

# Biotic and abiotic influences on wind disturbance in forests of NW Pennsylvania, USA

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## Abstract

Forests in northwestern Pennsylvania experienced a severe windstorm in July 2003. The storm damaged some forests and left others in its path intact. This varied impact raised the question of whether biotic and abiotic stand characteristics influenced storm damage. To answer this question we investigated data on windthrow severity, vegetation characteristics, and physiographic variables provided by the three largest landowners affected by the storm. These local forest managers provided stand level data on 258,000 ha, about half of the storm swath, of which about 5000 ha (2%) experienced moderate or severe blowdown. The study includes over 1002 disturbance patches, 60% of which were under 3 ha. We used classification tree analysis, a non-parametric method of statistical inquiry, to identify the variables that were most useful in predicting storm damage. Our model used biotic and abiotic site factors to correctly predict affected and unaffected stands 89% of the time (kappa value 0.63). The most predictive biotic variables were stand structure and stand age. Predictive abiotic variables included mean elevation, the range of elevations across the stand, and topographic position relative to neighboring stands. Results show that windthrow was more likely in older stands, stands at the highest elevations, and in flatter stands at lower elevations. Except for red maple stands on wet sites, which were disproportionately affected, forest type was not a useful predictor of the storm's impact.

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## 1. Introduction

Wind disturbances, from small-scale to stand-replacing, determine structure and function in many forested ecosystems (White and Pickett, 1985; Foster et al., 1998). Local biotic and abiotic factors, along with storm intensity, determine how windstorms impact forest ecosystems (Everham and Brokaw, 1996). Researchers have debated relative influences of vegetation and physiography on wind disturbance impact in a wide range of ecosystems (e.g. Boose et al., 1994; Mabry et al., 1998; Canham et al., 2001; Schulte et al., 2005). Biotic factors that influence the impact of wind events include species composition (Whitney, 1986; Frelich and Lorimer, 1991), tree size and density (Webb, 1989; Peterson and Rebertus, 1997), and interactions with other disturbances such as forest pathogens (Papaik et al., 2005). Abiotic features affecting the degree of wind damage include wind speed (Elie and Ruel,

2005), topography (Gardiner and Quine, 2000), and soils (Kramer et al., 2001). These factors interact in complex patterns and their relative importance can change with each new disturbance.

A severe windstorm struck northwestern Pennsylvania, USA, in July 2003, damaging thousands of hectares of forest (Fig. 1). We use this event to study the relative influence of biotic and abiotic factors on wind damage in forested ecosystems. The storm-damaged area is a particularly good site for the study of wind disturbance because it includes a broad spectrum of land ownerships, management regimes, stand characteristics, topography, and forest types. We hypothesized that the influence of biotic and abiotic stand characteristics would be detectable through the noise of natural variation due to storm strength. More specifically, we conjectured that species composition, tree size, stand density, stand age, topographic position, and elevation could predict which stands were damaged by the 2003 storm. We suspected that as stands aged they would go through stages of higher susceptibility to wind damage (Everham and Brokaw, 1996). At stand initiation, the low stature and flexibility of seedlings

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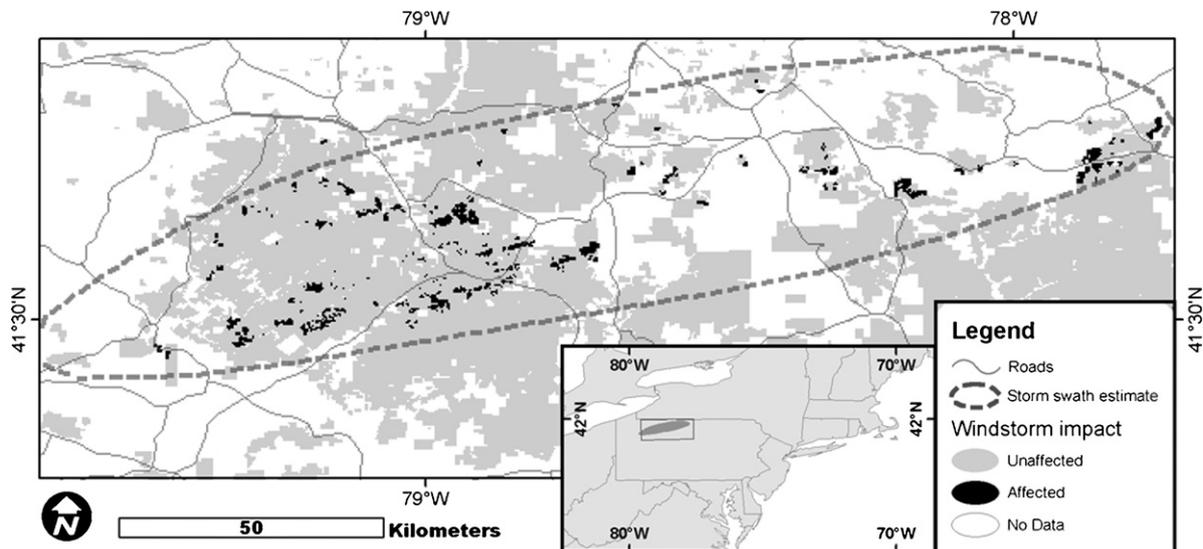


Fig. 1. Map of wind disturbance in NW Pennsylvania, July 2003. Forested lands included in this study are depicted in gray and storm damaged patches of forest are depicted in black. The estimated extent of the storm swath is pictured with a dotted line.

and saplings makes them less vulnerable to wind damage. In the stem exclusion stage (*sensu* Oliver and Larson, 1996), stands are more vulnerable to wind damage because of large height to diameter ratios caused by the process of self-thinning through density dependent mortality. During understory reinitiation, canopy dominants increase in diameter, resulting in lower height to diameter ratios, which makes stands more resistant to wind damage. The susceptibility of old growth stands appears mixed (Everham and Brokaw, 1996). We expected that both age and stand structure would be important predictors of wind damage because stand structure depends on a combination of age, management, and prior disturbance. Wind damage often varies by species (Canham et al., 2001), but the species effect may be obscured when viewed at the scale of a forest type classification. In our study area, the main forest types have many species in common. Therefore, we also hypothesized that abiotic factors, specifically topographic position and elevation, would be more important than forest type in determining the impact of the storm in the mixed species ecosystems of NW Pennsylvania.

An important objective of this study was to supply managers with information on the relative risk of wind damage based on what we could learn from this particular storm event. Researchers have used site characteristics to create risk maps for various disturbances including insect defoliation (Liebhold et al., 1994), disease (White et al., 2002), avalanche (Bebi et al., 2001), fire (Gustafson et al., 2004), and wind (Jalkanen and Mattila, 2000; DeGayner et al., 2005). Understanding conditions related to increased damage from one wind event may help managers identify areas at risk in future storms. Natural resource managers can reduce the negative impact of wind disturbance by factoring disturbance regimes and vulnerabilities into their planning (Dale et al., 1998).

## 2. Methods

### 2.1. Site description

Forests in the region are predominantly classified as northern hardwoods/Appalachian hardwoods, Appalachian oak, American beech-sugar maple (*Fagus grandifolia*–*Acer saccharum*), or hemlock (*Tsuga canadensis*) (McNab and Avers, 1994). Nearly 40% of the area in our analysis is classified as northern hardwoods and 32% as Allegheny hardwoods. Dominant trees in the northern hardwoods type include American beech, red maple (*Acer rubrum*), sugar maple, black cherry (*Prunus serotina*), black birch (*Betula lenta*), yellow birch (*Betula alleghaniensis*), paper birch (*Betula papyrifera*), northern red oak (*Quercus rubra*), and white ash (*Fraxinus americana*). The Allegheny hardwoods type is characterized by at least 40% black cherry with common associates being red maple, sugar maple, black birch, yellow birch, American beech, and oak (Marquis, 1975; Pennsylvania Division of Forest Advisory Services, 1999). Elevations in the study area range from 334 to 780 m (US Geological Survey, 2004). Land ownership in the storm swath is a patchwork of public and private lands, dominated by the Allegheny National Forest (ANF) in the western half of the study area. Management practices vary across the landscape from intensive commercial harvesting to wilderness areas.

### 2.2. Disturbance in NW Pennsylvania

Historically, wind was the major natural disturbance affecting the forests of NW Pennsylvania, while drought was a major ecosystem stress (Lutz, 1930; Bjorkbom and Larson, 1977). Research at the Tionesta Scenic and Research Area indicated severe wind disturbances occurred in 1808, 1870, 1950, and 1985 in addition to the 2003 storm (Hough, 1953;

Peterson and Pickett, 1995). Following European settlement in the early 19th century, logging and fire became the dominant disturbances, with stand-replacing harvests and post-harvest fire occurring across much of the landscape (Marquis, 1975). Today, under a policy of fire suppression, wind and logging are the predominant stand-scale disturbances. During the last 10 years, the study area experienced an average of 11 high wind events and one tornado per year (National Climate Data Center, 2005b).

The event that damaged forests in July 2003 was a mesoscale convection system, a storm with a vigorous squall line followed by an organized complex of thunderstorms (USDA Forest Service, 2004). The storm moved from southwest to northeast with wind speeds estimated up to 50m/s in some areas (Eppley et al., 2003). Precipitation during the event ranged from 8.1 to 12 cm (NOAA, 2005). This was within the range of precipitation that usually falls during the entire month of July (National Climate Data Center, 2002). Extremely moist conditions from May through July (National Climate Data Center, 2005a) probably exacerbated storm damage. In areas of moderate impact, the storm knocked down small clusters of trees. The most severe storm effect was large areas of completely uprooted or snapped off trees.

### 2.3. Biotic and abiotic data

We assessed the influence of biotic and abiotic factors on wind damage at the stand level by analyzing data from three of the largest landowners in the area affected by the storm. In addition, we collected field data in affected patches and

unaffected stands not included in the landowner databases. The landowners were the ANF, a state agency, and a private timber company. They represent the range of management objectives and land management practices for NW Pennsylvania. We created a geographic information system (GIS) database incorporating data on windthrow severity, stand characteristics, and site conditions. We used this database to develop models that identified the biotic and abiotic factors that increased susceptibility to storm damage.

Our ability to use stand-level variables to analyze windthrow susceptibility over the 525,000 ha storm swath is possible because of the current widespread use of GIS. From landowners' geographic databases we were able to assemble 19 attributes from nearly 19,000 stands and 1002 wind damaged patches (Table 1). Stands were defined by similar species mix and similar age structure. We chose to use stands as the unit of our analysis because the stand is the scale at which management decisions are made. They are relatively homogeneous in age, developmental stage, and species composition, with at least some of that homogeneity deriving from site factors. Each landowner delineated stands as part of their standard management. There were no significant differences in the size of stands between landowners. Further investigation of both the stand delineation methodologies and actual stand maps of the different landowners showed that stands were defined in a similar manner across the study area. Each landowner initially delineated the storm-damaged patches from aerial photos and subsequently checked the severity of damage and patch boundaries in the field. Landowners classified areas with dispersed clusters of down and snapped trees as moderate

Table 1  
Variables included in the models

Data source	Variable	Description
Landowner databases	Age	Years since stand initiation
	Cover type	Forest cover defined by the ANF forest type definitions
	Generalized cover	Forest cover generalized to five categories
	Aspect	Direction the stand faces as recorded by inventory crews
	Slope	Steepness of the site as recorded by inventory crews
	Soil type	Soil order
	Stand structure	A six level code describing stand stocking and tree size class
National elevation dataset	Elevation mean	Mean elevation of the stand
	Elevation range	Range of elevations within the stand
	Elevation max	Highest elevation within the stand
	Slope	Slope of the stand
	Aspect	Direction the stand faces
	Topographic position	Stand's position from ridge to valley
	Hillsides	Slopes of hills larger than 50 ha
Pennsylvania land cover map (PALULC2000)	Landcover	A 15 level code describing the vegetation, development or other land use
	Distance from flat	Distance within 500 m (1640') to the north, NE, or east of low stature vegetation, water, bare ground, or other open areas
Pennsylvania GIS compendium	Distance from roads	
	Distance from major roads	
	Distance from rivers	
	Distance from major rivers	
	Distance from 1985 tornado swath	
Digitized map of the 1985 tornado	Distance from the area affected by the 1985 tornado	

damage and large areas of completely uprooted or snapped off trees as severe damage. We collected data in the field on damaged patches that had not been previously ground-truthed. The field crew measured 46 plots chosen to include both affected and unaffected stands within designated wilderness areas and other lands where the management regime made detection of storm damage less likely. We assigned the biotic attributes of the stand to damaged patches within that stand (Table 1).

Attributes and their data sources are listed in Table 1. We created compatible codes for stand attributes from the different systems based on conversations with local experts and written descriptions of each landowner's classification scheme. For example all three landowners had a stand structure variable, although some used actual tree diameters to characterize groups while others used size class descriptions. We integrated the two systems by identifying tree diameter range for each size class description and reclassifying tree diameters by size class. We used the stocking classifications from the landowner databases to divide each structure classification. Our final stand structure classification had each of four tree size classes (mean DBH <15 cm, 15–31 cm, 31–46 cm, and >46 cm) at two stocking levels (<50% stocking and >50% stocking). The size/density information for some of the wind damaged stands on the ANF was out of date by several decades and thus did not represent the structural conditions of the stands at the time of the storm. However, basal area, age, and other variables for these stands were accurate and provided an alternative method for classifying stands. All three landowners recorded stand age based on their records of stand initiation.

In addition to the databases of stand-level attributes, we used four regional datasets to map abiotic factors. The national elevation dataset (NED) provides the best available elevation data at 30 m resolution for the coterminous USA (US Geological Survey, 2004). We used the NED to generate a map of mean and maximum elevation, slope, aspect, topographic position and hillsides (a variable identifying stands on slopes of hills larger than 50 ha). Topographic position was determined by comparing each cell to a neighborhood average elevation and recording if it was higher (ridge) or lower (valleys). Topographic position was measured on a gradient ranging from 0 to 8, but for model parsimony, we focused on the most important difference: ridge versus valley. Topographic position measured differences at the scale of the 30 m pixels from the NED dataset while the hillsides variable captured the effects of topography over larger areas. We used the Pennsylvania Land Cover map, with 15 land cover classifications, for exploring regional land use patterns (Warner, 2002). This enabled us to identify low stature vegetation, water, bare ground, and other open areas. We created a map where each cell within 500 m to the north, northeast, or east (downwind) of an open area was coded with the distance from that open area. Our goal was to capture the effect of increased wind impact that might occur to forest stands downwind of an open area. We also used maps of roads and rivers to investigate their importance with respect to stand vulnerability to wind (Pennsylvania Dept. of Environmental

Protection, 1996). We digitized a map of the path of the 1985 tornado to study the influence of distance from that previous disturbance (Eastern National Forest Interpretive Association and US Forest Service, 1999).

#### 2.4. Analysis

We tested the difference between the age distributions of affected stands and unaffected stands using the Mann–Whitney test, which compares the means of two distributions without the assumption of normality (Conover, 1980, p. 216). We used classification tree analysis for the main portion of our investigation because it is a non-parametric method of statistical inquiry suitable when many of the variables are spatially correlated and not normally distributed (Breiman et al., 1984). Classification tree analysis can be tailored to fit interactions not efficiently handled with regression or discriminant analysis, especially when data contain both categorical and continuous variables. Researchers have used classification tree modeling for numerous forestry questions: root disease locations (Byler et al., 1990), disease hazard rating (Baker et al., 1993), fire refugia (Camp et al., 1997), individual tree mortality (Dobbertin and Biging, 1998), species distribution (Brown and Timms, 2002), ungulate damage (Caudullo et al., 2003), bark beetle damage (Lawrence and Labus, 2003), tree cavity abundance (Fan et al., 2003), and forest invasion by exotic insects (Evans and Gregoire, 2006).

Our classification tree analysis predicts windthrow damage as a function of biotic and abiotic variables (Breiman et al., 1984; R Development Core Team, 2004). A classification tree is created by searching through the data to find the most effective variable for splitting the data into predefined groups, in this case affected and unaffected stands. Results of recursive partitioning can be visualized as a decision tree (e.g. Fig. 4). We set limits on the minimum number of stands that can be split at each node to avoid over-fitting the model. Allowing smaller splits encourages the model to fit too exactly to the training data, which limits the model's applicability to data not included in the study. Pruning the decision tree corrects over-fitting. We pruned our models based on a 10-fold cross validation. We determined the best model size by selecting the tree that was within one standard deviation of the minimum misclassification error (Breiman et al., 1984). We used both the misclassification percentage and the kappa statistic to compare models. The kappa statistic is a measure of the difference between correct classification and random coincidence of model and test data (Lillesand and Kiefer, 1994, p. 616). The kappa statistic is more resistant to the weight of a large number of correctly classified unaffected stands than the misclassification percentage. We validated our estimates of misclassification and the kappa statistics for the models by running 1000 iterations of random data selection, model construction, and validation.

#### 2.5. Model definition

We first classified stands as moderate, severe, or unaffected (3-level model) and then combined the moderate and severe

damage categories to create a more general category of affected stands (binary model). We selected unaffected polygons from within the path of the windstorm by identifying stand polygons within 200 m of affected stands. We chose not to include all undamaged stands within the storm swath because such a large number of unaffected stands would mask the pattern of biotic and abiotic variables for the affected stands. We analyzed a subset of the data using all the unaffected stands to test our inclusion method for unaffected stands. The classification tree model produced from this subset of data was very similar to our overall model for both variables included and percent accuracy, indicating our selection method did not bias the model.

### 3. Results

#### 3.1. Description of affected area

The distribution of blowdown patch size is highly skewed. Over 30% of the patches are less than one hectare and 60% are less than 3 ha. The median affected patch size is 2.18 and the mean is 4.78 ha. The size distribution of surrounding unaffected stands is less skewed, with a median of 6.04 ha and a mean of 9.35 ha. Table 2 provides more detail on the sizes of the patches of wind disturbance. The number of affected stands included in the analysis plotted by forest type reveals that some forest types sustained a much higher percentage of impact than others (Fig. 2). The storm damaged patches were 5% of the 18,000 stands within the storm swath for which data was available. Red maple stands on wet sites had the highest percentage of affected patches: 19%. Within the storm swath, wind damaged 5% of the mixed upland hardwood type, 5% of the northern hardwood type, and 7% of the stands in the Allegheny hardwood type.

Table 2

Disturbance patch size by quartile in hectares

Quartile	Mean size	Median size	Minimum size	Maximum size
1	0.34	0.31	0.01	0.73
2	1.38	1.37	0.73	2.17
3	3.5	3.28	2.17	5.58
4	13.82	9.88	5.6	114.13

Quartiles were calculated by ordering the database of affected patches by size and then dividing at the 25th, 50th, and 75th quartiles.

Unaffected stands have a bimodal age distribution (Fig. 3). The median age for mature stands ( $\geq 50$  years) was 87 years (mean 86 years) for unaffected stands and 91 years (mean 91 years) for affected patches. The Mann-Whitney test showed that the mean age of affected patches was an estimated 5 years older (95% confidence interval between 4 and 6 years) than the average of unaffected stands, when stands older than 50 years are considered.

#### 3.2. Classification tree model results

The three-level model predicted the level of blowdown correctly 86% of the time while the binary model was correct 89% of the time. The kappa statistics were 0.56 and 0.63, respectively. A simple majority classification rule would correctly classify 85% of stands, but fail to identify any of the blowdown stands since the majority of stands were not affected by the windstorm. Validation averages for 1000 iterations of random data selection, model construction, and validation were from 81 to 87% for the three-level model and from 84 to 91% for the binary model. The intervals for the kappa statistic were 0.39–0.60 and from 0.47 to 0.70.

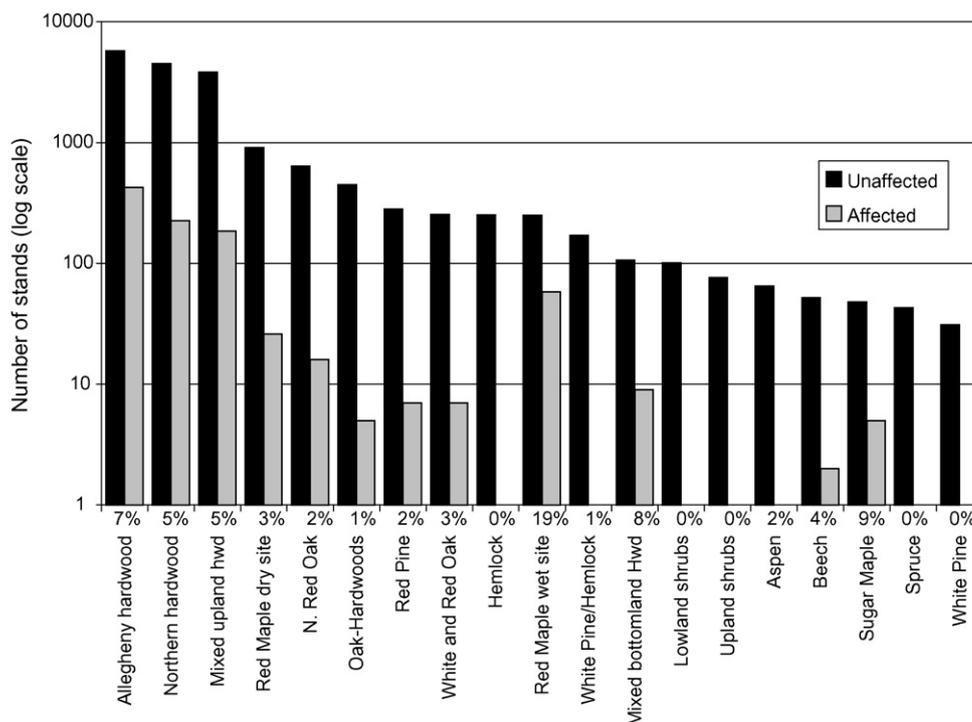


Fig. 2. Histogram of number of stands affect by forest type. The y axis of the plot is on the log scale, de-emphasizing the differences in counts of stands by forest type.

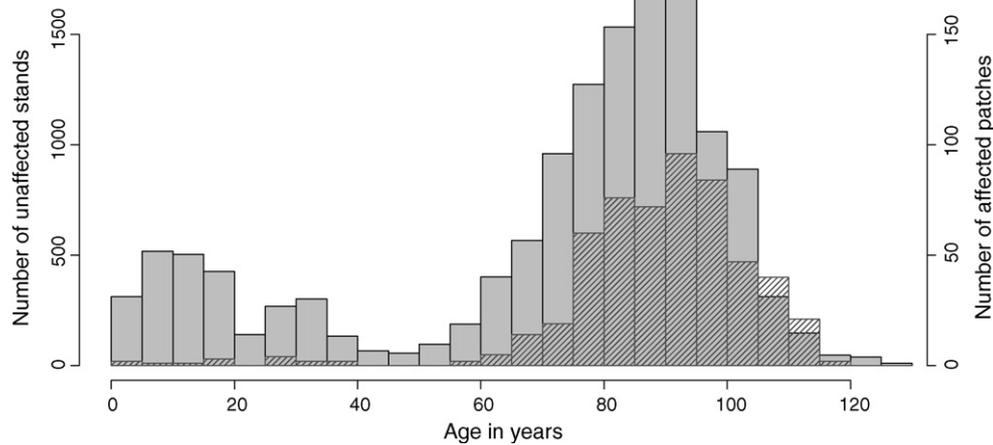


Fig. 3. Histogram of stand age. Dark columns are all stands and hashed columns are stands that were moderately or severely affected by the storm. The scale of the y axis for the unaffected stands is an order of magnitude larger than the scale of the y axis on which the affected patches are plotted.

In general, the model under-predicted windstorm effects. The three-level model correctly predicted only 19% of the areas severely impacted by the storm; 35% of the severe areas were predicted as moderate blowdowns. The binary model correctly predicted 60% of affected areas (Table 3). Fig. 4 shows the classification tree from the binary model. A more detailed description of both models as well as misclassification at each split is provided in Appendix A of supplementary information. The two models selected a similar subset of available variables to predict windthrow susceptibility. The most predictive biotic variables, those that divided affected and unaffected stands most effectively, were stand structure and stand age. Predictive abiotic variables were mean elevation, the range of elevations across the stand (which translates to either slope steepness or variability), and topographic position relative to neighboring stands. Vulnerability increased with increasing stand age, elevation, and topographic position and decreased with an increasing range of elevation within the stand. In general understocked stands were more vulnerable, although influence of stand structure varied in combination with other variables as explained in the discussion section. In addition to the variables that the binary model used, the three-level model also selected distance from roads and distance from open areas as useful variables for differentiating between risk for severe and moderate blowdown. Both greater distance from roads and proximity to flat areas were predictive of increased blowdown severity.

#### 4. Discussion

The hypothesis that the influence of stand variables would be evident despite variation in storm strength was supported by the

accuracy of our models. This is in contrast to previous studies of windstorm damage in forests that have shown that storm severity can override physiographic or biotic control (Foster et al., 1998), or affect the relative significance of biotic factors (Veblen et al., 2001). Binary classification tree modeling correctly predicted storm impact in 89% of our study stands and successfully identified a set of biotic and abiotic factors that influenced the impact of the windstorm. Although the binary model show a relatively small percentage improvement over a majority classification rule, both classification tree models have the distinct advantage of improving the identification of stands affected by the windstorm. The majority misclassification rule would classify all stands as unaffected and close off the possibility of analyzing biotic and abiotic influences on wind disturbance.

Our misclassification rate of 11% is similar to other windthrow models and other classification tree models of forest disturbance. For example, Kramer et al.'s (2001) logistic regression model of windthrow misclassified 28% of the stands. Other misclassification rates for predicting forest disturbances using classification tree models range from 18 to 35% (Baker et al., 1993; Camp et al., 1997; Lawrence and Wright, 2001; Evans and Gregoire, 2006), reflecting the inherent stochasticity of disturbance events as well as the difficulty of reducing ecological processes to models.

An auxiliary benefit of analyzing wind disturbance within a GIS was easy access to maps of disturbance patches, such as Fig. 1. Our maps showed that the landscape pattern of wind damage in NW Pennsylvania was a predominance of small patches of windthrow intermingled with intact forest. The forest openings caused by wind damage increased the randomness, or

Table 3

The percentage (and number) of correctly predicted stands for each class in the binary and three-level versions of the model

Three-level model	Percent correct	Binary model	Percent correct
Predicted severe	19% (76 stands)	Predicted affected	60% (601 stands)
Predicted moderate	65% (385 stands)	Predicted unaffected	97% (3428 stands)
Predicted unaffected	97% (3432 stands)		

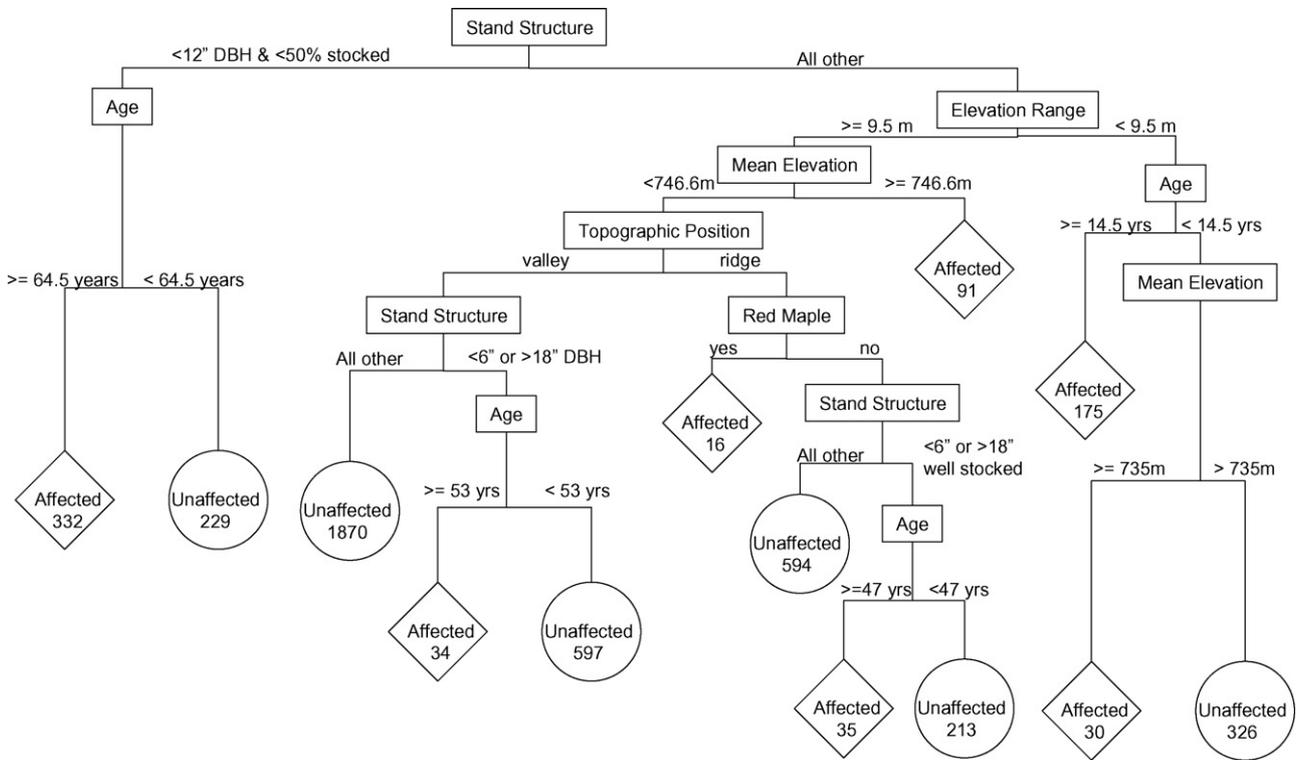


Fig. 4. Classification tree model for the binary model. The splitting variables are listed in rectangular boxes and final nodes in diamonds or circles for affected or unaffected nodes, respectively. The description of each split is listed above each branch. The vertical and horizontal connecting lines are sized for legibility. More details, including the proportion correctly classified at each node, are included in the digital appendix.

complexity, of the landscape as described by Boutet and Weishampel (2003) for a southern coniferous forest. For example, in our study the patches created by the windstorm were half of the size of the stands in the surrounding forest on average.

Our results showed that complicated interactions between biotic and abiotic factors determined the windstorm’s impact, which echoes previous studies on wind disturbance (Everham and Brokaw, 1996). Older stands were disproportionately impacted by the storm, as were those growing at higher elevations. Stands over 75 years old accounted for half of all the stands that blew down. The storm damaged just over one-third (37%) of the stands over 75 years old. The greater median age of affected patches indicates that the entire age distribution of affected patches is shifted relative to unaffected stands (Fig. 3). Rather than a sudden increase in vulnerability at 91 years old, our data show that a stand’s vulnerability increases with age. This may mark the move from stem exclusion to the understory reinitiation phase of stand dynamics. Previous studies have shown a positive, linear relationship between stand age and wind damage. Foster (1988) showed that hardwoods over 70 years old were more vulnerable to complete blowdown in the 1938 New England hurricane. It was found that increased canopy size and canopy roughness increased vulnerability of older stands in the mixed forests of New England (Foster, 1988). These same factors are likely to increase the vulnerability of older stands in our study area, since the species mix is similar. Other studies on windthrow focus on tree size, rather than age, or treat them as interchangeable (Webb,

1989; Everham and Brokaw, 1996; Canham et al., 2001). The importance of age as a separate variable from stem size suggests that future work may benefit from analyzing both age and size. Our study was a stand level investigation of a forest driven by initial floristics where tree age is relatively homogenous throughout stands and stands were young relative to species’ life spans. In uneven aged forests or forests in the understory reinitiation phase, it is important to investigate the utility of mean stand age as a measure of vulnerability. For instance, in old growth stands, individual tree characteristics may be more important than stand averages. Canham et al. (2001) demonstrated that in northern hardwood forests some species decrease in vulnerability to wind damage in old growth stands. The relatively young age of stands in this study (<140 years) compared to biological potential (>300 years) may also help explain the positive relationship between stand age and wind damage.

Stands younger than 75 years were most vulnerable on the very highest elevations, above 746 m. Most of the terrain in the study area can be described as locally hilly or steep, with a range of elevation throughout the stand greater than 9.5 m. About a third of the stands in this category blew down. Affected stands on this type of terrain tended to be on the highest elevations, older, or have high basal area (either dense small trees or large diameter trees). In contrast, although there is much less flat (<9.5 m elevation change across the stand) terrain in the study area, about half of the stands on the flatter terrain blew down. The importance of the range of elevations across the stands supports Everham and Brokaw’s statement

that the influence of topography on wind damage is more complicated than just exposure due to aspect (Everham and Brokaw, 1996). Other studies have also found that complex topographic variables influence storm damage (Kramer et al., 2001).

The least vulnerable stands were those with at least 9.5 m of elevation change within the stand, below about 746 m in elevation and located in valleys or at midslope positions. Stands with more than 9.5 m of elevation change may be less vulnerable to wind damage because the varied topography in these stands reduces wind speeds. The reduced vulnerability of all but the highest elevation stands in our results is similar to Hough's report (1953) that stands below about 600 m were less likely to be affected by storms in NW Pennsylvania. Kulakowski and Veblen (2002) also identified topographic position as an important influence on storm damage.

While our models strongly suggest that biotic characteristics are important, our ability to identify the stand structure variables that most reliably predict wind damage is limited by the available data. Hence, some mechanisms for increased vulnerability require further research. Stands that were at one time characterized as understocked with small diameter trees, and were older than 64 years when the storm hit, were disproportionately affected by the storm (94% of analysis stands affected). These could be older stands on poor sites, or could consist of scattered older trees with a dense understory cohort. Understocked stands would have greater canopy roughness than fully stocked stands, which would increase their vulnerability to wind damage (Foster, 1988). Future fieldwork may improve our understanding of the conditions these stands were in at the time they were damaged. These stands are likely to be similar to the sapling and pole stands that Hough described as being most affected by a storm that damaged the study area in 1950 (Hough, 1959).

Based on our data, forest type plays a much less important role than other biotic attributes in predicting wind damage. Although some studies have shown similar results (Mabry et al., 1998), others have demonstrated interspecies variation in wind damage (Peterson and Rebertus, 1997; Canham et al., 2001). The difference is likely due to the level of aggregation, the forest type classifications, and the age of the stands. We used stand level variables whereas studies focused on individual tree damage were more likely to identify species differences. Peterson (2004) shows species is a useful within-stand predictor of damage, but not between stands. The largest forest type categories had many species in common, which also obscured the effect of species on vulnerability to wind damage. The majority of stands on this landscape are relatively young. Differences between forest types may grow as stands age and long-lived species increase in importance more in some forest types than in others. Data that more completely characterizes species composition, such as species importance values, might further improve damage prediction. Greater detail on species composition within stands would also help tease out the relative vulnerability of more complex species assemblages versus monodominant stands.

The exceptional case where forest type did play a role was the red maple forest type, particularly red maple on wet sites. The storm damaged 19% of these red maple stands and the classification tree identified the red maple forest type as likely to blow down. The increased likelihood of storm damage in red maple stands is hardly surprising given red maple's tendency for lateral versus taproot growth in wet sites (Walters and Yawney, 1990). The lateral root systems would provide less stability, particularly in the saturated soil conditions during the 2003 storm. Otherwise, forest type was not an important variable in the models.

## 5. Conclusion

The widespread use of GIS to manage both detailed stand-level and regional data provides new opportunities to investigate disturbances such as the 2003 windstorm in NW Pennsylvania. Classification tree analysis is a powerful tool to study these kinds of data because it is accurate even with missing data values, lack of independence between observations, and non-Gaussian distributions. Our classification tree model was able to predict affected versus unaffected stands with 89% accuracy, and severe, moderate, or unaffected stands with 86% accuracy. Forest type was not a useful predictor of stand vulnerability to wind, with the exception of red maple stands on wet sites. The most important variables for determining the storm's impact across the landscape were biotic factors including stand structure and age. Abiotic landscape variables such as elevation and topographic position, proved useful for estimating windthrow risk within a stand structure class or in the absence of stand structure data.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at [doi:10.1016/j.foreco.2007.03.024](https://doi.org/10.1016/j.foreco.2007.03.024).

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