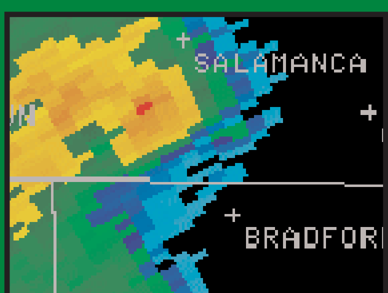
GISF Research Paper 004



Vulnerability of Northwestern Pennsylvania Forests to Major Windstorms

Alexander M. Evans, Mary L. Tyrrell,
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Global Institute of
Sustainable Forestry

Program on Forest Health

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August 2005

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This project was supported by a grant from the USDA Forest Service Northeast Research Station

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Acknowledgements

This project was made possible by the contributions of many people and organizations of northwestern Pennsylvania. Susan Stout, USDA Forest Service Warren Lab, provided funding, inspiration, and a steady review of our analysis. Land owners were very generous with their time and data, in some cases doing extra work to provide us with geospatial data on their forest stands. We are grateful to Wendell Wallace, Laura Drake, Andrea Hille, Ed Doane, and Jeanne Hickey at the Allegheny National Forest; Matt Sampson at The Forestland Group; Nancy McCloskey at FORECON; Mike McEntire at Forestland Investment Associates; Mike Hancharick and Ned Karger at Kane Hardwoods; Dave Haubrick, John Wambaugh, Jim McGarvey, Greg McPherson, and Gary Loudermil at the Pennsylvania DCNR Division of Forestry; Howard Wurzbacher, Scott Wolbert, Tony Ross, and Frank Chubon at the Pennsylvania Game Commission; and Dave Ondrejik at the State College National Weather Service Forecasting Center.

Abstract

Forests in northwestern Pennsylvania were subjected to a severe windstorm in July 2003. As high winds and thunderstorms are fairly frequent in this area, such events have major repercussions for landowners regardless of their management goals. Some forests within the storm swath were more severely impacted than others and this disparate effect on different forest stands raised questions about whether there are underlying causal factors of stand vulnerability to windthrow. We hypothesized that windthrow severity is a function of stand and site conditions. To assess vulnerability at the stand level to similar wind events we used a non-parametric method of statistical analysis called Classification and Regression Tree analysis (CART®) on data about windthrow severity, stand characteristics, and site variables collected from the three largest landowners affected by the storm.

According to our data, which include just about half of the lands in the storm swath, about 5,000 hectares (12,500 acres) experienced moderate or severe blowdown. This represents about 2% of the 258,000 hectares (645,000 acres) of forest on the ownerships in our study. We first modeled 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). The 3-level model predicted the level of blowdown correctly 86% of the time while the binary model was correct 89% of the time.

The most predictive biotic variables 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. Results show that windthrow was more likely to occur in older stands, at the highest elevations, and in flatter areas at lower elevations. Except for red maple stands on wet sites, forest type was not a useful predictor of the storm's impact.

Introduction

Forests in northwestern Pennsylvania were subjected to a severe windstorm in July 2003. Such events have major repercussions for landowners regardless of their management goals. Wind is a common small-scale disturbance, and occasionally a stand-replacing event, in these forest ecosystems. High winds and thunderstorms are fairly frequent in northwestern Pennsylvania and tornadoes occur about once a year (National Climate Data Center 2005b).

Some forests within the storm swath were more severely affected than others and this disparate impact on different forest stands raised questions about whether there are underlying causal factors of stand vulnerability to windthrow. This windstorm provided an opportunity to relate stand characteristics (i.e., composition and structure), management history, and site variables (soil type, topographic setting) to the amount of damage sustained by different stands. Knowledge about the relationships among stand characteristics, management history, site variables, and susceptibility to windthrow can be used in developing models of risk.

We hypothesized that windthrow severity is a function of stand and site conditions. This hypothesis implies that at least some abiotic and biotic variables influence windthrow severity at the stand level. Topographic variables such as slope and elevation are relatively fixed on the landscape and not likely to change over time. However, land management history may influence other variables, such as mean diameter (DBH) or density. Insight into how these variables influence windstorm damage could be useful to forest management planning.

To assess vulnerability at the stand level to similar wind events we collected and analyzed data about windthrow severity, stand characteristics, and site variables from the three largest landowners in the area affected by the storm. The landowners—the USDA Forest Service (Allegheny National Forest), State of Pennsylvania (state game lands and state forests), and Kane Hardwoods, a private commercial timber company—represent a diverse range of management objectives and land management practices for the general northern hardwoods/Allegheny hardwoods forest types. A fourth landowner, the Forestland Group, a Timber Investment Management Organization (TIMO), provided maps of their lands and areas affected by the storm. While their stands are shown on the blowdown and ownership maps in this document, their geo-spatial data on stand characteristics were insufficient for us to include their lands in statistical analyses.

We created a geographical information system (GIS) database using data on windthrow severity, stand characteristics, and site conditions, from which we developed predictive models relating windthrow severity to stand and site conditions. We used a non-parametric method of statistical analysis called Classification and Regression Tree analysis (CART®), or recursive partitioning, since many of the variables are spatially correlated and not normally distributed (Breiman et al. 1984). An advantage of classification tree analysis is that it can be tailored to fit interactions not efficiently handled with regression or discriminant analyses, 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 2004).

2003 Windstorm

A severe windstorm struck northern and central Pennsylvania during the afternoon of July 21, 2003, with a second day of severe weather on the 22nd (figure 1). This was an unusual Mesoscale Convection System, a group of storms often dominated by a vigorous squall line and a number of weaker multi-cell clusters of storms in its interior. These systems often bring severe weather and heavy rain at the squall line with additional heavy rainfall in interior storms (USDA Forest Service 2004).

Precipitation for the two days of July 21 and 22 ranged from 8.1 to 11.9 centimeters (3.2 to 4.7 inches) across Warren, McKean and Potter counties (NOAA 2005). Most of the rainfall occurred on the 22nd. In comparison, 30-year mean precipitation amounts in this area for the entire month of July were 8.9 to 11.4 centimeters (3.5 to 4.5 inches) (National Climate Data Center 2002). Storm damage was exacerbated by the exceptionally wet conditions at the time. The months of May through July 2003 were extremely moist (National Climate Data Center 2005a), leaving soils saturated and making shallow rooted trees such as red maple (*Acer rubrum*) and black cherry (*Prunus serotina*) more susceptible to blowdown. The storm moved in a northeasterly direction, with the worst damage occurring over the northern Pennsylvania counties of McKean and Potter, where tornadoes were confirmed southwest of Ellisburg, and at the Kinzua Viaduct Bridge near Kane (USDA Forest Service 2004; NOAA 2005).

Damage to forests ranged from light (scattered toppling or snapping of single trees) to moderate (small clusters of downed trees) to severe (large areas of trees completely uprooted or snapped off). The areas most affected were on the Allegheny National Forest, Pennsylvania State Game Lands, the Susquehannock State Forest, and four large private commercial forests. Numerous small private forestlands in the path of the storm were undoubtedly affected, but damage went largely unreported. The most spectacular damage was the collapse of the historic Kinzua Viaduct Bridge (see star on the map in figure 2).

According to our data, which include just about half of the lands in the storm swath, about 5,000 hectares (12,500 acres) experienced moderate or severe blowdown. This represents about 2% of the 258,000 hectares (645,000 acres) of forest on the four ownerships in our study (figure 2).

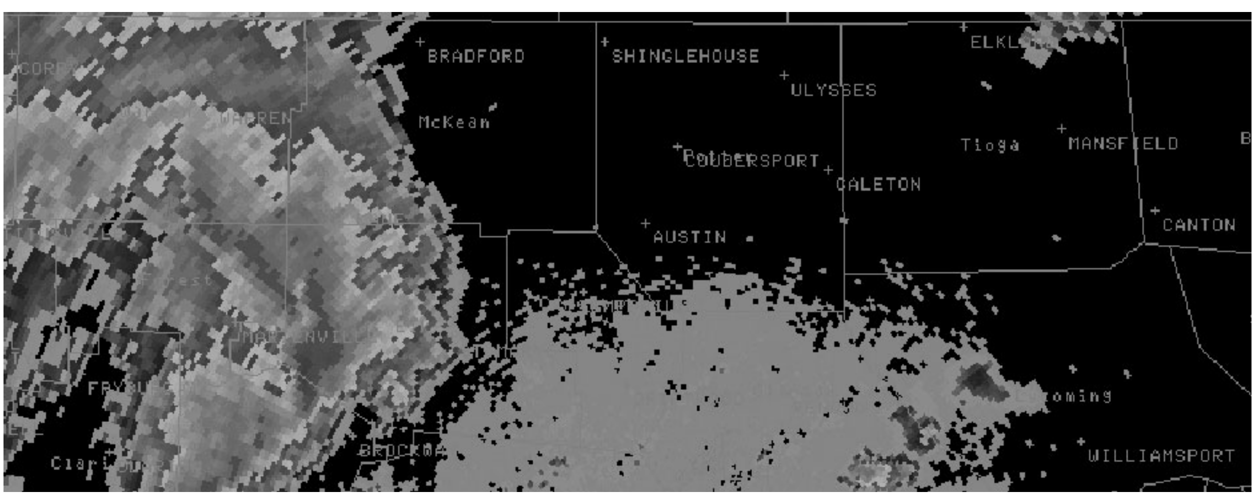

Figure 1. Radar reflectivity of the storm as it swept across Warren, Forest, Elk and McKean counties at 2:00 p.m. on July 21, 2003. Source: National Weather Service Forecast Office 2003

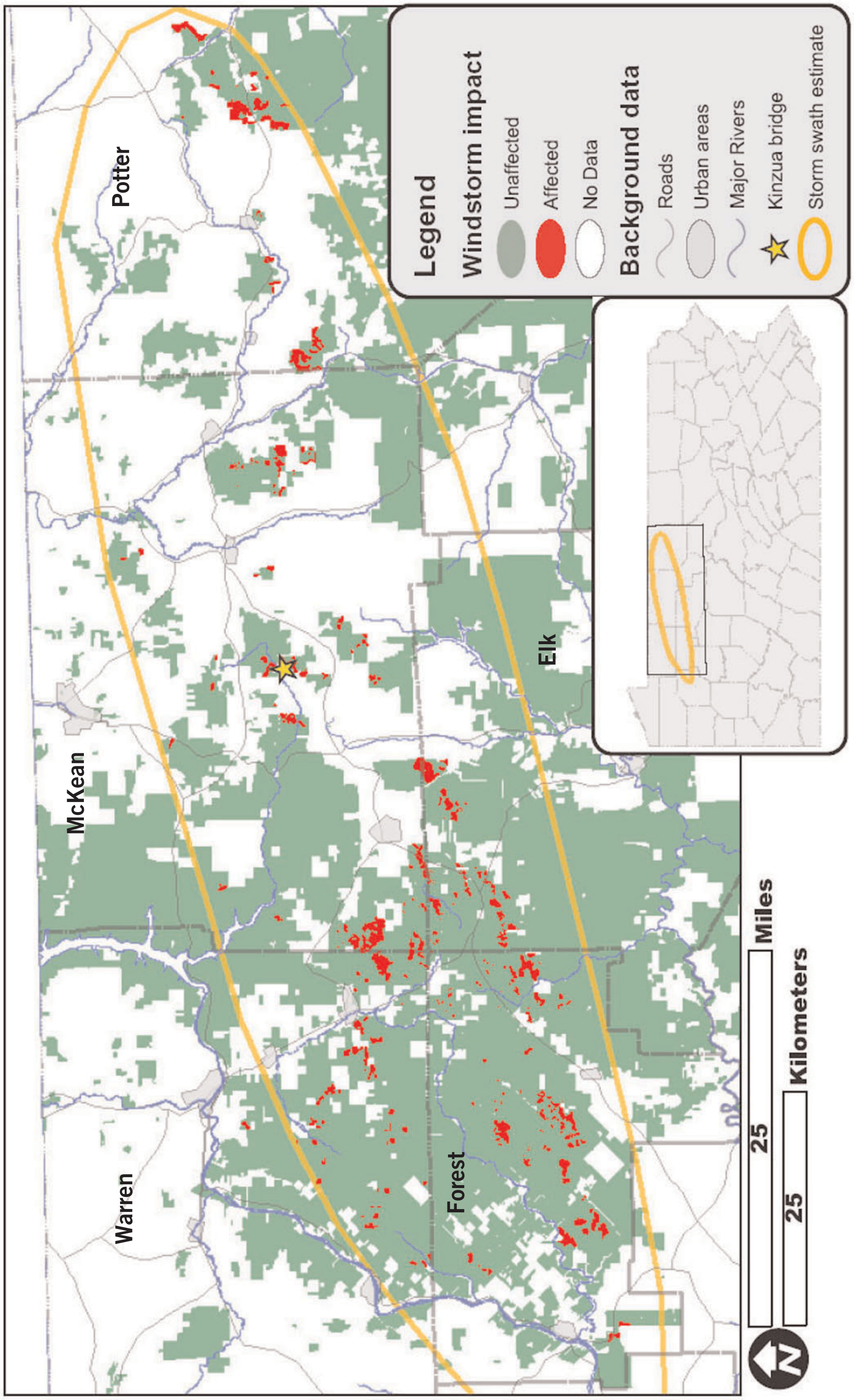

Figure 2. Damage from the 2003 windstorm in northwestern Pennsylvania.

Allegheny Forest

This study includes the area severely impacted by the 2003 storm, which is most of McKean county, and large sections of Potter, Warren, Forest and Elk counties in northwestern Pennsylvania (figure 2) in the unglaciated northern Allegheny Plateau Province. Forests are classified as predominantly northern hardwoods/Appalachian hardwoods, Appalachian oak, American beech-sugar maple (*Fagus grandifolia - Acer saccharum*), and some remaining old growth Hemlock (*Tsuga canadensis*) (McNab and Avers 1994). Elevations range from 334 to 780 meters (1,096 to 2,559 feet) (USGS 2004). Black cherry, sugar maple, and red maple are the predominant species and usually represent 65-95% of stand basal area, with associated species being American beech, eastern hemlock, yellow birch (*Betula alleghaniensis*), black birch (*Betula lenta*), white ash (*Fraxinus americana*), yellow poplar (*Liriodendron tulipifera*) and cucumber tree (*Magnolia acuminata*) (Marquis 1975).

Our data, from forests managed by three different landowners, indicate that nearly 40% of the area in our analysis is comprised of northern hardwoods, and 32% Allegheny hardwoods. Dominant trees in the northern hardwoods type usually include American beech, red maple, sugar maple, black cherry (at less than 40% relative cover), black birch, yellow birch, paper birch (*Betula papyrifera*), northern red oak (*Quercus rubra*), and white ash. 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 (Pennsylvania Division of Forest Advisory Services 1999).

In the pre-European settlement forests of this region, hemlock-beech was by far the most common forest type. Beech-sugar maple stands and scattered stands of pure white pine (*Pinus strobus*) were also prevalent, with beech being the most ubiquitous hardwood in nearly all ages and sizes (Hough and Forbes 1943). In original land surveys, beech and hemlock are the most commonly mentioned species (30% and 27% respectively), with the next most frequently mentioned being sugar maple at 8%. Cherry is infrequent at 3% (Lutz 1930b). The Allegheny Plateau was not settled by Europeans until 1796 and remained a heavily forested inaccessible frontier until about 1860. Early logging for pine and hemlock resulted in a mosaic of old growth with scattered second growth patches in accessible areas. With the advent of logging railroads, the demand for chemical wood, and to a lesser extent, charcoal for iron works operations further south, most of the forests on the Allegheny Plateau were completely clearcut between 1890 and 1920 (Marquis 1975).

Today's forests are either second or third growth, mostly even-aged stands dominated by black cherry. This is a legacy of intensive fires and clearcut logging, conditions which favor the regeneration of shade intolerant, fast growing cherry (Marquis 1992, Hough and Forbes 1943, Collins and Picket 1982). Beech, sugar maple, and red maple are also common. However, it is hard to overestimate the importance and prevalence of black cherry in these forests. In stands on the Kane Experimental Forest that were clearcut in 1937, black cherry was 100% of the dominant and co-dominant crown strata by age 35, and 75% of the basal area by age 50 (Marquis 1992). Thirty-two percent of the area analyzed for this study is in the cherry-dominated Allegheny hardwoods forest type. Black cherry is a valuable commercial timber tree with stumpage prices in northwestern Pennsylvania ranging from $844 to $2,436 per thousand board feet. This compares to the next most valuable timber, northern red oak at $330 to $704 per thousand board feet (Pennsylvania Woodlands 2005).

Land ownership in northwestern Pennsylvania is a patchwork of public and private lands, dominated by the Allegheny National Forest (ANF) in the western half of the study area (figure 3). Inholdings in the ANF are mostly state game lands and land owned by Kane Hardwoods, a division of Collins Pine, which also owns lands scattered throughout the entire study area. The eastern half of the study area has a more diverse ownership, with private commercial owners (Kane Hardwoods, The Forestland Group, Forestland Investment Associates, Seneca Resources, and Ram Forest Products), state forests, state game lands, and small private landowners. Management practices vary across the landscape, from intensive commercial harvesting to wilderness areas.

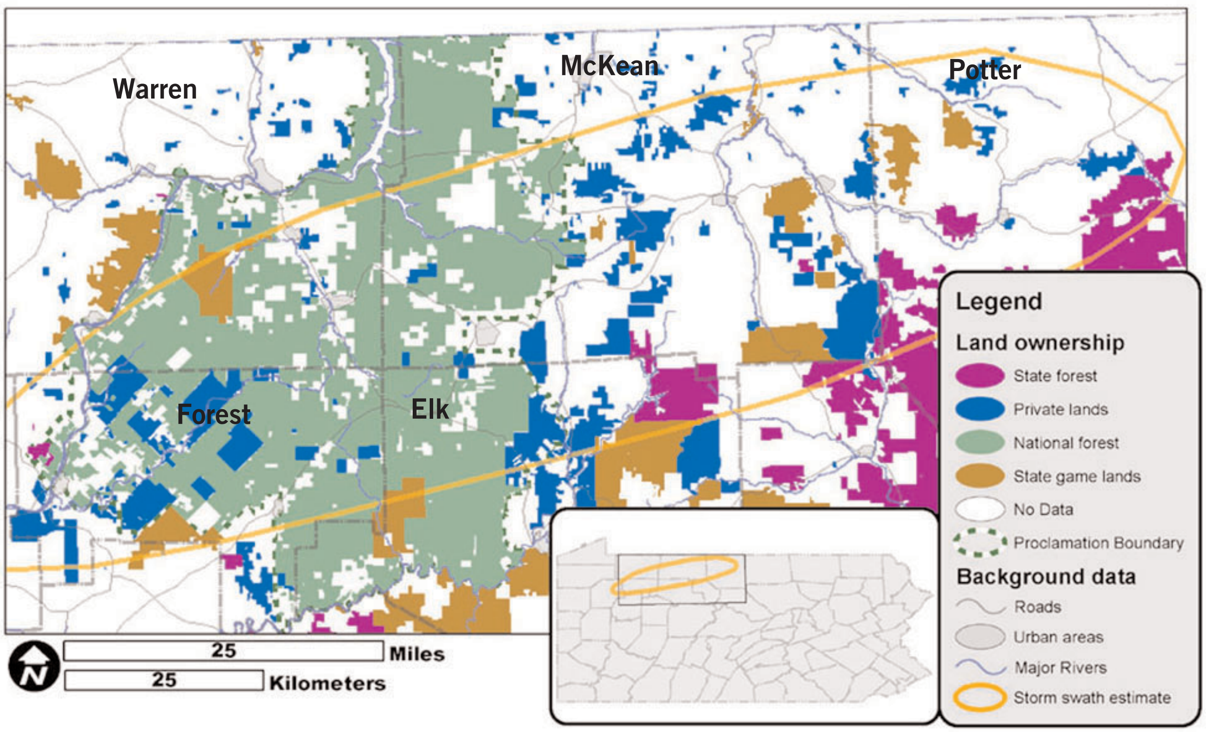

Figure 3. Forestland ownership map of northwestern Pennsylvania.

Role of Disturbance

Historically, wind and drought were the major natural disturbances affecting the forests of the Allegheny Plateau (Lutz 1930a; Bjorksborn and Larson 1977). With European settlement in the early 19th century, logging and fire became the dominant disturbance, with complete stand replacing harvests and post-harvest fire occurring across much of the landscape (Marquis 1975). Wind has historically been the most significant natural disturbance, and today, with a policy of fire suppression, wind and logging are the predominant landscape scale disturbances. Collins and Pickett (1982), in their study of conditions in 1.2 hectares (3 acres) of second growth hardwoods on the Kane Experimental Forest, found that pits and mounds occupied 42% of the study site, occurring uniformly throughout the area. Pits and mounds are legacies of large tree falls, usually from wind (Stephens 1956). Tornadoes were recorded in 1805, 1808 and 1870, causing large areas of blowdown (Bjorksborn and Larson 1977). Two of these occurred in the Tionesta Scenic and Research Area (1808 and 1870), which also experienced a severe windthrow event in 1950, a tornado in 1985, and was again affected by the 2003 storm (Hough 1953, Peterson and Pickett 1995).

During the last 10 years the study area experienced an average of 11 high wind events per year. Tornadoes were historically infrequent, with nineteen days of tornado activity in the last fifty years. However, in the last ten years, there have been 10 tornado events, an average of once a year. Either tornado activity has increased or reporting has improved. There have been a few "tornado events" in the past twenty years where several tornadoes hit on the same day, the most spectacular being on May 31, 1985 when twelve tornadoes were recorded across four counties (figure 4) (National Climate Data Center 2005b).

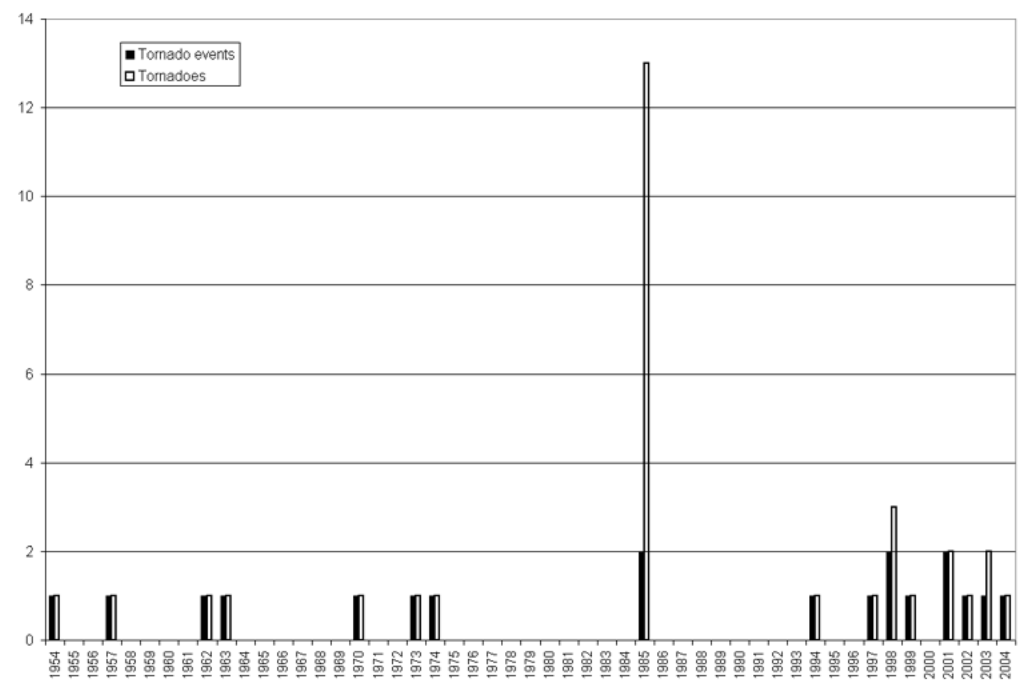

Figure 4. Tornado events (days with tornado activity) and number of tornadoes in Potter, McKean, Elk, Forest, and Warren counties Pennsylvania 1950 - 2004. (National Climate Data Center 2005b)

Methods

Our ability to use stand level variables to analyze windthrow susceptibility over the 525,000 hectare (1,312,500 acre) storm swath is only possible because of the widespread use of geographic information systems. We were able to assemble 19 attributes from over 4,500 stands from the geographic databases of three major landowners in the Allegheny region. The stand databases are part of the standard mapping for the three landowners and were generously provided for use in this study. Two other landowners provided information on blowdown locations, but could not supply the stand attributes needed for the model. We used their maps of blowdown locations to help map the storm's path and describe the area affected by blowdowns.

In addition to the databases of stand-level attributes, we used four regional datasets in order to include geographic variables in the model (table 1). The national elevation dataset (NED) provides the best available elevation data in 1-arc second resolution for the coterminous U.S. (U.S. Geological Survey 2004). We used the NED to generate a map of mean and maximum elevation as well as slope, aspect, topographic position and hillsides (a variable identifying stands on major hill slopes). Topographic position was determined by comparing each cell to a neighborhood average elevation and recording if it was higher (ridge) or lower (valleys). We used the Pennsylvania Land Cover map, with 15 landcover 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 meters (1,640 feet) to the north, NE, 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 for 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 Department of Environmental Protection 1996). We digitized a map of the path of the 1985 tornado to study the influence of distance from that disturbance (Eastern National Forest Interpretive Association and U.S. Forest Service 1999).

We also collected data in the field to ensure that the model was not biased towards lands that are actively managed. Sampling sites on the ANF were located in wilderness areas and the Tionesta Scenic Research Natural Area where the Forest Service had not ground-truthed the aerial survey storm damage maps. State Game Lands were included in the field survey because far less GIS ("digitized") data is presently available on these lands. The field crew measured 46 plots purposefully chosen to include both affected and unaffected areas within the wilderness areas and game lands.

A great deal of work went into reconciling stand attributes as recorded by each organization in their databases. Each landowner uses slightly different stand attributes, classification systems, and codes. We created compatible codes for stand attributes based on conversations with local experts and written descriptions of each landowner's classification system. Geographic attributes had to be reconciled because landowners mapped some variables using stand boundaries and other data with different boundaries. We assigned soil attributes to a stand based on the majority soil type within that stand. Similarly, the impact of the windstorm did not necessarily follow stand boundaries. Where blowdown polygons crossed stand polygon boundaries we assigned the majority stand type to the blowdown polygon.

We first modeled 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). The private landowner used a category called light blowdown (only a few scattered trees toppled or broken) in addition to

Stand variables

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 (see appendix I)

Regional dataset variables

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**
  Stands on major hill slopes

Pennsylvania Land Cover map (PALULC2000) Landcover
A 15 level code describing the vegetation, development or other land use

Distance from flat
Distance within 500m (1,640') 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**
  Distance from the area affected by the 1985 tornado

Table 1. Variables included in the models

moderate and severe. Because the other landowners did not make this distinction, we were unable to include light blowdown in the model. For consistency, the few patches classified as light were included in the model as unaffected, conforming to how the other landowners classified this minimal damage. We selected unaffected polygons from the path of the windstorm by identifying stand polygons within 200 meters (660 feet) of affected stands. We chose not to include all unaffected stands within the storm swath because such a large number of unaffected stands would mask patterns of stand and site 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. The results of the subset analysis indicated our selection of unaffected stands did not bias the model.

In addition to the full model we used subsets of the data to create specific classification trees and to examine the affect of the windstorm more closely. The six models we investigated are listed in table 2. We developed individual models based on data and variables from each of the three landowners. The ANF database included more detailed stand attributes such as stand basal area and DBH, and we incorporated these in the ANF classification tree. In order to examine the affect of forest type on windthrow, we developed a fifth model using only the 1,500 Allegheny hardwood stands in the dataset. For the last model we only used stands likely to be intensively managed in order to focus on the management implications of this research. This commercial timber model included the sawtimber stands on the ANF classified as Allegheny hardwoods, northern hardwoods, or mixed upland hardwoods. In all six models we considered both 3-level and binary classification of windstorm impact.

Model Name	Data Included in Model
Full Model	All 4,542 stands (all ownerships)
ANF Model	Only stands owned by the U.S. Forest Service on the ANF
DCNR Model	Only stands owned by Pennsylvania DCNR
Private Landowner Model	Only stands owned by one private landowner
Allegheny hardwood model	All Allegheny hardwood stand types across all ownerships
Commercial timber model	Allegheny hardwood, northern hardwood, and mixed upland stands of sawtimber size on the ANF

Table 2. Description of stands included in each model. All models were examined as both binary (unaffected, affected) and 3-level (unaffected, moderate, severe).

Analysis

We used the rpart package in the statistical language R to build a model to predict windthrow severity as a function of stand and site variables. The rpart package implements a recursive partitioning algorithm, which closely follows the classification tree methodology of Breiman et al. (Breiman et al. 1984, R Development Core Team 2004). Recursive partitioning searches through the data to find the most effective method 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. A complexity parameter measures how well different variables and splits separate the data. To avoid over-fitting the model, limits are set on the minimum number of stands that can be split at each node. Allowing smaller splits encourages the rpart to tailor the model 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. It is important to note that classification tree models are able to classify elements with missing values. In other words, a stand may be missing a value for a given split and still be included in the model. The rpart function uses surrogate variables to assign an element with a missing value to a category.

We used 19 variables from stand and regional level data to classify 4,542 stands. Six of the explanatory variables were stand level attributes provided by the landowners and 13 were derived from regional datasets. All models were examined two ways: binary (affected/unaffected) and 3-level (severe/moderate/unaffected). Each model used the same dataset, explanatory variables, and splitting decision rules. 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.

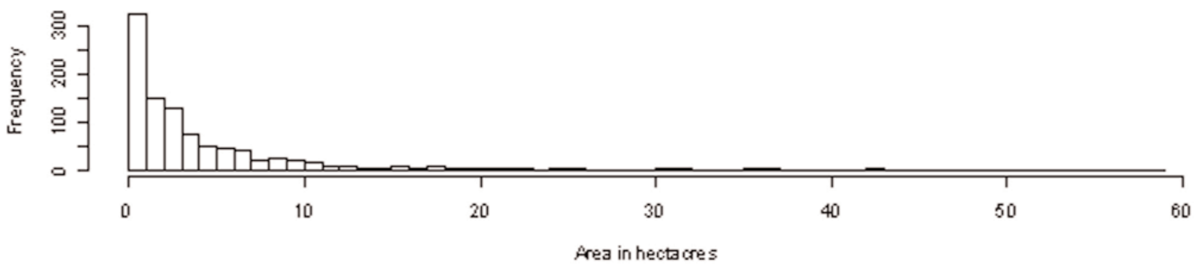

Figure 5. Histogram of blowdown patch size.

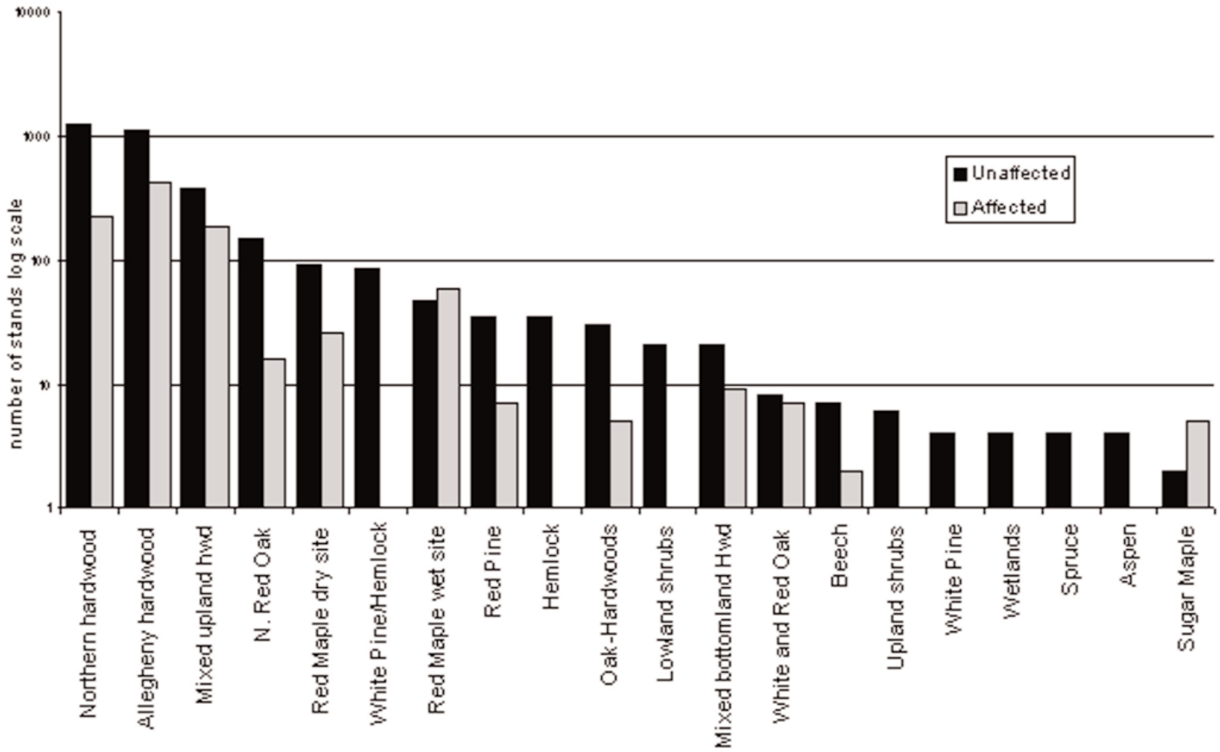

Figure 6: Number of stands by forest type.
NB: The y axis of the plot is logarithmic, de-emphasizing the differences in counts of stands by forest type.

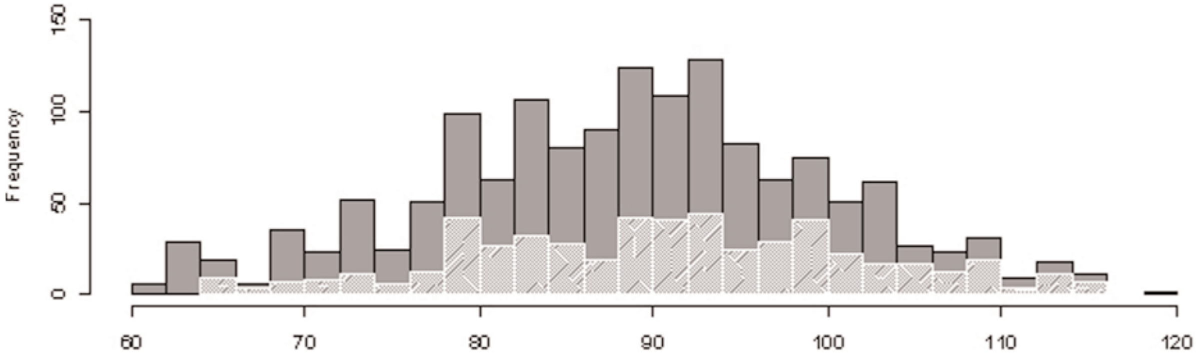

Figure 7. Histogram of stand age. Dark columns are all stands; lighter columns stands that blew down.

Results

Description of windthrow patches

We summarized attributes of stands affected by the 2003 windstorm based on our geographic database. The distribution of blowdown patch size is highly skewed. Over 30% of the patches are less than one hectare (2.5 acres) and 60% are less than 3 hectares (7.4 acres) (figure 5). Figure 6 shows a logarithmic plot of number of stands by forest type for both affected and unaffected stands. Looking at just those stands included in the analysis, the number of affected stands plotted by forest type reveals that some forest types had a much higher percentage of impact than others. Besides sugar maple, which is an uncommon type in the study area, red maple stands on wet sites were the most affected—fifty-five percent blew down. Thirty-three percent of the stands in the mixed upland hardwood type and 28% in the Allegheny hardwood type were affected by the windstorm. These percentages, however, are not indicative of the damage incurred across the entire landscape, because not all of the unaffected stands in the storm swath were included in the analysis. Nevertheless, these data do indicate which forest types were most affected in the area where the storm had an impact.

The range and distribution of stand ages for affected and unaffected stands are similar, as shown in figure 7. Since stands and blowdown patches are not independent random samples it is difficult to test if there is a difference between the age distribution in affected and unaffected areas. In contrast, the classification tree methodology focuses on those variables that are most useful for predicting windthrow severity and this method is robust and not constrained by lack of independent samples.

Model Results

The 3-level full model predicted the level of blowdown correctly 86% of the time while the binary full model was correct 89% of the time. The kappa statistics were 0.56 and 0.63 respectively. We tested the accuracy of the classification tree modeling process by generating models based on 80% of the data randomly selected and reserving 20% for validation. Validation averages for 1000 iterations of random data selection, model construction, and validation were from 81 to 87% for the 3-level model and from 84 to 91% for the binary model. The intervals for the Kappa statistic were 0.39 to 0.60 and from 0.47 to 0.70. Figure 8 shows the model and validation intervals from 1000 iterations and the final model values.

In table 3 the percentage (and number) of correctly predicted stands are listed for each class in the two versions of the full model (binary and 3-level). Figure 9 shows the classification tree from the binary model. A more detailed description of both models as well as a list of the exact splits and affected/unaffected percentages at each split is provided in appendix II.

In general the model under-predicted windstorm effects. The 3-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. Both models selected a subset of available variables that were the most useful for predicting susceptibility to windthrow, and the variables that were selected were similar for both models. The most predictive biotic variables 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. The 3-level model also selected distance from roads and distance from open areas as useful variables for differentiating between risk for severe and moderate blowdown.

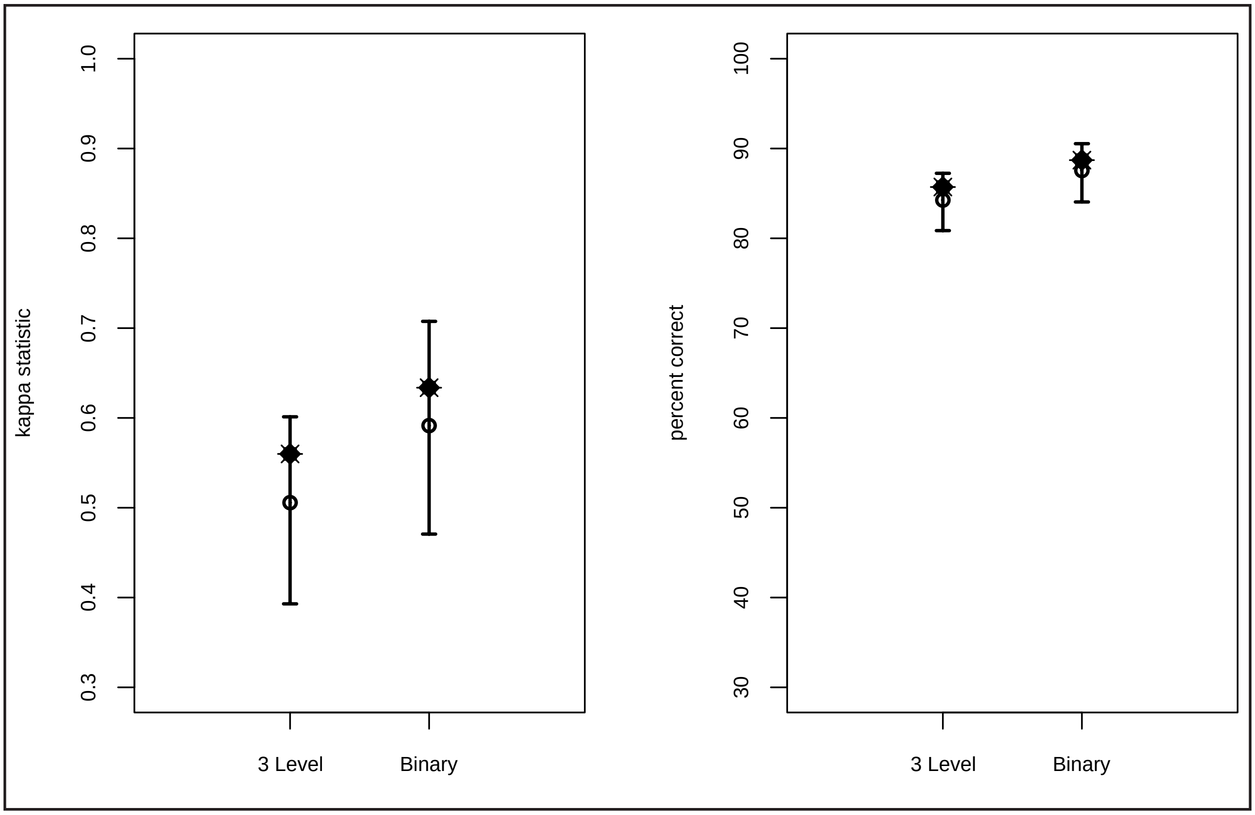

Figure 8: Test of full model accuracy. Intervals are from 1,000 model runs; stars are final model estimates.

3-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% (3,428 stands)
Predicted Unaffected	97% (3,432 stands)		

Table 3: Full model results.

Because each of the ownerships used somewhat different variables, we also developed some specific models for each ownership using only their data and classification system (see table 2).The ANF model data was the most effective, both with respect to the overall accuracy of prediction and the correct classification of the severe and moderate blowdown classes; the binary version correctly classified 95% of all stands and 89% of affected stands (kappa .87). The DCNR model was similar to, although slightly less accurate than the full model (kappa .62). The private landowner model was the least accurate and incorporated a different set of splitting variables (kappa .27). We also developed models based on forest type across the various ownerships. Results from the Allegheny hardwood model were similar to the full model; it used many of the same splitting variables and predicted nearly 60% of affected areas correctly (kappa .62). The commercial timber model used fewer stand variables since we only included a small set of stand types. Again its accuracy was similar to the full model (kappa .60).

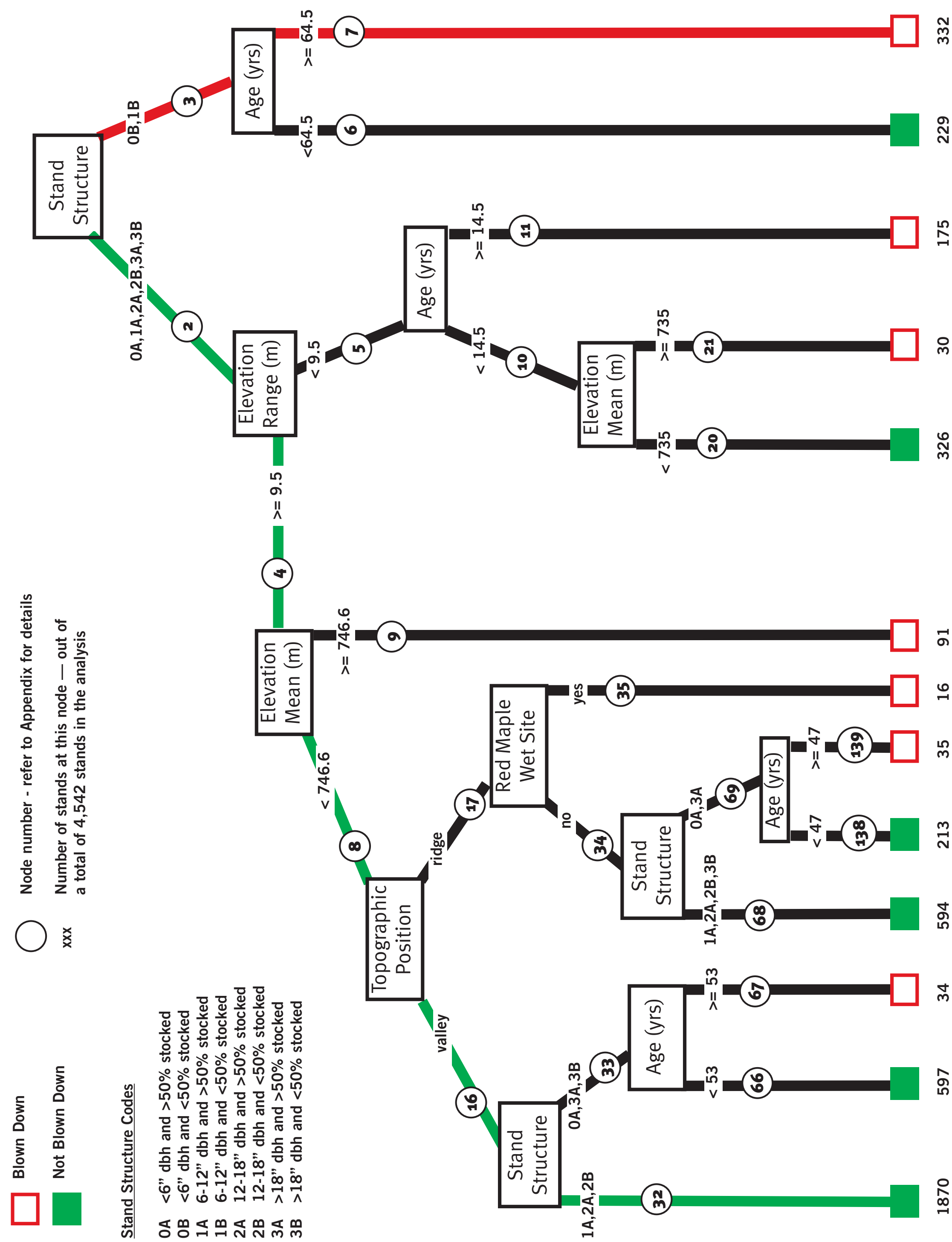

Figure 9. Classification tree for binary model.

Discussion

Wind is a natural disturbance agent that affects forests throughout the world at both stand- and landscape-levels. Our hypothesis that windthrow severity is a function of biotic stand and abiotic site variables is supported by previous work on windstorm impacts in temperate forests. Models have used similar variables to those included in this study to predict windthrow. EXPOS used topography (Foster and Boose 1992, Boose et al. 1994) and ForestGALES used height, DBH, spacing, canopy width, stand edges, and topographic exposure to predict windthrow (Gardiner and Quine 2000). Studies have shown that a variety of related metrics can be used to differentiate stands affected by wind events from unaffected stands: vegetation height, species composition, aspect and slope (Foster and Boose 1992); forest composition and structure without topographic effects (Peterson and Rebertus 1997); topographic position, aspect, age, and fire history (Kulakowski and Veblen 2002); species (Canham et al. 2001); slope, elevation, soil type, and exposure to prevailing storm winds (Kramer et al. 2001); and size and species for within-stand variation (Peterson 2004).

Our misclassification rate of 11% (binary model) is similar to other windthrow models and to other classifiction 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 2004), reflecting the inherent stochasticity of disturbance events as well as the difficulty of reducing ecological processes to numeric models. Our misclassification rate is particularly low because it is much easier to predict a common occurrence than a rare one and so the model classified the vast majority of the unaffected stands correctly.

The landscape pattern of blowdown in Northwestern Pennsylvania is similar to a study in Colorado that also reported a predominance of small patches of windthrow intermingled with intact forest (Lindemann and Baker 2001). This addition of forest openings increases the randomness, or complexity, of the landscape as described by Boutet and Weishampel for a southern coniferous forest (2003).

Our modeling identified a number of characteristics that increase or decrease the probability of windthrow from such a storm. Older stands were disproportionately impacted by the storm, as were those growing at higher elevations. Just over one third (37%) of stands over 75 years old blew down. These stands accounted for half of all the stands that blew down. Stands younger than 75 years were most vulnerable on the very highest elevations, above 746 meters (2,447 feet). 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 meters (31 feet). 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 terrain in the study area, about half of the stands on the flatter terrain blew down. These flat areas within a hilly landscape would tend to have wetter soils and shallow rooted trees, making them vulnerable to wind.

The least vulnerable stands were those with at least 9.5 meters (31 feet) of elevation change within the stand, below about 746 meters (2,447 feet) in elevation and located in valleys or at midslope positions. These results are similar to what Hough (1953) reported—stands below about 600 meters (2,000 feet) were less likely to be affected by storms. Stands that were least vulnerable were at lower elevation valleys and were either in the lower dbh classes or in higher dbh classes, but younger than 53 years (figure 9, nodes 32 and 66).

Besides these topographic features, it is also important that managers have information about the biotic characteristics of stands that are vulnerable to windthrow. While our models strongly suggest that biotic characteristics are important, our ability to report on the stand structure variables that reliably predict the effects of windstorms on stands is limited. The size/density information for many of the affected stands on the ANF is out of date by several decades and thus does not represent the structural conditions of the stand when it blew down. However, we are confident that the basal area, age, and other variables for these stands are accurate (personal communication, ANF). The stands that were at one time characterized as understocked, with small diameter trees, are now older than 64 years, and were disproportionately affected by the storm. These could be older stands on poor sites, or consist of scattered older trees with a dense understory cohort. We anticipate further fieldwork to better our understanding of the conditions these stands were in at the time they were destroyed.

Because of this problem with the stand structure variable in the ANF data, we ran a model without stand structure to see if the results would point to different predictive variables. Essentially, they did not. This alternative model was much less predictive than the full model, with a Kappa value of .39 and an 83% percent correct classification. Nevertheless, this alternative model shows that, disregarding stand structure, age is a very strong predictor. In particular, stands over 75 years old are highly vulnerable.

Our data shed light on one structural variable that did not seem to play an important role: stand composition. Following the windstorm, there was speculation among forest owners, land managers, and the environmental community that stands comprised of a high number of black cherry were disproportionately impacted. Because of its commercial value much attention was directed on private and state lands towards salvaging black cherry downed or weakened by the windstorm. Our research does not support this assumption that cherry stands, which are a major component of the Allegheny hardwoods forest type, were disproportionately impacted. Even when individual ownerships were modeled separately, forest type was not a useful predictor of the storm's impact. The similarity of the full model to the Allegheny hardwood model further supports the idea that forest type does not influence windstorm impact, at least as forest type is currently recorded.

Downed trees in the Kane Experimental Forest.

Perhaps data that more completely characterize stand structure and composition (such as species importance values) would better assist in predicting damage. Alternatively, stand composition may play a much less important role than purely structural attributes such as dbh or density.

Risk of windthrow can have dramatic management implications. Despite being a natural agent of disturbance, the windstorms that periodically impact forests on the Allegheny Plateau considerably constrain landowner's abilities to meet their management goals. We used the commercial timber model to explore the management implications of our research. Of the many combinations of variables incorporated into the model, four were found to be useful to predict risk of windthrow. Windthrow was more likely to occur in: stands with 60 -79% relative density with open areas (defined as low vegetation, water, and bare ground) to the southwest; stands on or just below ridges; stands on the upper-mid slope where the average slope was greater than 14%; and stands on slopes of large topographic features (mountainsides as opposed to smaller ridges).

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 Northwestern Pennsylvania. Differences between ownerships in classifications and codes impede regional analysis, but can be overcome with careful integration and local knowledge. Classification and regression tree analysis is a powerful tool to study this kind of data because it is robust in the face of 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 did not prove to be a useful predictor of 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 stand level, biotic factors including stand structure and age. Stand structure information that was out of date limited our ability to correlate blowdown risk with current structures in some of the most affected stands. 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 I - Stand Structure

Stand structure code	Size / Stocking
3A	> 18" Dbh and > 50% stocked
3B	> 18" Dbh and < 50% stocked
2A	12-18" Dbh and > 50% stocked
2B	12-18" Dbh and < 50% stocked
1A	6-12" Dbh and > 50% stocked
1B	6-12" Dbh and < 50% stocked
0A	< 6" Dbh and > 50% stocked
0B	< 6" Dbh and < 50% stocked

Appendix II - Model Outputs

3-level model

		Total	Number		Probability			
Node	Split	Number	Incorrect	Node Type	Unaffected	Moderate	Severe	
1)	root	4542	1002	Unaffected	0.779	0.131	0.090	
2)	structure =0B,1B	499	272	Moderate	0.349	0.455	0.196	
4)	age>=64.5	332	115	Moderate	0.063	0.654	0.283	terminal
5)	age<64.5	167	14	Unaffected	0.916	0.060	0.024	terminal
3)	structure =0A,1A,2A,2B,3A,3B	4043	677	Unaffected	0.833	0.091	0.076	
6)	MEAN<746.2455	3916	583	Unaffected	0.851	0.085	0.064	
12)	RANGE<9.5	531	201	Unaffected	0.621	0.241	0.137	
24)	age>=14.5	175	71	Moderate	0.291	0.594	0.114	
48)	nearriver<7691.5	158	55	Moderate	0.241	0.652	0.108	terminal
49)	nearriver>=7691.5	17	4	Unaffected	0.765	0.059	0.176	terminal
25)	age<14.5	356	77	Unaffected	0.784	0.067	0.149	terminal
13)	RANGE>=9.5	3385	382	Unaffected	0.887	0.061	0.052	
26)	redmaplew=N	3323	355	Unaffected	0.893	0.062	0.045	
52)	z_dev_code=0A,3A	862	164	Unaffected	0.810	0.121	0.070	
104)	age>=50.5	68	31	Moderate	0.059	0.544	0.397	terminal
105)	age<50.5	794	100	Unaffected	0.874	0.084	0.042	terminal
53)	structure =1A,2A,2B,3B	2461	191	Unaffected	0.922	0.041	0.037	terminal
27)	redmaplew=Y	62	27	Unaffected	0.565	0.000	0.435	
54)	RANGE>=41.5	26	3	Unaffected	0.885	0.000	0.115	terminal
55)	RANGE<41.5	36	12	Severe	0.333	0.000	0.667	terminal
7)	MEAN>=746.2455	127	68	Severe	0.260	0.276	0.465	
14)	nearroad<2086	82	47	Moderate	0.207	0.427	0.366	
28)	DIST_FLAT>=174.5	39	11	Moderate	0.103	0.718	0.179	terminal
29)	DIST_FLAT<174.5	43	20	Severe	0.302	0.163	0.535	terminal
15)	nearroad>=2086	45	16	Severe	0.356	0.000	0.644	terminal

Binary Model

		Total	Number		Probability		
Node	Split	Number	Incorrect	Node Type	Unaffected	Affected	
1)	root	4542	1002	Unaffected	0.779	0.221	
2)	structure =0A,1A,2A,2B,3A,3B	3981	668	Unaffected	0.832	0.168	
4)	RANGE>=9.5	3450	441	Unaffected	0.872	0.128	
8)	MEAN<746.583	3359	380	Unaffected	0.887	0.113	
16)	topo_mean<5.8	2501	218	Unaffected	0.913	0.087	
32)	structure =1A,2A,2B	1870	125	Unaffected	0.933	0.067	terminal
33)	structure =0A,3A,3B	631	93	Unaffected	0.853	0.147	
66)	age<53	597	62	Unaffected	0.896	0.104	terminal
67)	age>=53	34	3	Affected	0.088	0.912	terminal
17)	topo_mean>=5.83704	858	162	Unaffected	0.811	0.189	
34)	redmaplew=N	842	150	Unaffected	0.822	0.178	
68)	structure =1A,2A,2B,3B	594	78	Unaffected	0.869	0.131	terminal
69)	structure =0A,3A	248	72	Unaffected	0.710	0.290	
138)	age<47	213	39	Unaffected	0.817	0.183	terminal
139)	age>=47	35	2	Affected	0.057	0.943	terminal
35)	redmaplew=Y	16	4	Affected	0.250	0.750	terminal
9)	MEAN>=746.583	91	30	Affected	0.330	0.670	terminal
5)	RANGE<9.5	531	227	Unaffected	0.573	0.427	
10)	age<14.5	356	103	Unaffected	0.711	0.289	
20)	MEAN<735	326	74	Unaffected	0.773	0.227	terminal
21)	MEAN>=735	30	1	Affected	0.033	0.967	terminal
11)	age>=14.5	175	51	Affected	0.291	0.709	terminal
3)	structure =0B,1B	561	227	Affected	0.405	0.595	
6)	age<64.5	229	23	Unaffected	0.900	0.100	terminal
7)	age>=64.5	332	21	Affected	0.063	0.937	terminal