Spatial variables explain windthrow on a fine scale in a microtopographic forest

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Abstract

Windthrow is of major ecological and economic importance. In the coming years, as the frequency and severity of extreme storm events increases due to greenhouse forcing, understanding windthrow gains increased urgency for forest management. This study compares spatial predictors of windthrow at the stand and site level in a naturally fragmented, microtopographic northern Midwestern forest. We compared 15 blowdown sites from a major wind disturbance in July of 2016, with same-stand and different-stand control sites. Slope, aspect, and distance to forest and stand edge all proved to be predictors of blowdown sites. Among blowdown sites, forest density predicted blowdown area, while slope predicted number of down trees. Fetch predicted intensity of windthrow at sites near forest edges. Results suggest that in a forest characterized by microtopography and fragmentation, spatial variables are effective predictors of windthrow on a fine scale. Fetch results have implications for forest management, forest diversity, and lake sedimentation.

Introduction

In Northern American forests, windthrow represents an important disturbance with diverse and far-reaching effects on forest composition, forest structure, physical topography, and ecology (Nolet et al. 2012). Windthrow causes damage to silvicultural operations ranging from minor to catastrophic timber losses (Grayson 1989). Managing forests to mitigate windthrow is therefore valuable, but can be challenging, especially in areas where partial cutting practices leave forest reserves or buffer strips that are then highly exposed to wind (Ruel 1995, Scott & Mitchell 2005). Despite the immediate economic consequences of windthrow, blowdowns may be integral to the perpetuation of healthy forests. Canopy gaps created by windthrow are essential for almost all tree species to join the canopy, and play an important role in maintaining tree species heterogeneity and diversity (Barden 1980, Runkle 1981, Canham 1989, Poulson & Platt 1989). Effective forest management must thus take into consideration the economic and ecological consequences of windthrow.

Exploring the causes and results of windthrow is particularly important because changing climate conditions will likely alter the severity and frequency of major wind events in northern forests (Pinto et al. 2012). There are a wide range of factors which previous studies indicate increase susceptibility to windthrow, many involving the physical mechanics by which trees are broken or knocked down by wind. Whether a tree will fall is determined by wind loads on the tree, weight of the above-ground plant, soil shear strength, tensile strength of the roots on the windward side, mass of the soil root plate, and root resistance to bending or compression on the leeward side (Ruel et al. 1995). These variables change with the species of tree, the age of the tree, the composition and moisture content of the soil, as well as the immediate physical factors that determine how a tree grows in a given environment (Ruel et al. 1995). While several of these factors could be influenced by climate change, the link between climate change and wind intensity is particularly clear (Solomon et al. 2007). Climate models have consistently demonstrated a strong connection between greenhouse forcing and increases in frequency and intensity of severe convective weather events (Diffenbaugh et al. 2013, Gensini et al. 2013, Seely & Romps 2015, Trapp et al. 2007, Van Klooster & Roebber 2009). Investigating the relationship between windthrow and wind intensity is therefore valuable for effective forest planning in a changing future.

Spatial characteristics of the forested landscape, such as slope, aspect, edge area, and stand density play a major role in determining wind speed. Forest edges experience high wind loads, as they are hit with forceful, unobstructed wind. Edges therefore have high rates of windthrow (Esseen 1994). Forests fragmented by human disturbances, like clearcutting, or by natural features, like lakes, often have high edge space compared to area (Esseen 1994). Edge effects are also dependent on fetch. Fetch is defined as the distance wind can travel unimpeded before encountering a forest edge, and influences the amount of force wind has when it hits an edge (Burton 2001). Previous studies conducted in forests fragmented by logging have demonstrated a strong link between fetch and windthrow (Scott & Mitchell 2005).

The physical topography of the forests also affects wind speed. Wind is compressed and accelerated as it moves over ridges, in accordance with the Bernoulli principle (Sun and Sun 2015). Therefore it is reasonable to predict windthrow is related to slope, as windward areas with high slope will experience higher windspeeds. Whether a stand is windward with regard to slope is determined by its aspect. When intense winds come from one direction, the aspect of a stand could determine whether it experiences powerful, compressed wind, or wind that is slowing and expanding on the leeward side of a ridge. Stand density is also related to windspeed. When wind moving through a forest hits the edge of a dense stand, the wind is slowed as it transfers its energy to a dense perimeter of trees (Somerville 1980). The trees on the windward edge of the stand absorbs the full energy of the unimpeded wind, while the trees within the stand experience slowed wind (Becquey and Riou-Nivert 1987). These processes may result in a pattern where the leading edge of a dense stand has more windthrow, but the rest of the stand will have a less windthrow. It is likely that in many cases, windthrow results from a combination of spatial conditions favorable to high wind speeds.

On July 21, 2016, the forest surrounding the Notre Dame Environmental Research Center experienced a storm disturbance with high west northwest (WNW) winds that resulted in a large amount of windthrow. These blowdown sites are distributed heterogeneously throughout the forest. While studies have addressed the spatial characteristics of blowdowns in areas with extreme topography (Essen 1994, Evans et al. 2005, Scott and Mitchell 2005), little work has been done on abiotic predictors of windthrow in forests that exhibit strong microtopography, characterized by frequent but brief changes in slope and aspect. Furthermore, while much study has been directed at windthrow in forests fragmented by human activities, little work has been done to understand the impact of natural fragmentation by lakes, fields, and wetlands. This study investigated the hypothesis that the spatial distribution of blowdowns will be related to factors influencing windspeed, such as stand density, forest and stand edges, fetch and ridge topography. More specifically, we expected that blowdowns would have higher slope, more frequently have a WNW aspect, have a higher forest density, and be closer to forest and stand edges. For those blowdowns near forest edges, we expected that blowdown size and completeness would be related to the fetch of the non-forested area. Lastly, we predicted that proportion of blowdown-damaged area in blowdown stands would be correlated with stand slope, and that blowdown stands would have higher slope than non-blowdown stands.

These predictions operate on the assumption that even in an environment without large topographical features, factors influencing windspeed will still play a role in determining the location and extremity of blowdown sites. Two other primary goals of this study were to provide information that could be useful in future management or scientific study. Accordingly, we generated two map layers. One layer is a map of 15 blowdown sites with accompanying information on site slope, aspect, habitat type, number of down trees, density, site area and perimeter, fetch, and proximity to forest and stand edge. The other layer is a map of areas that are at high risk for blowdowns.

Methods

Finding Blowdowns

Blowdown sites were identified using National Ecological Observatory Network (NEON) Normalized Difference Vegetation Index (NDVI) data in ENVI software. Sites with low NDVI were identified and overlaid with a hillshade generated from NEON Lidar data, as well as an UNDERC habitat type layer. This allowed us to determine whether the NDVI drop was likely explained by wetland, clearings, or windthrow. The habitat layer was first georeferenced to the NDVI layer.

Blowdown sampling

Sites were sampled by running a transect through the longest possible axis of the blowdown area. At a random point more than 10m from either end along this axis, a perpendicular 20 meter transect was dropped, creating a plot with a 10 meter radius. Within this plot, trees with Diameter Breast Height (DBH) greater than 5cm were counted as either standing or down. Only trees that had stumps or tip-ups inside the plot were counted, to avoid counting trees that would have been outside the plot when alive. Broken trees and hang-ups (partially blown over trees leaning on other trees) were counted as down. Trees decayed enough to support a moss layer were not counted. These counts were used to reconstruct the density of the forest before the blowdown by adding the down trees to the standing trees and dividing by the plot area. The total number of down trees in the blowdown site were counted using the same DBH cutoff.

The perimeter of the blowdown site was mapped using a Garmin eTrex H GPS. Blowdown contiguity was determined by the proximity of a downed tree to the edge of the blowdown site. If a tree trunk or stump was less than 5m away from the contiguous blowdown site, it was considered to be part of the site. The perimeter of each site was mapped by walking around its edge, recording GPS coordinates at site vertices.

Control plots

We placed local control plots by picking a random direction, running a 50m transect away from the blowdown site in that direction, and picking a random point more than 10m from either end along that transect to run a perpendicular 20m transect. If there was not enough room in the same stand to run a 50m transect, we picked a different direction. In three cases, the stand was so small or so completely blown down that a control plot was placed haphazardly in the only possible area within the stand. We sampled the control plots for density using the same method as the blowdown plots.

We place non-local control sites by dropping random points within the UNDERC property using ArcGIS software. Points were buffered geodesically to create circular polygons with a 19.90m radius, so as to have the same area as the average blowdown site area. We placed 10m radius circular plots at the center of these control sites, and sampled using the same methods as the blowdown plots (figure 1).

GIS data collection

We digitized blowdown site GPS coordinates into polygons in ArcGIS in the Universal Transverse Mercator (UTM) zone 16N, yielding the area of each blowdown. A slope layer was created using the "slope" tool on a NEON Digital Terrain Model (DTM). We calculated mean slope for all sites using the "zonal statistics" tool. We calculated mean aspect using a script called "CalcZonalMeanAspect" from the Cocino National Forest service. Aspect for each site was categorized corresponding to the cardinal or primary intercardinal directions of the slope. Forest and stand edge proximity were calculated by generating a line layer of forest features and a line layers of non-forest features from the UNDERC habitat type layer. The near tool was used to find the shortest distance between site polygons and lines representing the edge of the forest or stand. We isolated sites that could have been affected by fetch of an open area by geodesically buffering all non-forest features 30m, and creating a new layer of sites that overlapped with the buffer, and were thus 30m or less from a forest edge. For these sites, we calculated fetch by marking the point where a non-forest area was closest to the site. We used the measure tool to find the distance across the non-forest feature starting from this point, roughly perpendicular to the edge of the feature.

Blowdown and control stands

Stands that contained blowdowns were considered blowdown stands. Stands that contained non-local control sites were considered control stands. We calculated proportion of stand damaged by dividing total blowdown area within the stand by the stand area from the UNDERC habitat type layer. In the case where a single blowdown site was in two stands, the site was split along the stand border, and both stands were considered blowdown stands.

Statistical analysis

Statistical analysis was done using R software. Slope data and stand proportion damaged were normalized with an arcsin transformation. We used a Shapiro-Wilks test to determine whether data was normal. Total down tree data was normalized with a log transformation. For normally distributed data, a one-way ANOVA with a Tukey post-hoc was used to compare blowdown sites, local control sites, and non-local control sites. For non-normally distributed data, we used a Kruskal-Wallis test with a pairwise Wilcoxon post-hoc. To compare normally distributed continuous data between blowdown sites, fetch-influenced blowdown sites, or blowdown stands, we used linear regression. To compare non-normally distributed data between these sites, we used a Spearman rank-order correlation. Aspect data was analyzed using a chi-squared test.

Risk map

The map of high-risk sites for windthrow (figure 2) was created in ArcGIS. Slope was classified into four categories: 0º-10º, 10º-20º, 20º-30º, and 30º-80º. Aspect was classified into two categories, with 270º-90º corresponding to 1, and 91º-269º and -1 (flat areas) corresponding to 0. These two rasters were multiplied together, yielding a slope raster with 4 categories, where all slopes not facing broadly northward were put into the lowest category. We turned non-forested areas from the UNDERC habitat layer into a raster layer, and used euclidean distance and reclassify tools to create five categories corresponding to distance from a non-forest area: 0-10m to 5, 10-20m to 4, 20-30m to 3, 30-50m to 2, and 50-6000m to 1. We multiplied this layer by the combined slope and aspect raster to produce a raster with values ranging from 1-20, where higher values represented higher blowdown risk. Actual values do not correspond to any established metric. The scoring system is purely relative, and should be interpreted as such.

Results

Site level results

Within blowdown stands, blowdown sites (bd) had significantly higher slope than local control sites (lc) (mean ± SD; bd, 12.46 ± 5.44; lc, 8.36 ± 4.45, df = 28, F = 5.88, n = 30, p = 0.043, figure 3). We found no significant difference in forest edge or stand edge proximity between local control and blowdown sites (mean ± SD; bd, 41.38 ± 60.45; lc, 57.16 ± 61.01, df =

28, n = 30, p =0.36; bd, 9.75 ± 17.27; lc, 12.50 ± 13.14, df = 28, n = 30, p = 0.60). Forest density did not significantly differ between blowdown sites and local or non-local control sites (nlc) (mean ± SD; bd, 0.128 ± 0.0522; lc, 0.113 ± 0.0471; nlc, 0.101 ± 0.040, df = 42, n = 45, p = 0.53). However, blowdown sites had significantly higher slope than non-local control sites (mean ± SD; bd, 12.46 ± 5.44; nlc, 6.68 ± 2.88, df = 28, F = 5.88, n = 30, p = 0.0057, figure 2). Blowdown sites also tended to be closer to forest edges and stand edges than non-local control sites (mean ± SD; bd, 41.38 ± 60.45; nlc, 81.56 ± 50.57, df = 28, n = 30, p = 0.067; bd, 9.75 ± 17.27; nlc, 24.48 ± 28.46, df = 28, n = 30, p = 0.100, figure 4). Blowdown sites had a west or northwest aspect significantly more often than expected when compared to the aspects of local and non-local control sites (X^2 = 24.75, df = 14, p = 0.037, table 1).

Stand level results

Stands that contained blowdowns had no significant difference in average slope compared to non-blowdown stands (mean ± SD; blowdown stands 8.17 ± 1.88, n = 11; control stands 7.37 ± 1.99, n = 15, df = 24, F = 1.12, p = 0.30). Furthermore, proportion of blowdown area to total area in stands was not explained by slope (df = 9, R^2 = 0.001, F = 0.086, n = 11, p = 0.776).

Blowdown results

Among blowdown sites, forest density was negatively correlated with blowdown area (df = 13, R_s = - 0.64, n = 15, p = 0.013, figure 5), but not correlated with total number of downed trees (df = 13, R^2 = 0.066, n = 15, F = 1.99, p = 0.18). Site slope was negatively correlated with total number of down trees (df = 13, R^2 = 0.34, n = 15, F = 8.38, p = 0.012, figure 6), and not correlated with site area (df = 13, $R_s = -0.31$, n = 15, p = 0.26). Blowdown sites that were within 30m of a non-forested area were considered to be possibly explained by fetch. In these sites, fetch was positively correlated with site area and total number of down trees (df = 8, $R_s = 0.83$, n = 10, p = 0.0056; df = 8, $R_s = 0.96$, n = 10, p = 2.2e-16, figure 7).

Discussion

Our predictive variables consistently correlated with increased windthrow at the site level, but not on the stand level. Blowdown site slope was significantly higher than local and non-local control slope. This indicates that on a fine spatial scale, on the order of tens or hundreds of square meters, higher slope increases the chance of a forested area blowing down through the predicted wind compression mechanism. It also suggests that within a stand, there is appreciable topographic variation that helps determine which areas blow down. We did not find significant differences in our broader spatial comparison between blowdown stand slope and control stand slope (note again that blowdown stands refer to the entire stand that a blowdown occurred in, not the specific blowdown site). Topographic differences between stands, such as areas of extreme slope, may be in small, specific regions that do not totally represent the terrain of the stand. Stands may not have topography conducive to windthrow except in a few small sites. Given that this region is dominated by microtopography, and large-scale topographic changes are uncommon, it makes sense that there are not significant changes in stand-size topography. The absence of a relationship between windthrow and topography at the stand level runs counter to findings from some studies in areas with more dramatic topography (Scott & Mitchell 2005).

We found that slope was negatively correlated with total number of down trees, but not correlated with blowdown area. This may be due to absorption of wind energy by the ground itself. In highly sloped areas, the sloped ground as opposed to the tree canopy likely dissipates much of the wind energy, which could result in fewer trees being blown over. A possible explanation for why blowdown slope is not correlated with blowdown area is that in sloped sites, canopy-level wind encounters hillside and is forced against the sloped ground. The tree canopy no longer disperses wind energy, so wind energy is conserved along the course of the slope, and can blow down vulnerable trees deeper in the forest (figure 8). Rough objects such as trees disperse wind energy far more efficiently than smoother objects such as the forest ground (Mayaud et al. 2015). In UNDERC forests, slopes rarely last more than 50m, so wind energy may not be totally dispersed over the course of the slope, which may explain the absence of protected midslope areas found in other studies (Evans et al 2007). It is also possible that protected midslope areas are more likely in landscapes where extreme slope (more than 40º) is common, as the wind would encounter the ground more quickly. Additionally, trees living on slopes may be adapted to dealing with high winds. Trees further up the slope, which experience less wind, may be less adapted to high winds, meaning that they blow over more easily when forceful ground-level wind reaches them. This could also explain why blowdowns on slopes do not tend to be smaller, as trees are blown down further from the site of initial wind compression. Slope was overall a stronger predictor of blowdown sites in our study than it has been in previous studies, likely because slopes in the UNDERC disperse wind energy incompletely, resulting in higher amounts of windthrow per slope area.

Like slope, aspect appeared to predict windthrow on fine spatial scales, but not on coarser spatial scales. Blowdown sites faced northwest more commonly than local or non-local control sites, and more than expected according to a chi-squared test. This can be explained by the northwesterly storm gusts of the 2016 wind disturbance. Slopes facing northwest were hit with wind more directly, transferring more energy to the canopy.

We found that forest density also significantly altered the way forests interacted with wind. Among blowdown sites, forest density was negatively correlated with blowdown area, and not correlated with total number of down trees. We predicted that dense stands might exhibit a pattern where the leading edge of the stand is subject to substantial windthrow, but the interior of the stand was protected. Our results seem to reflect this prediction, as blowdowns in dense stands tended to be smaller. Wind energy absorption is proportional to the density of the stand (Somerville 1980). In dense stands, a large number of trees over a small area likely absorbed the brunt of the wind, protecting the downwind forest, thus limiting the size of the blowdown area but not the number of damaged trees.

Previous research at UNDERC has pointed to the importance of edge effects in the locations of windthrow (Depies 2017). We found that there was no significant difference in distance to stand edge or forest edge between blowdown sites and local control sites, but that blowdowns sites did tend to be closer to both forest and stand edges than non-local control sites. Blowdown sites may tend to be closer to forest edges because wind is unimpeded in non-forested areas, allowing it to gain larger momentum. When it does encounter a forest edge, this increased force is dispersed among the trees, causing damage. Blowdown sites may tend to be closer to stand edges because of differences in tree density between stands. Widely spaced stands allow wind to travel faster through them, and when this high-velocity wind encounters the edge of a dense stand, it may result in blowdown damage. However, the fact that we did not find a significant difference in the forest density of blowdown site and local or non-local control sites suggests that there are more complicated wind dynamics at play near stand edges that result in blowdowns, and that change in density may not be as important as other biotic factors such as change in tree species, height, and age.

Among those sites that were within 30m a forest edge, fetch of the closest non-forested area was strongly positively correlated with both blowdown size and total number of down trees, a result that is in agreement with work done by Scott & Mitchell (2005). As wind travels over an unobstructed area, it gains momentum. The momentum it has when it hits a forest edge depends on the amount of distance it traveled without obstruction (Burton 2001). The greater distance it can travel, the more energy it is able to impart on a forest edge, corresponding to greater windthrown area and a greater number of total down trees. Many previous studies have focused on fetch where the non-forested area was logged land. Most of the non-forested area in this study was lake surfaces. The corresponding increase in the surface smoothness of the non-forested area may help explain the particularly strong effects of fetch observed in this study.

Previous work on windthrow in northern Midwestern forests has surmised that predictors of windthrow on small spatial scales are primarily biotic, and may even be on a tree by tree basis (Peterson 2004). Other studies on the spatial dynamics of windthrow have concluded that the influence of topography on windthrow become more complex or less predictable at finer spatial scales (Everham 1996). However, the evidence for this conclusion comes from studies where the topography itself is constant over large spatial scales (Evans et al. 2007). This study adds an important caveat to that idea. The scale of blowdown predictability appears to vary with the scale of the landscape's topography. In an area with only microtopography, fine spatial variables are significant predictors of windthrow, but stand level variables are not. Furthermore, a solely biotic approach to predicting windthrow susceptibility on fine spatial scales is incomplete in areas where the topography varies over fine spatial scales.

Future management implications

We found that lake fetch correlated with larger and more complete blowdown areas. This result supports the findings of previous studies indicating that controlling the shape of logged areas to minimize fetch could be a useful strategy for protecting timber from windthrow (Macisaac & Krygier 2009). In addition, as blowdowns occur along the edges of lakes, more open area is created, increasing the open-area fetch. This may lead to further blowdowns in the same area, creating a feedback mechanism that could result in large amounts of windthrow. Further work dating the age of blowdowns would be useful to quantify to what degree blowdowns beget more blowdowns.

The blowdown-risk map we generated for the UNDERC property could be used for studies in areas like sediment flow into lakes and understory diversity. Many high-risk sites have not yet experienced major blowdowns. Testing could be done to establish baseline forest characteristics, with the expectation that the plots will probably experience significant windthrow in the coming years. Additional research into biotic factors or wind direction and intensity could be added to increase the predictive power of the map.

In sum, those tasked with managing microtopographic forests should consider topography on a fine spatial scale. While practices in highly topographic forests may call for analysis of blowdown risk on a stand by stand level, analysis of blowdown risk in the forests of the northern Midwest would be more accurately done on a site by site level. The high resolution (1m) map generated for the UNDERC property could facilitate detailed and accurate comparisons, and the blowdowns layer provides a good understanding of what factors put a site at high risk for windthrow.

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Tables

Table 1. Aspect categories of blowdown sites, local control sites, and non-local control sites. Aspect was calculated using the "CalcZonalMeanAspect" script from the Cocino National Forest Service. Blowdown sites and Local control sites faced NW more often than expected ($p = 0.037$, $n = 15$).

	N	NE	E	SE	S	SW	W	NW
Blowdown	0	3	0	2	0	2	3	5
Local control	5	0	0	3	2	0	1	4
Non-local control	1	3	2	2	3	2	2	0

Figures

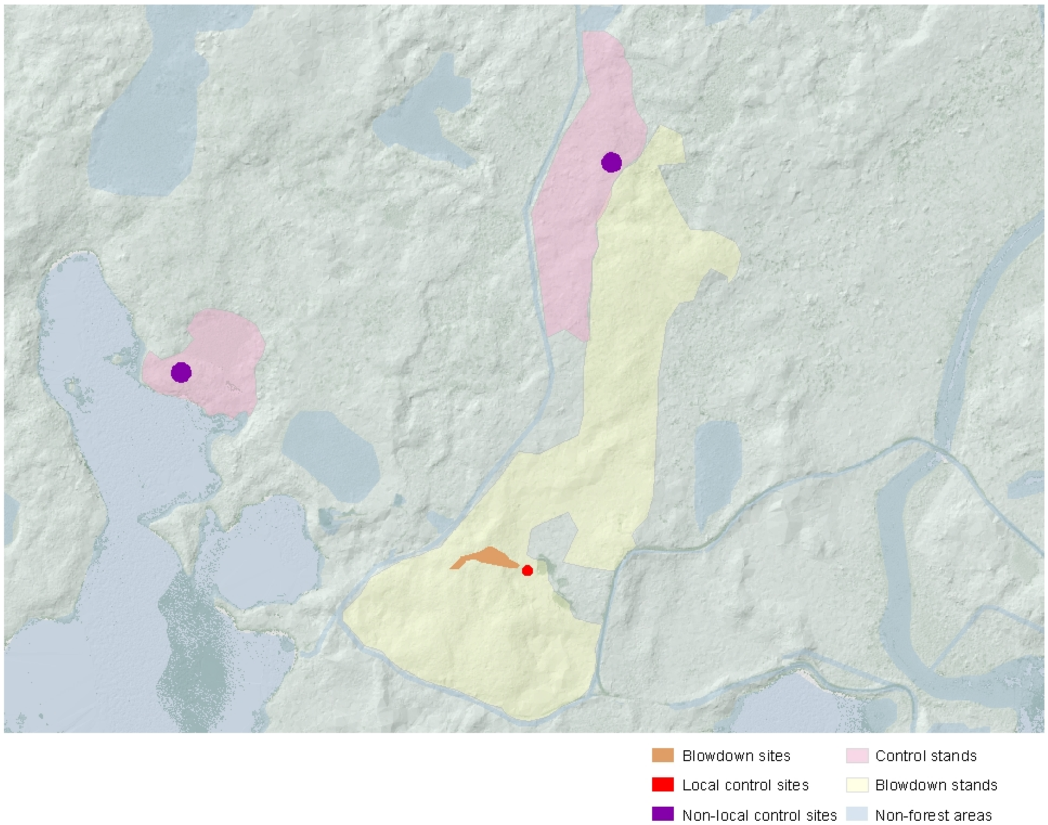

Figure 1. Map showing digitized blowdown site, local control site, blowdown stand, non-local control sites, and control stands. Stand boundaries were taken from the UNDERC habitat type layer. Blowdown sites were digitized from GPS coordinates from the site. Local control sites were selected by running a 50m transect in a random direction from the site and putting a 10m plot at a random point along the grid. Non-local control sites were placed by dropping random points on the map, and buffering these points 19.90m.

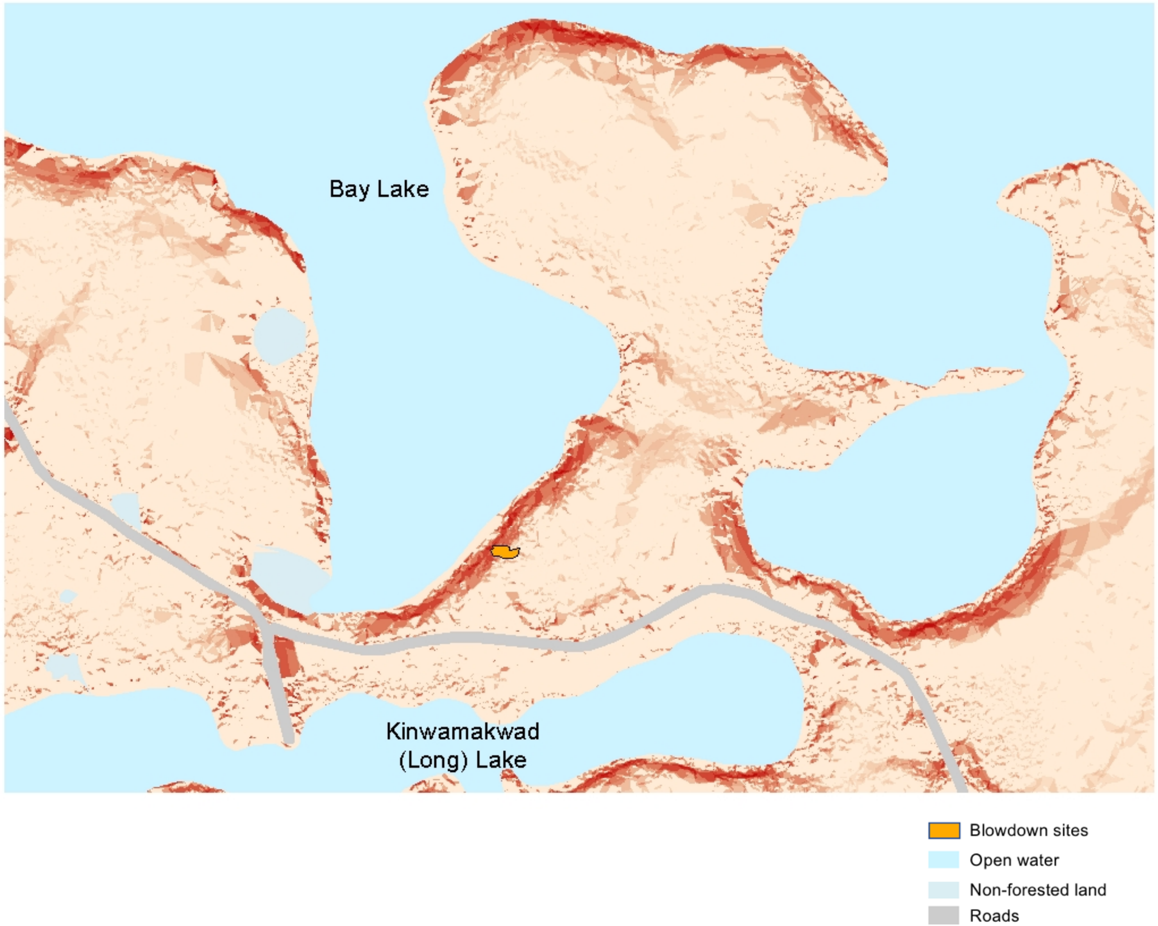

Figure 2. Portion of blowdown risk map. Darker red areas are a higher risk of blowdown based on aspect, slope, and distance from forest edge. Aspect and slope data were created from a NEON DTM. Distance to forest edge is based on the UNDERC habitat type layer.

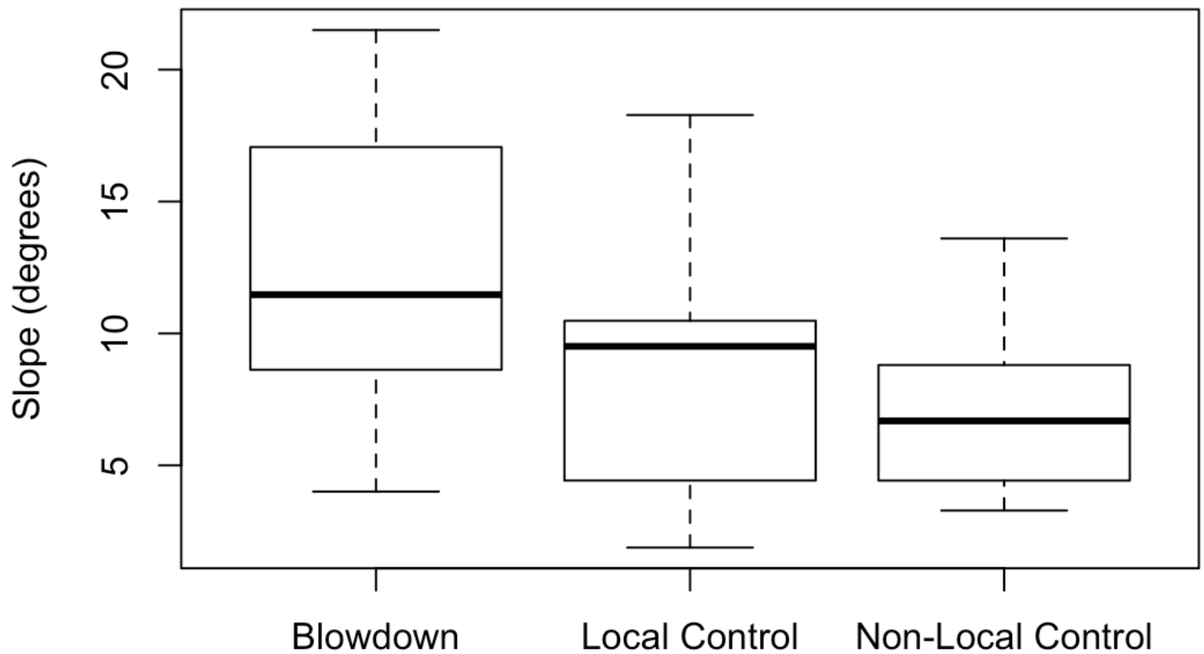

Figure 3. Differences in slope of blowdown sites, local control sites, and non-local control sites. Slope was calculated for all sites using the ArcGIS zonal statistics tool on a slope layer generated from a NEON Lidar DTM. Blowdown sites had significantly higher average slope than local and non-local control sites ($p = 0.043$, $p = 0.0057$, $n = 15$).

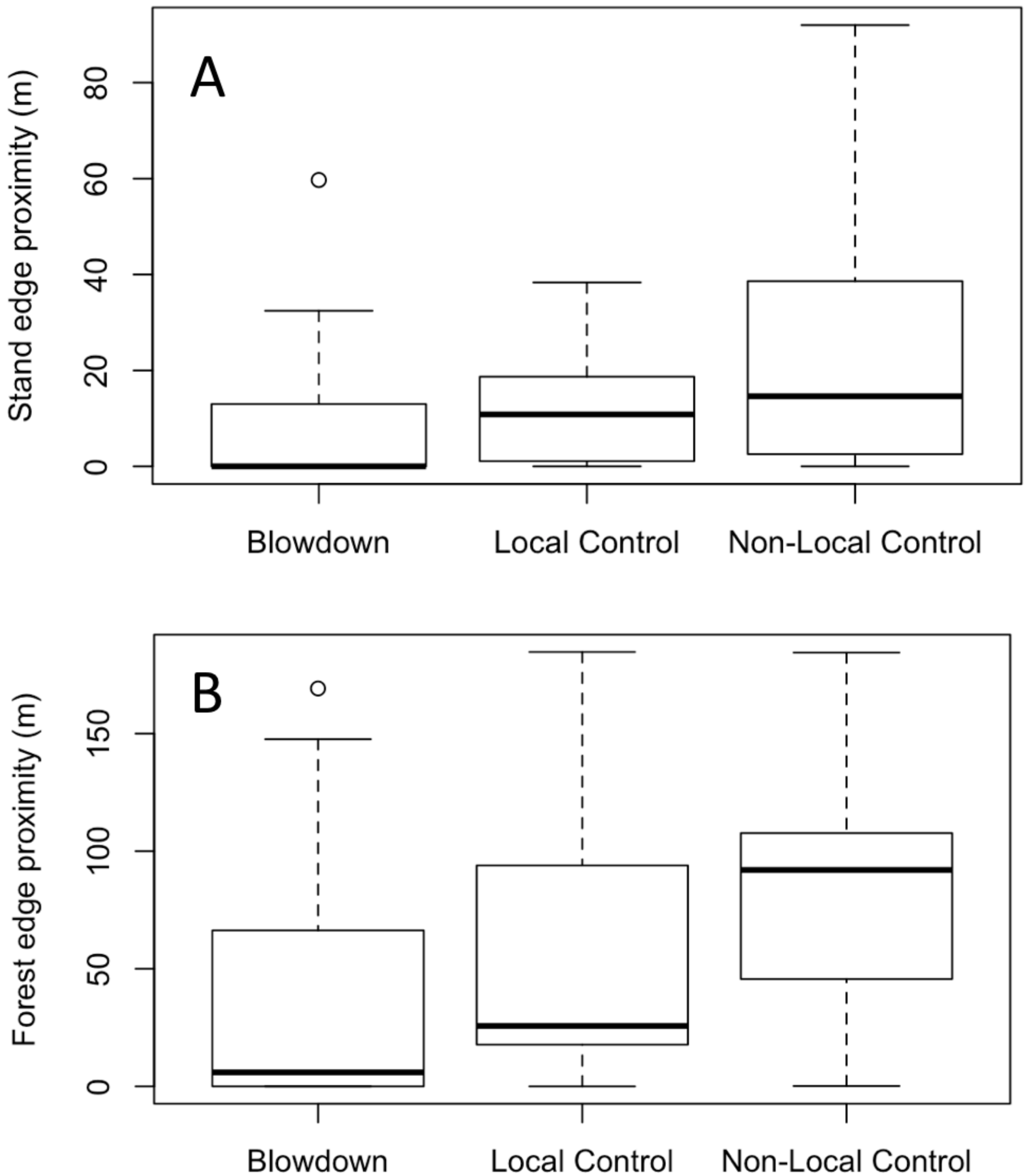

Figure 4. Average distance to stand edge (A) and forest edge (B) for blowdown sites, local control sites, and non-local control sites. Stand and forest edges were taken from the UNDERC habitat type layer. Distance to stand and forest edge was calculated from the edge of each site to the closest point on the edge using the ArcGIS near tool. Blowdown sites tended to be closer to the edge of forests and stands than non-local control sites ($p = 0.067$, $p = 0.10$, $n = 15$).

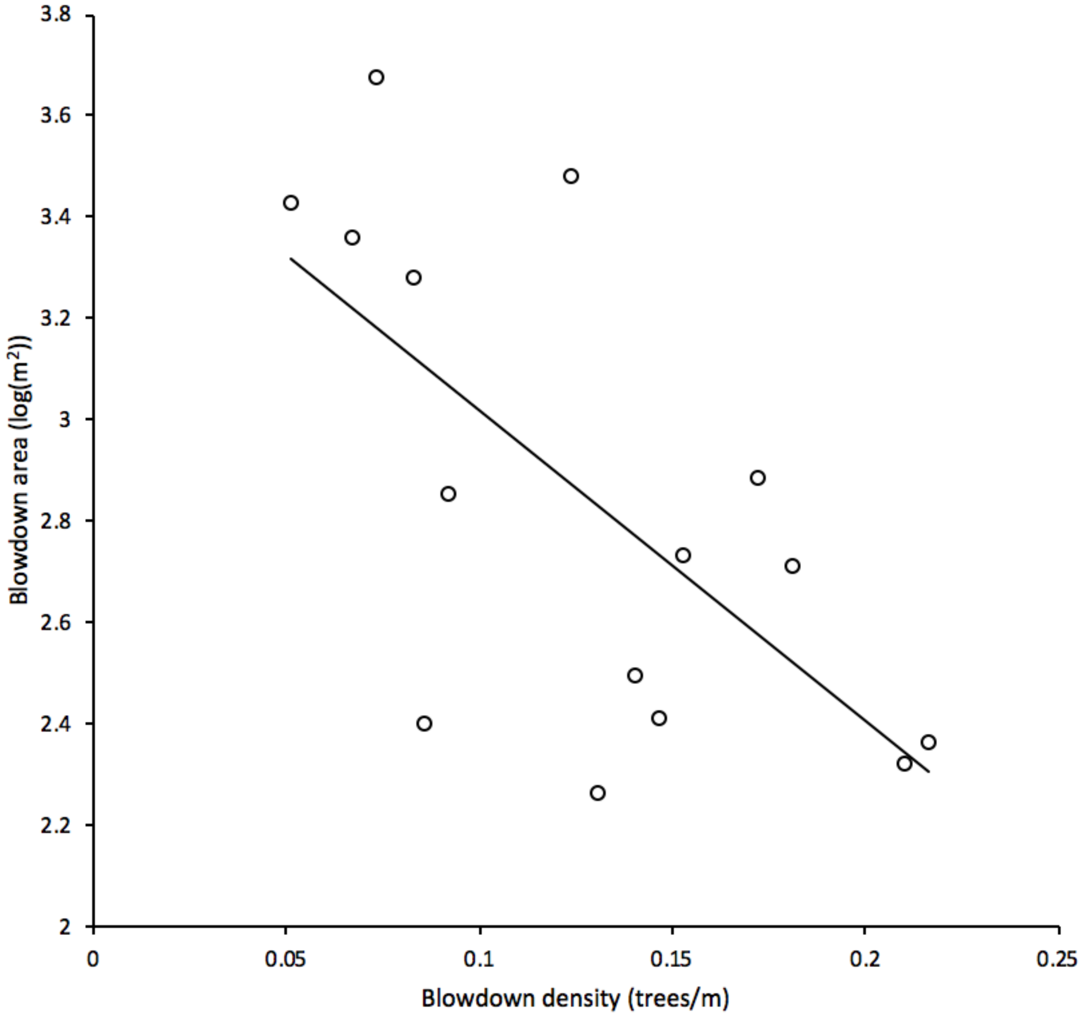

Figure 5. Correlation between blowdown density and blowdown area. Blowdown density was calculated by counting the stumps, tip-ups, and standing trees in a 10m radius circular plot placed randomly on a transect along the long axis of the blowdown. Blowdown area was calculated from digitized blowdown site polygons. Blowdown density was negatively correlated with blowdown area ($p = 0.013$, $n = 15$).

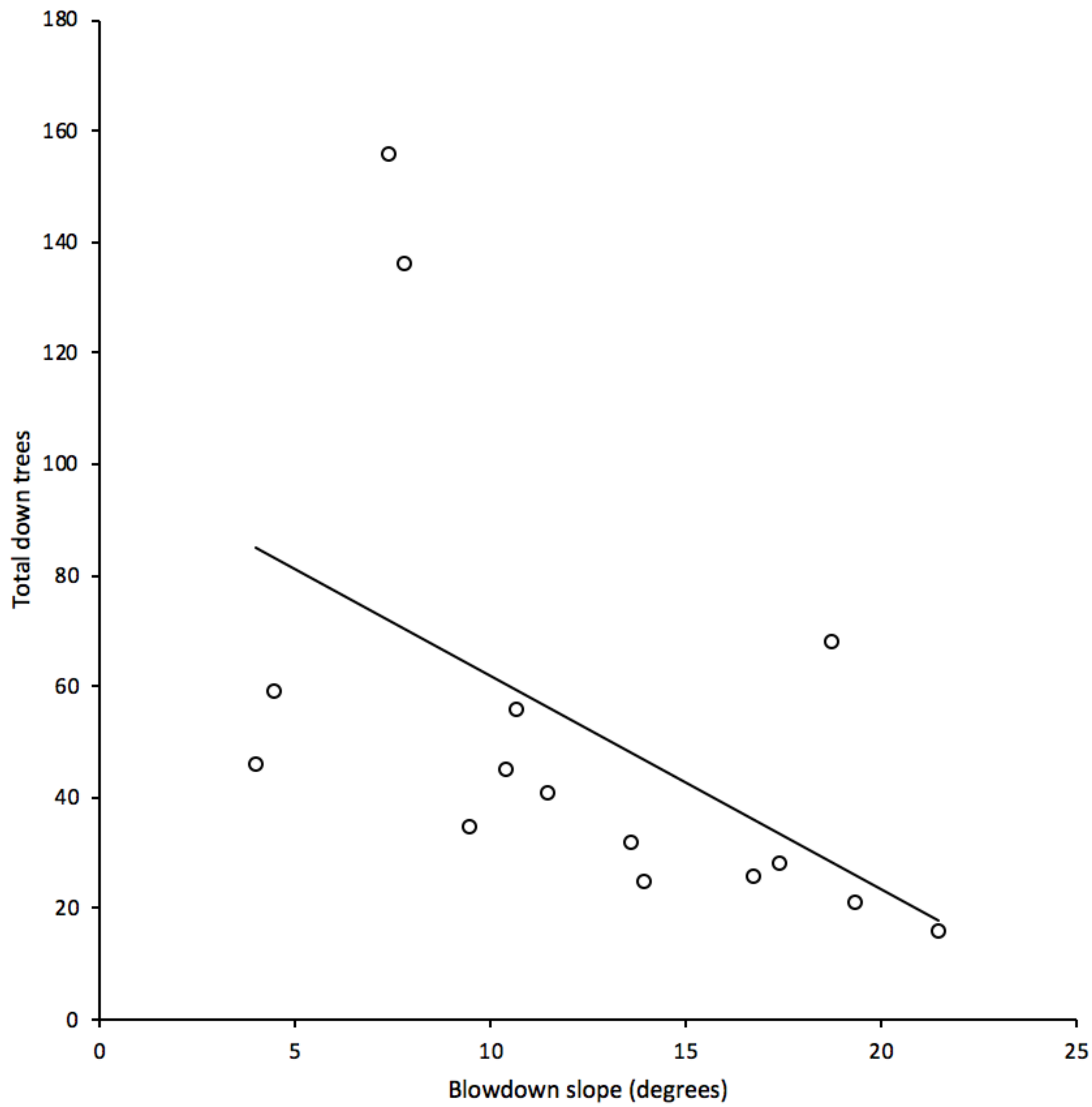

Figure 6. Correlation between blowdown slope and number of total down trees. Slope was calculated for all sites using the ArcGIS zonal statistics tool on a slope layer generated from a NEON Lidar DTM. Blowdown slope was negatively correlated with total number of down trees ($p = 0.012$, $n = 15$)

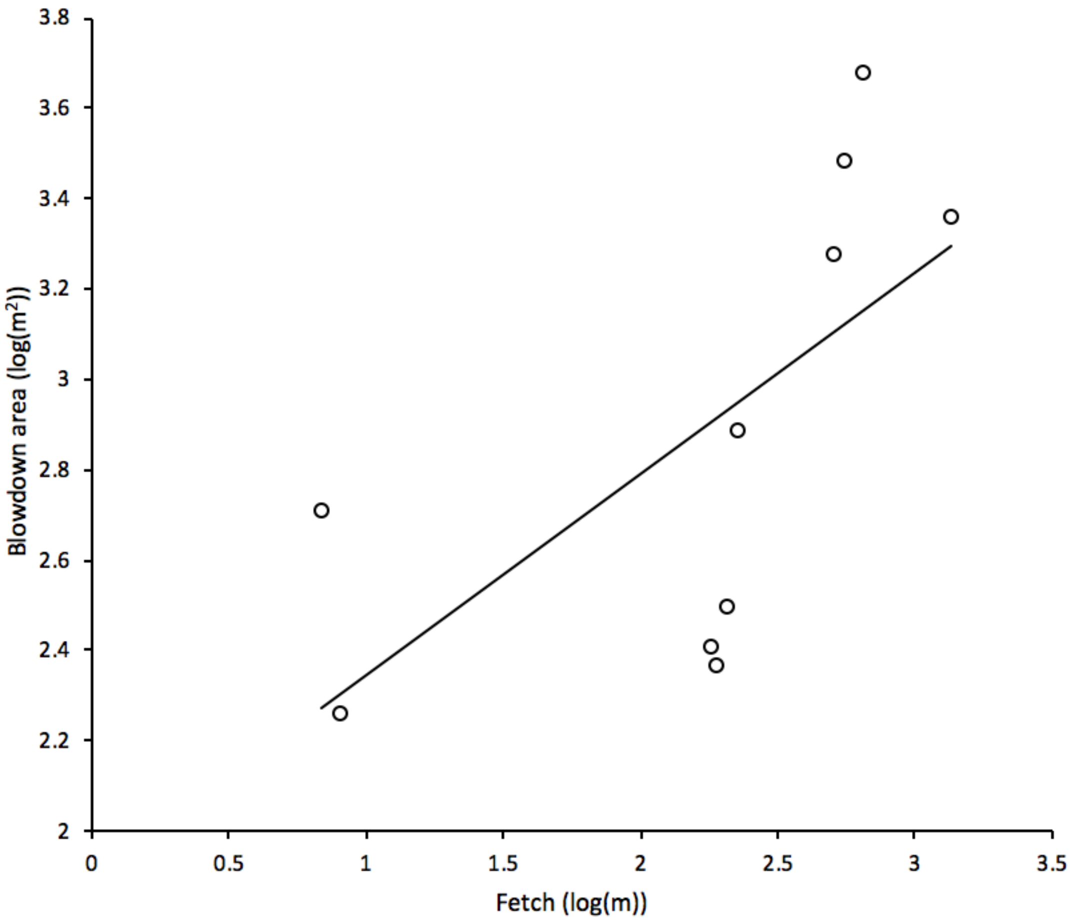

Figure 7. Correlation between fetch and blowdown area. Fetch was calculated by marking the point where a non-forest layer was closest to the blowdown site. The measure tool in ArcGIS was used to find the distance across the non-forest feature starting from this point, roughly perpendicular to the edge of the feature. Fetch was positively correlated with blowdown area ($p = 0.0056$, $n = 10$).

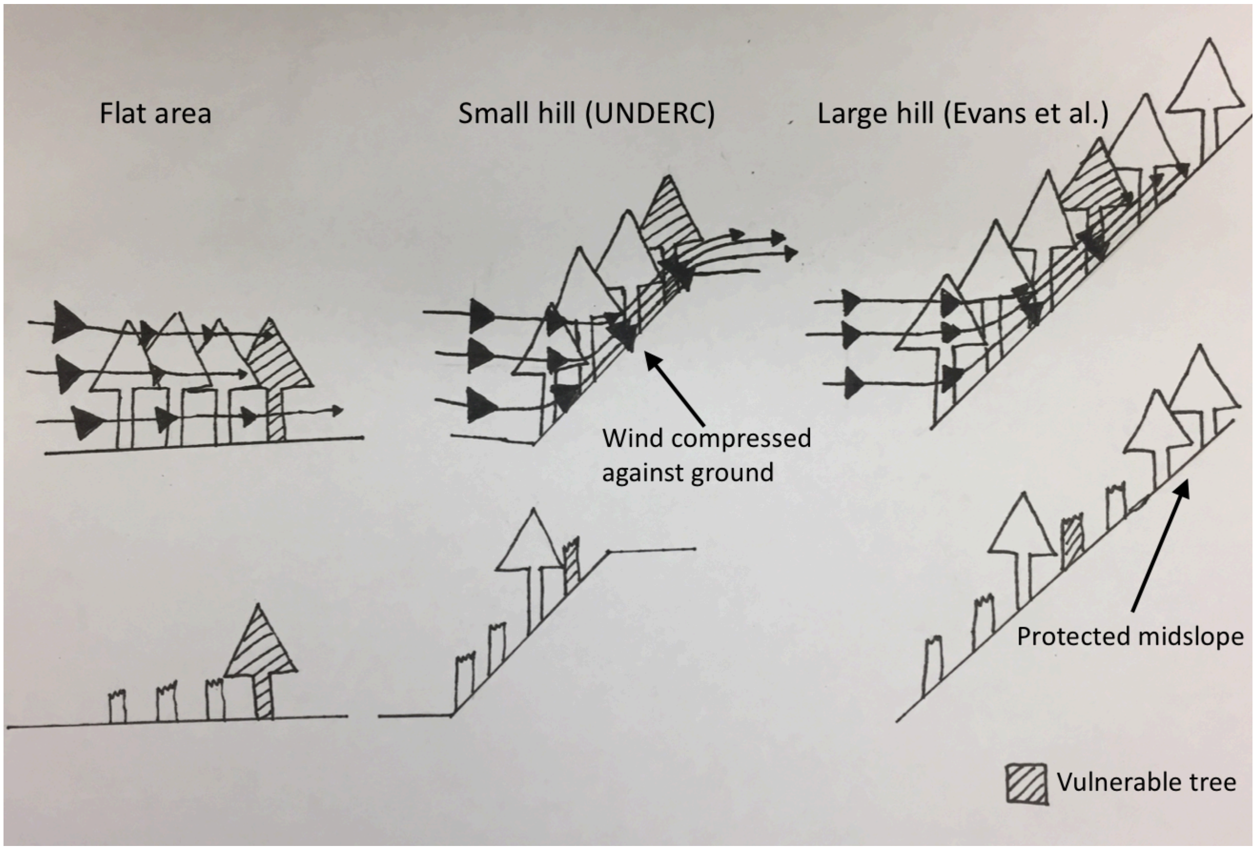

Figure 8. Diagram showing proposed mechanism of wind travel on small hills. Black vectors represent wind. Arrow size represents wind velocity. Slash pattern represents vulnerable trees. As wind is compressed along the forest floor, it is able to travel further up the hill, reaching vulnerable trees. In areas with larger hills, wind momentum is eventually lost, leading to protected midslope areas.