0.003	0.111	0.025	0.168	0.153
site_sw	0.106	0.123	0.343	0.125	0.009	0.002	0.104	[redacted]	0.224	0.158
site_west	0.260	0.210	0.425	0.116	0.064	0.005	0.147	0.128	0.272	0.180
site_nw	0.919	0.545	0.371	0.210	0.333	[redacted]	0.379	0.198	0.690	0.395
cmltv_1500	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
cmltv_1000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
cmltv_north	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
cmltv_ne	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
cmltv_east	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
cmltv_se	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
cmltv_south	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
cmltv_sw	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
cmltv_west	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
cmltv_nw	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Four variables had the potential to influence the results of the consistency tests. Potential to influence the consistency results depends on a significant result in at least four of the ten samples. These variables were tested for normality (Table 2.8). Three of the four variables met the model assumptions of normally distributed residuals. Results from the T-tests indicate two of the three tested variables had a significant positive difference between sample population means (Table 2.9)

Table 2.8: Normality Test Results for Four Variables with Potential to Influence the Consistency Analysis. The number following the variable rename refers to the corresponding random sample.

	Shapiro Wilk test statistic for normality				
variable	site: south_1	site: 1000_3	site: 1500_3	edge_5	edge_8
test statistic	0.992442	0.992409	0.992774	0.703574	0.696456
distribution	normal	normal	normal	not normal	not normal

Table 2.9: T-test Results for the Three Variables Meeting the Model Assumptions of Normality.

	2-sample t-test; comparison of population means		
variable	site: south_1	site: 1000_3	site: 1500_3
p-value	0.127	0.045	0.046
null hypothesis	fail to reject	reject	reject

The results from the two sample T-tests were used to update the data for the consistency analysis. The consistency analysis utilized a one sample t-test. Results from the difference in means analysis were created for each variable from the ten iterations (0= no significant difference between population means; 1= positive significant difference between population means; -1= negative significant difference between population means), and served as the samples for this analysis. Variables that displayed the same relationship in all ten iterations cannot be tested for consistency in this manner. But, variables that displayed the same relationship in all ten iterations are considered inherently consistent. The thinning, elevation, composite stand, and all ten cumulative risk variables displayed a positive difference between the population means through all ten iterations and are considered statistically consistent.

The following tables summarize the results from the consistency analysis. Direction of difference between means, the percentage of random samples the relationship was demonstrated in, and test statistics evaluating the potential significance of these relationships are provided in Tables 2.10 through 2.14. Positive difference indicates that the mean risk value for the population of stands with recorded wind damage was higher than the mean risk value for the population of stands without recorded wind damage. Positive differences agree with the assumptions used during model construction. Negative difference indicates that the mean risk value for the population of stands with recorded wind damage was lower than the mean risk value for the population of stands without recorded wind damage. Negative differences do not agree with the assumptions used during model construction.

Table 2.10 Direction of the Difference Between the Means of Component Variables. Results displayed were all tested with an alpha of 0.05.

component variables	direction of mean difference	percent of iterations relationship is demonstrated
density	none	100%
edge	negative	30%
height	positive	90%
species	none	100%
thinning	positive	100%
soil depth	negative	70%
elevation	positive	100%
topex_1500	none	100%
topex_1000	positive	10%
topex_north	negative	20%
topex_ne	negative	10%
topex_east	none	100%
topex_se	none	100%
topex_south	none	100%
topex_sw	positive	10%
topex_west	none	100%
topex_nw	negative	20%

Table 2.11: Direction of the Difference Between the Means of Composite Variables. Results displayed were all tested with an alpha of 0.05.

composite variables	direction of model correlation	percent of iterations relationship is demonstrated
stand_cmltv	positive	100%
site_1500	positive	40%
site_1000	positive	40%
site_north	None	100%
site_ne	None	100%
site_east	positive	20%
site_se	positive	40%
site_south	positive	30%
site_sw	positive	20%
site_west	positive	10%
site_nw	none	100%

Table 2.12: Direction of the Difference Between the Means of the Cumulative Windthrow Risk Variables. Results displayed were all tested with an alpha of 0.05.

cumulative risk variables	direction of model correlation	percent of iterations relationship is demonstrated
cmltv_1500	positive	100%
cmltv_1000	positive	100%
cmltv_north	positive	100%
cmltv_ne	positive	100%
cmltv_east	positive	100%
cmltv_se	positive	100%
cmltv_south	positive	100%
cmltv_sw	positive	100%
cmltv_west	positive	100%
cmltv_nw	positive	100%

Table 2.13: Results from the Consistency Analysis of Component Variables. P-values, hypothesis test results and direction of the difference between means are reported.

component variables	p-value (a=0.05)	H_o: means are equal	direction of difference between means
edge	0.081	fail to reject	non-significant
height	0.000	reject	positive
soil depth	0.001	reject	negative
tpx_1000	0.343	fail to reject	non-significant
tpx_ne	0.343	fail to reject	non-significant
tpx_north	0.168	fail to reject	non-significant
tpx_nw	0.168	fail to reject	non-significant
tpx_sw	0.343	fail to reject	non-significant

Table 2.14: Results from the Consistency Analysis of Composite Variables. P-values, hypothesis test results and direction of the difference between means are reported.

composite variables	p-value (a=0.05)	H_0: means are equal	direction of difference between means
site_1500	0.037	reject	positive
site_1000	0.037	reject	positive
site_east	0.168	fail to reject	non-significant
site_se	0.037	reject	positive
site_south	0.081	fail to reject	non-significant
site_sw	0.168	fail to reject	non-significant
site_west	0.343	fail to reject	non-significant

The density variable did not produce significant differences between the population means in any of the iterations. The assumption based on the wind vulnerability literature (Lohmander and Helles, 1987; Gardiner, 1997) was that the less dense stands will be more susceptible. This was thought to be the case in an area with a long management history of natural regeneration and frequent stand entry. Stands thinned to a lower density are generally very susceptible to wind damage, conversely stands developing at lower densities tend to have more favorable height to diameter ratios. The fact that there was no significant difference between population means for this variable may indicate that the lower density classes are occupied by stands that have both developed at low initial densities or have harvest reduced densities.

The edge variable had a negative difference between population means with the model 30% of the time, not frequent enough to be considered statistically consistent. Most of the stands in the landscape being evaluated are in the two tallest height classes. This trend results in a landscape with very little edge in general. The edge that is present may be in areas at lower risk to wind or edge may not be a critical factor in this landscape. A graphic representation of the edge variable is provided in the methods sections (Figure 2.14).

The height had a positive difference between population means 90% of the time. This statistically consistent difference likely reflects the increased vulnerability to wind damage with increased tree size (Lohmander and Helles, 1987; Smith et al., 1987; Peltola and Kellomaki, 1993).

The species variable did not have a significant differences between the population means in any of the iterations. This was surprising considering managers all cited softwoods, and most notably balsam fir as being the most sensitive to wind disturbance. It may indicate a homogeneity within the landscape or an insensitivity of the index to differences in composition. The comparison of means would not detect differences if the landscape values are relatively similar, or if the range of index values was not large enough.

The thinning variable had statistically significant positive differences between the population means 100% of the time. This agrees with conventional wisdom of the land managers, windthrow is much more common in previously thinned stands. An evaluation of the landscape shows that 99.72% of the recorded blowdown occurred in thinned stands. However, as mentioned in chapter one, recording of wind damage is severely limited. The likelihood of damage detection depends on damage proximity to areas of recent and active operations and an unknown amount of undetected damage is being incurred. This may result in less detection of differences between the population means, and the actual differences between the population means could also be reduced. Many portions of the study area have high risk values, but blowdown is not recorded at these locations. It is not known whether this is because blowdown did not occur or it was not detected, and subsequently recorded due its remote location.

The composite stand grid, referred to as "stand_cmltv" in results tables, also had significant positive differences between the population means 100% of the time. This may primarily driven by the combination of the height and thinning components that comprise this composite variable. The thinning variables binary property makes it a relatively powerful component of the composite grid, 1.0 indicates thinning and 0.0 indicates that no thinning has occurred.

Differences between population means for the topographic exposure variables were never statistically consistent. This trend was noticed by Mitchell et al. (2001) when an analysis of their model revealed a level of contribution from topographic variables to the model lower than expected. Five of the exposure variables did not show any difference between population means in the ten iterations. Three exposure variables displayed a negative difference between population means with the model and two displayed a positive difference between population means. The model tested the effectiveness of two exposure variables with equal directional weighting but unique limiting distances (topex_1500 and topex_1000). Topex_1000 had a positive difference between population means in a single iteration, while topex_1500 did not display a difference between population means in any of the iterations. A limiting distance of 1000 meters was used for the remaining eight directionally weighted topographic exposure variables.

The exposure variables for the directions southeast, south and southwest appear to correlate well with visual evaluation of the topographic exposure variables. However, topex_sw (exposure to the southwest) is the only directionally weighted exposure variable to show a positive difference between population means, and this occurred in only one iteration. It is of interest that topex_ne, the northeast directionally weighted exposure variable (opposite of topex_sw), displayed a negative difference between population means. Both variables describing exposure to the north (topex_north) and northwest (topex_nw) also had a negative difference between population means. Simple terrain variables may not adequately describe airflow phenomenon induced by complex terrain (Mitchell et al., 2001). These trends in exposure variable means may also indicate the sensitivity of lee-slopes to damage.

The elevation variable had a positive difference between population means in the model 100% of the time. This agrees with the assumptions of susceptibility increasing in higher areas of the landscape, where exposure and wind speed are greater (Bair,1992).

The soil variable had a negative difference between population means. This trend was statistically consistent, occurring 70% of the time. This is counter to the original assumptions of the model, forests growing in areas with more restricted rooting depths would be more vulnerable to wind disturbance (Day,1950; Mergen, 1954). Two different explanations are possible. An analysis of the correlation between soil depth and elevation in this landscape yields a mean Pearson correlation of 0.344 for the ten iterations. This is substantially larger than the test statistic (0.088) for an alpha of 0.05 and a sample size greater than 100. This statistic indicates a statistically significant positive correlation between the two variables (Zar, 1984), deeper soils are correlated with higher elevations in the landscape being evaluated. Soils data available for this analysis tends to increase in depth with increases in the elevation data.

The resolution of the data may also account for the negative correlation with the model. Soils data for this analysis is exceptionally coarse. Conversely, data from the depth to groundwater raster is available at a fairly fine scale, the resolution of the raster is ten meters. However, restricted rooting depth from the depth to groundwater raster only reflects restricted rooting depth associated with water bodies. Restricted rooting depth associated with shallow soils, hardpans, and bedrock for example, are not covered by this data. The limitation of this data source necessitated the inclusion and combination of the NRCS soils data.

The NRCS data is recorded in mapping units with an average size of 40 acres. Substantially larger than the scale most of the forest stands in the landscape are mapped. These depth data were created mainly by interpretation of vegetation from aerial photos. It does not have the resolution to capture bedrock intrusions or other abrupt changes in soil depth. Potential rooting depth is reported as a range in the NRCS data, and the midpoint of this range was used for the model. In some cases this range spanned 50cm, with a minimum value of 10cm. Enormous differences in wind vulnerability should be expected on soils 10 cm in depth verse 60 cm in depth due to the dramatic increase in potential rooting space in the deeper soils. Using the minimum soil range may be more effective at capturing the maximum risk of the area mapped; however, the mean value is a more appropriate descriptor of the depth across the mapping unit.

Differences between population means for the composite site variables was positive with the exception of the site grids incorporating topographic exposure to the north, northeast and northwest, which did not display any significant difference between population means in the model. Differences between population means were statistically consistent for three exposure variants. This consistent positive difference between population means was found for both site grids with non-directionally weighted exposure input variables (site_1500 and site_1000) and for site_se, the site variant modeling topographic exposure to the southeast. Site_east, site_south, site_sw, and site_west all had positive difference between model population means in at least one of the ten iterations.

The strength of the elevation variable does not appear to override the other two input variables in the current model; the soil components negative difference between the population means may reduce the strength of the elevation components positive difference between the population means when integrated in the composite site variable. The positive difference between the population means of all site variables (with the exception of the north, northeast, and northwest exposure variants) suggests that topographic exposure is important, even though significant difference between the population means were not consistently detected for exposure as an individual variable. As mentioned above in the discussion of the exposure variables, the northern directions exhibited negative difference between the population means when evaluated as individual variables. This trend is in agreement with a visual assessment of blowdown in the landscape.

Although the data within the GIS database is fairly coarse, the general spatial model developed associates moderate to high vulnerability ratings with reported wind damage in the landscape. All of the final risk assessment variables "cmltv_*direction*" have a positive difference between the population means. This validated the model's ability to differentiate vulnerability between damaged and undamaged stands. The difference between the population means in the cumulative risk variables is highly significant with p-values of 0.000 recorded in all ten iterations for all ten exposure variants. This strong relationship is boosted by the power of the thinning variable but as described before the strength of this thinning variable is justified by responses from managers. Only one area where wind damage impacted an unthinned stand is recorded in the database. This area is directly attributed to damage from a strong convective storm system, characterized as a catastrophic event. The storm traveled from the southwest to the northeast on October, 31 1995, causing extensive damage to stands to the southwest of the study area. This supports the concept of diminishing importance of site and stand characteristics with increasingly strong and chaotic winds (Wilson, 1998).

Similar to the issues with soil, wind damage cannot be detected at resolutions finer than the stand scale for this study. Taking the mean value for stand polygons reduces the resolution of the data, but is the only way to account for the limitations of the database. Wind recorded in the stand history may have occurred throughout the stand or it may be confined to the highest risk areas in the stand itself. Unfortunately this cannot be detected from the data available for this project.

2.5 Conclusion:

Wind damage to forests in Maine is a continual consideration for forest managers across the region. The importance of wind damage is likely to increase in the future as large forest areas in the state, regenerated during the spruce budworm outbreak of the 1970's and 80's, continue to mature. In addition, the vast majority of harvesting in the state utilizes partial harvesting techniques. If these trends in stand height and area thinned continue, managers will need tools and techniques to help them manage the growing wind damage threat. Spatial risk index modeling with GIS provides an alternative view of the landscape, allowing for threat assessment and more informed decision making. The wind vulnerability model developed for this project can be used as a tool to assist in forest planning and provide insight into historic trends in forest dynamics and habitat associations. This tool should be portable to other regions since it contains variables that are frequently identified as critical in predicting windthrow vulnerability. The stand level variables are general enough to adapt to similar forest typing schemes used by other managers in the state.

There are multiple complexities associated with modeling vulnerability to wind damage in forests. Foremost among these is modeling the interaction of rare regional wind events, chaotic local wind behavior, changing soil conditions (saturation and freezing), and dynamic stand characteristics (growth and manipulation).

One approach for managing the uncertainty surrounding wind damage is to develop relatively simple models of vulnerability based on past observations of factors influencing damage. These more general models, like the one developed for this project, would not be expected to predict past wind damage as well as models developed directly from damage information collected after a particular storm or in a specific landscape. However, they may prove less biased towards particular site, stand, or storm conditions and therefore be more useful for guiding future forest management across a large region or as stand conditions change.

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Thomas Perry was born in New London, New Hampshire on February 2nd 1976. He grew up in Andover, New Hampshire, spending summers on a quest for the regions best swimming hole. He graduated High School in Tilton New Hampshire in 1994. After much debauchery and mayhem he headed west to Northern California in the summer of 1997.

There he was able to extend his undergraduate studies behind the redwood curtain at Humboldt State University over a seven year period, with forays into farming and countless hours spent surfing, backpacking, exploring the creeks and playing some serious ultimate. This period resulted in the author's acquisition of a BS in Forestry with a minor in Environmental Ethics, and an induction into Xi Sigma Pi, National Forestry Honor Society, in 2003.

With the undergrad degree complete the author took a job as a forester for a small consulting firm in the mountain village of Weaverville, California. After spending a year in the most beautiful place the author has had the good fortune to live he sought to improve his employability through graduate education. The author packed up and came to Maine to study under the guidance of Dr. Jeremy Wilson in the summer of 2004. Thomas is a candidate for the Master of Science degree in Forestry from the University of Maine in December, 2006.