



The effect of species, size, failure mode, and fire-scarring on tree stability



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ABSTRACT

Understanding of wind disturbance remains predominantly at a phenomenological rather than a mechanistic or predictive level. Although wind-damage surveys in forests have identified broad trends among species, sizes, and stand structures, most of these variables are unavoidably confounded in descriptive studies. To provide improved insights into the impacts of wind on forests, static winching studies allow direct measurement of wind resistance with minimal confounding of potentially influential tree features. Here we report results from a static winching study of loblolly pine (*Pinus taeda*) and tulip poplar (*Liriodendron tulipifera*) on the Georgia Piedmont. This study is one of only a few that directly compares tree stability (and by extension, windfirmness) between two species across a wide size range, and is apparently only the second to directly compare a conifer to a hardwood species. Because previous fires scarred some of the trees, we opportunistically recorded fire scar presence and size along with the primary predictor variables of tree size and species. Because the calculation of critical turning moment – an indication of tree stability – relies on several field measurements that are often estimated, we included a sensitivity analysis to determine the most sensitive parameters in the calculation of critical turning moment. Our analysis of critical turning moments of winched trees revealed that tree stability increased with tree size. Surprisingly, critical turning moment did not differ between species. Moreover, fire scars were associated with a non-significant trend toward reduced tree stability, a trend that may have been significant with a larger sample size. These findings suggest that interspecific differences in tree damage documented by post-event damage surveys may be due more to variation in wind load among trees, than to innate interspecific differences in tree windfirmness.

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1. Introduction

1.1. Tree Stability

Wind disturbance to forests that causes snapping or uprooting of individual trees is a widespread occurrence with important ecological effects on forests. Wind damage (all types, including thunderstorms, derechos, hurricanes, and tornadoes) may affect up to 1.65 million ha of forest annually in North America (Dale et al., 2001), and influence numerous forest processes such as regeneration (Peterson and Pickett, 1990), maintenance of herb diversity (Beatty, 2003), and carbon cycling (Chambers et al., 2007). Furthermore, studies suggest that recent and future changes in climate will lead to an increase in the frequency of thunderstorms and tornados (Difffenbaugh et al., 2013), and an increased severity of tropical cyclones (Webster et al., 2005).

The ubiquity and ecological importance of disturbances call for a predictive understanding of the phenomenon of wind disturbance (Johnson and Miyanishi, 2007). Descriptive studies of wind damage have documented robust trends in effects of size, species, and stand and site conditions (e.g. Everham and Brokaw, 1996; Peterson, 2007). Such descriptive work, however, is necessarily constrained by small-scale spatial variation in wind loads that severely limits the number of trees that experience similar wind impacts, biotic neighborhoods, and soil conditions and make generalization to other storms or regions more difficult (e.g., Albrecht et al., 2012). As a result, potential predictor variables are often confounded, and it may not be clear, for example, whether a particular species in a study was less vulnerable to damage than its neighbors because it is more windfirm, or because it grew in more sheltered locations. A way forward is offered using experimental methods that directly measure physical parameters such as windfirmness that will be major determinants of realized damage patterns.

Static winching is the most widely used experimental method to directly infer the critical turning moment of a tree, i.e. the

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rotational force at the moment of failure (breaking or uprooting), and an indicator of tree stability or wind resistance. It is well-documented that critical turning moment increases greatly with tree size (e.g., Peltola, 2006; Quine and Gardiner, 2007), but species differences in stability are also expected due to factors such as wood strength, plant architecture, and rooting depth (Peterson, 2007). Several studies have found only slight differences in stability among conifer species (Achim et al., 2005; Elie and Ruel, 2005; Byrne and Mitchell, 2007), while at least one found greater differences (e.g. Nicoll et al., 2006). In a rare study comparing hardwood species, Peterson and Claassen (2013) found a trend toward greater stability in *Quercus lobata* than *Populus fremontii*, although high among site variation caused the interspecific differences to be non-significant.

More broadly, conifers in general are expected to be more susceptible to wind damage relative to hardwoods due to factors such as architecture and wood density (Everham and Brokaw, 1996; Peterson, 2007; Hanewinkel et al., 2013). One study in support of this expectation found consistently higher stability in birch (*Betula* spp.) compared to two conifer species in Finland, but was based on a sample of only 11 birch trees (Peltola et al., 2000). We know of no other static winching study that compared a conifer to a hardwood species.

1.2. Failure mode

Independent of particular tree characteristics, the mode of tree failure may result in differential tree stability. There are numerous post-storm damage surveys that document that tree failure by uprooting is often more common than trunk breakage (Peterson and Pickett, 1991; Peterson, 2007). Since trees will fail by whatever mode offers the least windfirmness, the greater abundance of uprooting suggests that uprooted trees should have lower critical turning moments than those of trees that fail by trunk breakage. A number of static winching studies also report that uprooting is more common than trunk breakage (Peltola et al., 2000; Elie and Ruel, 2005; Nicoll et al., 2006; Byrne and Mitchell, 2007), but many of these studies exclude the trunk-broken trees from analysis, so the presumed difference in critical turning moment is rarely directly tested. Two studies, however, have tested for differences in critical turning moment between uprooted and trunk-broken trees: Elie and Ruel (2005) found no difference, but Peltola et al. (2000) found that trunk-broken trees had much higher critical turning moments than uprooted trees.

1.3. Forest disturbance interactions

In addition to species- and size-specific influences, the disturbance history of particular trees – especially scarring from fire – may also affect tree stability. Like wind disturbance, prescribed fire is a common in southeastern forests and has important ecological effects.

Several studies have investigated or theorized how wind damage may alter the behavior of subsequent fire, such as by increasing fuel loads (e.g., Webb, 1958; Myers and van Lear, 1998; Urquhart, 2009; Liu et al., 2008) or by altering fuel composition and arrangement (Cannon et al., 2014). Conversely, it is unknown whether presence or absence of fire alters the vulnerability of a forest to wind damage. One study suggests that timing of fires may differentially affect subsequent vulnerability to wind. Platt et al. (2002) measured tree mortality following Hurricane Andrew in 14 sites varying in burning regime and reported that anthropogenic dry season fire regimes left trees more vulnerable to hurricane winds, compared to natural wet season burns or no fire, because faster growth in dry-season burned sites resulted in weaker trees. Alternatively, fires could affect subsequent vulnerability to wind

via scarring. Matlack et al. (1993) found that trees with previous fungal rot were more vulnerable to hurricane damage, and that presence of fungal rot was linked to previous fire scarring. In addition to examining differences in tree stability, we also test for experimental evidence that fire-scarring weakens trees, as a possible mechanism by which fire may influence subsequent wind damage.

In this study, we used static winching to examine experimentally how tree stability is influenced by tree size, species, failure mode, and fire disturbance history. We hypothesized that (1) stability is a non-linear function of tree size (i.e., tree diameter or mass), (2) that *Liriodendron tulipifera* has greater stability than *Pinus taeda*, and (3) that tree stability decreases with the size of fire scars.

2. Methods

2.1. Study site

This experiment was conducted at the Piedmont National Wildlife Refuge in central Georgia (33.11°N, 83.68°W). Forests at the refuge are typical southern Piedmont secondary forests, dominated by *P. taeda* (loblolly pine) and lesser amounts of *L. tulipifera* (tulip poplar), with *Liquidambar styraciflua* (sweetgum) and *Acer rubrum* (red maple) in the understory. Mixed pine-broadleaf forests, such as our study site, are common throughout the Piedmont region of the Southeastern U.S., and experience low intensity surface fires between 3 and 10 years (Mitchell et al., 2014). Prescribed fire in state of Georgia is particularly common with over 400,000 burned in 2011 (Melvin, 2012). The U.S. Fish and Wildlife Service is currently managing the study area using a combination of tree thinning and prescribed fire to restore open pine stand habitat for use by the Red-cockaded woodpecker and other wildlife. To this end, the study area received low-intensity prescribed surface fires in 2004, 2006, and 2009. Soils in the study area are well drained, consisting of Davidson Series loams on broad ridge tops and clay loams on rounded ridges and hillsides adjacent to streams (Payne, 1976). Precipitation averages approximately 110 cm per year. Winching was conducted during the summer of 2012.

2.2. Field methods

Static winching followed well-established procedures (e.g., Nicoll et al., 2006; Peterson and Claassen, 2013). A 2 m nylon collar strap was wrapped around the trunk of the pulled tree as high as possible yet below major branches (Fig. 1). Height of attachment ranged from 6 to 14 m. Depending on distance to the anchor tree, 10 m nylon pulling straps (7.5 cm width, two ply; working load limit 13,600 kg; Wiscolift, Greenville, WI) were placed between the collar strap and the steel cable (1.6 cm diam.). All connections between straps, cable, and pulley were via 2.5 cm diameter steel tractor clevis hitches. For small trees, the distal end of the cable was linked directly to the pulling strap(s) and the proximal end routed through the winch. For larger trees, a pulley (snatch block) was positioned roughly at the midpoint of the cable and the distal end of cable turned back to attach to the anchor tree. The winch (Tirfor model T-532, Tractel, Inc., Norwood, MA) was secured to the base of the anchor tree with a second collar strap. Two inclinometers (model A2, US Digital, Vancouver, WA) were attached to the pulled tree at 1.5 m above ground and just above the point of collar strap attachment. The collar strap and upper inclinometer were attached using a tree-climbing hunting stand (Summit Viper SS model, Decatur, AL). Inclinometers measured the angle from vertical in 0.1-degree units and transmitted readings every 0.5 s

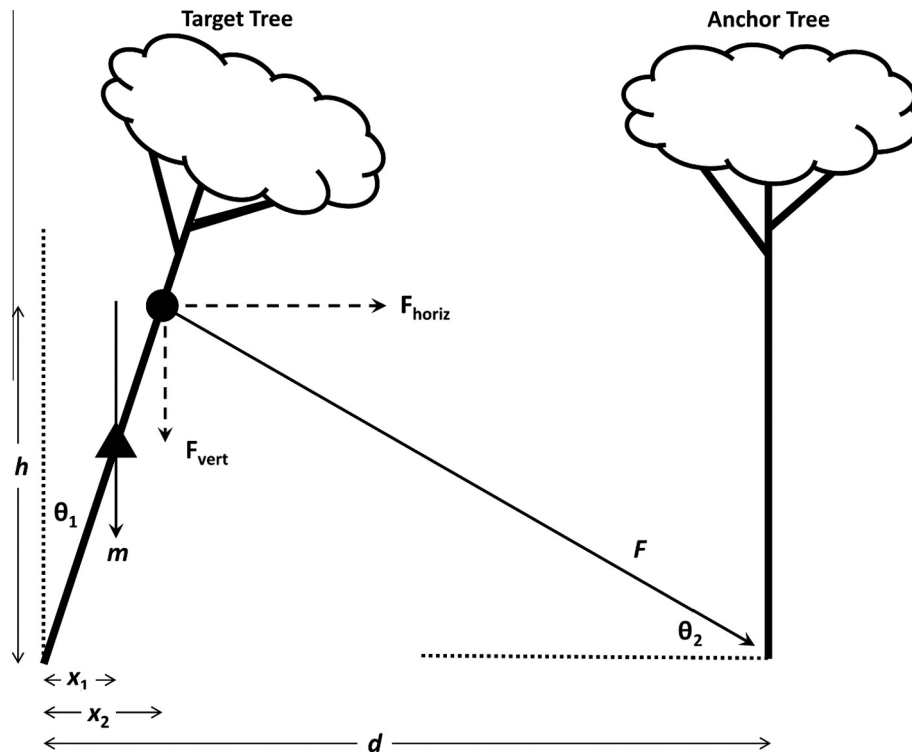


Fig. 1. Diagram of measurements used in calculation of critical turning moment. Black triangle on target tree indicates center of mass. Black circle indicates the point of strap attachment. F = maximum measured force in the winch/strap combination composed of its horizontal (F_{horiz}) and vertical (F_{vert}) components. m = weight of tree in Newtons. θ_1 = stem deflection from vertical measured by averaging two inclinometers. θ_2 = angle of strap with horizontal. d = distance between pulled tree and anchor tree. h = height of point of strap attachment at moment of maximum force. x_1 = horizontal displacement of center of mass at moment of maximum force. x_2 = horizontal displacement from the point of strap attachment at moment of maximum force.

to a laptop computer, where readings were recorded with a 0.1 s time stamp. A 10.9 Mg load cell (Straightpoint model Radiolink Plus, Camarillo, CA) was installed between the collar strap and the pulling straps, this transmitted tension in the strap every 0.5 s to a receiver plugged into the laptop computer where readings were recorded, again with a time stamp. Tension was taken up from the strap and the tree was winched until failure. Two measurements were of primary interest: the maximal force in the winch–strap–cable system during the pull and the tilt of the tree from vertical at the time of maximal force. These were determined by examining the data files to determine the maximal force, the time at which that force occurred, and the tilt of the two inclinometers at that time. We winched a total of 69 trees: 23 *Liriodendron*, 36 *Pinus*, and 10 other hardwood individuals (5 *Acer floridanum*, 1 *Cornus florida*, 1 *Fraxinus americana*, 1 *L. styraciflua*, 1 *Quercus alba*, and 1 *Quercus rubra*). Tree diameters of winched trees ranged from 16.1 to 53.5 cm dbh.

Calculation of critical turning moment requires knowledge of the tree's center of mass, calculated from the vertical distribution of mass. After each tree fell, we recorded trunk diameter at 1 m intervals, and the location and basal diameter of all branches. We cut 3 pines and 3 tulip poplars into 1 m sections and carefully measured length, upper and lower diameter, and weight of the sections, enabling the development of a volume:mass relationship for trunk sections of these two species. Branches ($n = 50$ for each species) were cut at their point of attachment, measured for basal diameter, and weighed; these defined a similar basal diameter:mass relationship for branches. We applied the volume:mass relationships developed from tulip poplar to estimate weights and center of mass for the other 10 hardwood individuals adjusting for differences in wood density by multiplying the mass of each trunk section by the wood density ratio between each species

and the wood density of tulip poplar (Kretschmann, 2010). For any tree with a fire scar, we calculated a fire scar index as the proportion of trunk circumference covered by the scar, multiplied by the vertical extent of the scar in meters. In addition to fire, our study site also experienced low-intensity harvesting in previous decades, which likely initiated some scars that were subsequently enlarged by the fires.

2.3. Analytical methods

Put simply, the critical turning moment of a tree is the rotational force at the moment of failure (breaking or uprooting), and indicates tree stability or wind resistance. The critical turning moment (M_{critical} , in N-m) at the base of each pulled tree was calculated as the sum of M_{applied} and M_{weight} , where M_{applied} represents the moment resulting from pulling on the strap and M_{weight} represents the additional moment resulting from the mass of the tree itself once it has moved from vertical (self-loading). M_{critical} is calculated when the maximum cable tension (force) is reached. M_{weight} is best envisioned as a weight at the end of a zero-mass lateral beam rigidly attached to the base of the tree, and extending in the direction of the pull. The beam has a length equal to the horizontal displacement of the tree's center of mass at the time of maximal force. The weight at the end of the beam is the aboveground weight of the tree. It is therefore calculated as:

$$M_{\text{weight}} = m * x_1 \quad (1)$$

where m is tree weight (N) and x_1 is the horizontal displacement (m) of the center of mass of the tree at the time of maximum force (Fig. 1). M_{applied} is the sum of a horizontal and a vertical component, and is calculated as:

$$M_{\text{applied}} = M_{\text{horizontal}} + M_{\text{vertical}} \quad (2a)$$

$$M_{\text{horiz}} = F * \cos(\theta_2) * h \quad (2b)$$

$$M_{\text{vert}} = F * \sin(\theta_2) * x_2 \quad (2c)$$

where F is the total force (N) applied by the winch and strap, θ_2 is the angle of the strap relative to horizontal, and h and x_2 are the height (m) and the horizontal displacement (m), respectively, of the point of strap attachment at time of maximum load. As with the self-loading described above, the vertical component of the pulling force can be envisioned as a weight at the end of a zero-mass lateral beam, where the length of the beam is again the horizontal displacement of the point of strap attachment, and the magnitude of the weight is the vertical (downward) vector of the pull force (if the pull is partitioned into two vectors). Note that h becomes somewhat less than the height of strap attachment on the pulled tree, as the pulled tree deflects further from vertical. The values of x_1 , x_2 , and h were calculated based on the inclinometer readings at the time of maximum load. Because trees under wind loads are not a straight beam rotating at the base, and because bending increases with tree height, the best approximation of tree deflection from vertical (θ_1) was taken as the mean of the two inclinometer readings. While this could slightly over- or underestimate M_{critical} depending on trunk stiffness, the approach used here is consistent with previously published static winching studies (e.g. Nicoll et al., 2006). We also used a sensitivity analysis to measure the impact of this and other winching parameters (see below).

2.4. Winching parameter sensitivity analysis

For some parameters used to calculate M_{critical} such as winching force, F , and the height of strap attachment, we were able to obtain precise field measurements during the winching process. However, estimates of tree tilt (θ_1) were averaged from two inclinometer readings, and measurements of tree biomass and the height of the center of mass were estimated using volume:mass relationships. Thus, we used a sensitivity analysis for each of the six winching parameters (including height of strap attachment, F , θ_1 , height of center of mass, tree weight, and distance between trees) to ensure that estimates of M_{critical} were not sensitive to small variations in estimated parameters. For each of the six parameters, we adjusted a given parameter between -25% and $+25\%$ (in increments of 0.1%) and calculated the percent change in M_{critical} for each tree in the study ($n = 69$). Plots of percent change in a given parameter versus percent change in M_{critical} were built and the resulting slope was compared to a 1:1 line to determine the relative sensitivity of each parameter.

2.5. Factors influencing tree stability

To test which measure of tree size best predicted M_{critical} , simple linear regressions were run between M_{critical} versus various measurements of tree size, including dbh, dbh^2 , dbh^3 , $\text{dbh}^2 \times \text{height}$, stem mass (kg), and tree mass (kg). Because of widespread interest in predicting critical turning moment, and to make our results more comparable to other studies, we also ran simple linear regressions between M_{critical} versus each measurement of tree size for snapped and uprooted trees separately to determine if turning moment for trees with varying failure types (snapped versus uprooted) were best predicted by different size parameters. Subsequently, the effects of tree species, tree stem mass, tree failure type (uproot versus snapped), and fire scar size on critical turning moment were tested using an analysis of covariance (ANCOVA), with species as the categorical variable and stem mass and fire scar index as covariates. The ANCOVA showed no significant main effect of species or fire scar index. Therefore, to further explore the combined effect

of stem mass and failure mode, a second ANCOVA was performed with species pooled, with critical turning moment as the response variable, and stem mass and failure mode as the regressors.

3. Results

Mode of failure differed significantly among the species groups (*Liriodendron* vs. *Pinus* vs. others): For *Liriodendron*, 35% failed by snapping and 65% by uprooting; for *Pinus*, 55% failed by snapping and 45% by uprooting; while for the other hardwoods, each failure mode was observed in 50% of the trees. The critical turning moment at the base of the tree ranged from 8700 N-m to 307,900 N-m for *Liriodendron*; from 10,300 N-m to 494,300 N-m for *Pinus*; and from 5300 to 128,000 N-m for the other hardwoods (Fig. 2). Critical turning moment was best predicted by stem mass (regression $R^2 = 0.92$); all other regressors performed more poorly (regression R^2 values were 0.82 for dbh; 0.85 for dbh^2 ; 0.84 for dbh^3 ; 0.89 for $\text{dbh}^2 \times \text{height}$; and 0.90 for tree mass). The relationship of critical turning moment (N-m) to stem mass (kg) for species and modes of treefall pooled (Fig. 2) was $M_{\text{critical}} = (174.22 \times \text{stem mass}) - 8478.2$. Considering only snapped trees, critical turning moment was best predicted by stem mass ($R^2 = 0.96$), with other regressors performing more poorly (R^2 values were 0.85 for dbh; 0.90 for dbh^2 ; 0.93 for dbh^3 ; 0.94 for $\text{dbh}^2 \times \text{height}$; and 0.95 for tree mass). Likewise, for uprooted trees, stem mass was the best predictor of turning moment ($R^2 = 0.91$), with other regressors performing more poorly (R^2 values were 0.84 for dbh; 0.85 for dbh^2 ; 0.83 for dbh^3 ; 0.88 for $\text{dbh}^2 \times \text{height}$; and 0.88 for tree mass).

Critical turning moment was significantly influenced by tree size and failure mode (ANCOVA, p -values for stem mass and failure mode were <0.0001 and 0.005 , respectively), but not by species (ANCOVA, main effect, $p = 0.103$) or fire scar index (ANCOVA, main effect, $p = 0.130$). A second ANCOVA (with species pooled) showed that critical turning moment significantly increased with stem mass and differed between failure modes (Fig. 3); together these two independent variables explained 92.9% of the variation in critical turning moments. As expected, snapped trees, on average, had critical turning moments 17% greater than uprooted trees. Surprisingly, trees with fire scars were less likely to fail by trunk breakage. Scarred trees failed by trunk breakage 38% of the time (8 of 21), whereas unscarred trees failed by trunk breakage 52% of the time (25 of 48). Although the proportions of trees that experience the two different failure modes did not differ significantly between scarred and unscarred trees ($\chi^2 = 1.15$, $P = 0.28$), it is notable that the three trees with the largest scar index values all uprooted.

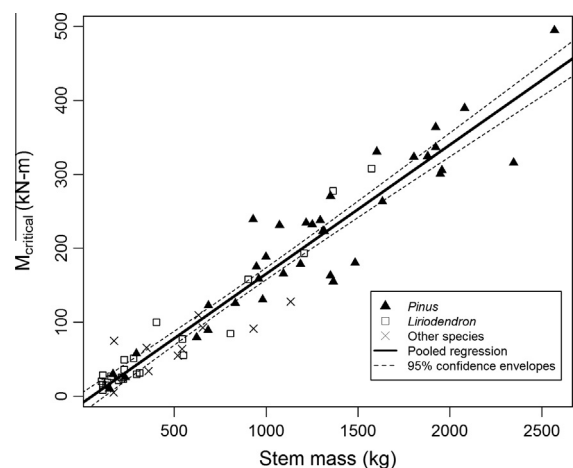


Fig. 2. Critical turning moment (N-m) vs. stem mass (kg). Regression line and confidence envelopes are for all species pooled.

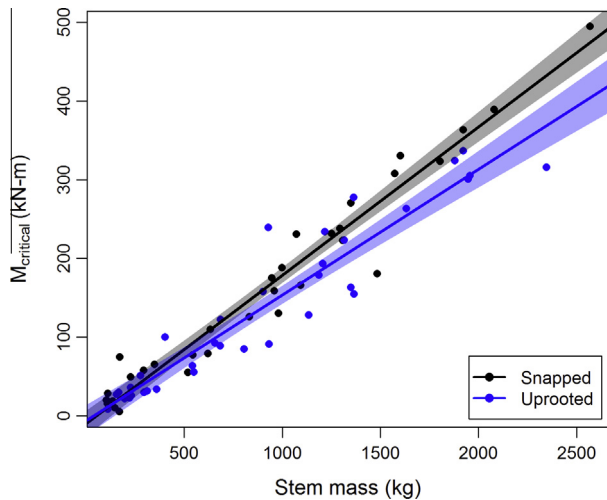


Fig. 3. Critical turning moment (kN-m) vs. stem mass (kg) illustrating differences between snapped and uprooted trees. Regression line and confidence envelopes are for all species pooled. Shaded areas represent 95% confidence envelopes of each linear regression with species pooled.

Results of the sensitivity analysis suggest that the calculation of $M_{critical}$ is predominately sensitive to changes in the tension force when winching, F , and the height of strap attachment (Fig. 4). Varying F or height of strap attachment by $\pm 25\%$ led to changes in $M_{critical}$ of approximately $\pm 23\%$. Varying other field parameters by $\pm 25\%$ led to very small changes in $M_{critical}$ for tilt ($\pm 2\%$), center of tree mass ($\pm 2\%$), tree weight ($\pm 2\%$), and distance between trees ($\pm 0.5\%$).

4. Discussion

Our winching experiment confirmed several trends seen in previous studies related to the effects tree size and failure mode on tree stability, but our results are also novel in relating the effects of fire scarring to tree stability. As expected, tree stability increased substantially with tree size (Nicoll et al., 2006; Peltola, 2006; Quine and Gardiner, 2007). Our results were best described by a linear relationship between stem mass and critical turning moment, although numerous previous studies find that critical turning moment correlated better with dbh^2 , tree mass, or stem volume (e.g. Peltola et al., 2000; Cucchi et al., 2004; Elie and Ruel, 2005; Nicoll et al., 2006). Nevertheless, actual values of critical turning moments for particular tree sizes in this study closely match those previously reported, when publications present raw dbh or stem mass and critical turning moment values (e.g. Meunier et al., 2002; Achim et al., 2005; Elie and Ruel, 2005; Nicoll et al., 2006; Byrne and Mitchell, 2007; Lundström et al., 2007; Peterson and Claassen, 2013). We plotted the regression line relating critical turning moment to stem mass from this study as well as several other studies (Fig. 5). The consistency between our findings and those of Lundström et al. (2007) is striking, despite widely varying species, soils, and conditions in these studies. Trees in these two studies appear to have substantially greater stability than trees from the other three studies, which were quite similar to one another. A comprehensive meta-analysis of critical turning moment across numerous studies is underway and will reveal whether the size-stability relationship is highly variable on a case-by-case basis or grouped according to species, soil types, or some other variable. Nevertheless, the implication is that tree stability in upland sites is in some cases remarkably similar despite distinct species, soils, and stand histories.

Contrary to expectations, there was no difference in stability between *Liriodendron* and *Pinus* at this site. This interspecific similarity was reinforced by the individuals of other species, which exhibited similar critical turning moments for a given size as the *Liriodendron* and *Pinus* (Fig. 2). Previous static winching studies are inconsistent, with some finding interspecific differences (Peltola et al., 2000; Meunier et al., 2002; Nicoll et al., 2006) but others not (Achim et al., 2005; Elie and Ruel, 2005; Byrne and Mitchell, 2007; Lundström et al., 2007; Peterson and Claassen, 2013). An emerging picture is that while interspecific differences are sometimes detectable, they are usually subtle when detected.

Surveys of tree damage after catastrophic winds have commonly reported interspecific differences, in particular finding greater damage to conifers than hardwood species (e.g. Foster, 1988; Everham and Brokaw, 1996; Peterson, 2007). At first, the pattern from field damage surveys seems difficult to reconcile with the findings reported herein. However, static winching quantifies only the mechanical stability of trees, whereas observed damage levels are the result of the interplay between tree wind resistance and actual wind forces against that tree. Numerous factors influence the wind force experienced by a tree, such as relative exposure, absolute height, crown width, streamlining, and position within the stand (Quine and Gardiner, 2007). Thus, the observed differences among species in wind damage may be due more to differences in wind impact than to inherent differences in windfirmness.

Type of tree failure differed somewhat between the focal species, with *Liriodendron* more prone to uprooting than either *Pinus* or the non-focal species. There are several possible explanations for this pattern. (1) *Liriodendron* may be more likely than *Pinus* to be fire-scarred, which was associated with higher incidence of uprooting. (2) *Liriodendron* may have a higher occurrence of root pathogens causing a reduction in root stability. (3) *P. taeda* roots commonly form root grafts in natural pine forests (Burns and Honkala, 1990), which may increase root stability in this species. Our experiment does not provided data to support the second and third explanation, however we did find that 15 of the 23 (65%) of the *Liriodendron* trees included in our study had fire scars, whereas only 2 of the 36 (6%) of the *Pinus* had fire scars.

In a review of static winching studies, Peltola (2006) reported that uprooting is the most common mode of tree failure in unfrozen soils; and Nicoll et al. (2006) in their summary of winching studies in Britain, state that only 8% of trees snapped. Thus, our finding of 35–55% of trees failing by snapping is unusual. It is worth noting that many previous studies have been carried out on shallow or highly organic substrates; we hypothesize that the deep loams of our study site allow development of stronger root systems than in many previous studies, thus leaving the stem as the weakest stability component more often.

The sensitivity analysis of field-measured parameters suggests that our method for calculating of $M_{critical}$ (from Nicoll et al., 2006 and Peterson and Claassen, 2013) is robust to relatively large variation in some field-measured parameters. Some field measurements such as the tree tilt (θ_1) are difficult to measure precisely and others such as tree weight and center of mass must be estimated. Encouragingly, the calculation of $M_{critical}$ was least sensitive to these difficult to measure parameters. Thus we suggest that future studies focus on careful measurement of sensitive winching parameters such as winching force and height of strap attachment, but difficult to measure parameters such as tree biomass and tree center of mass can be estimated from volume:mass equations.

4.1. Fire scar mediated interaction between wind damage and fire

Two previous studies speculate on how forest wind disturbance and fire interact when fire precedes wind damage. Although not significant, we did find a trend toward lower tree stability in

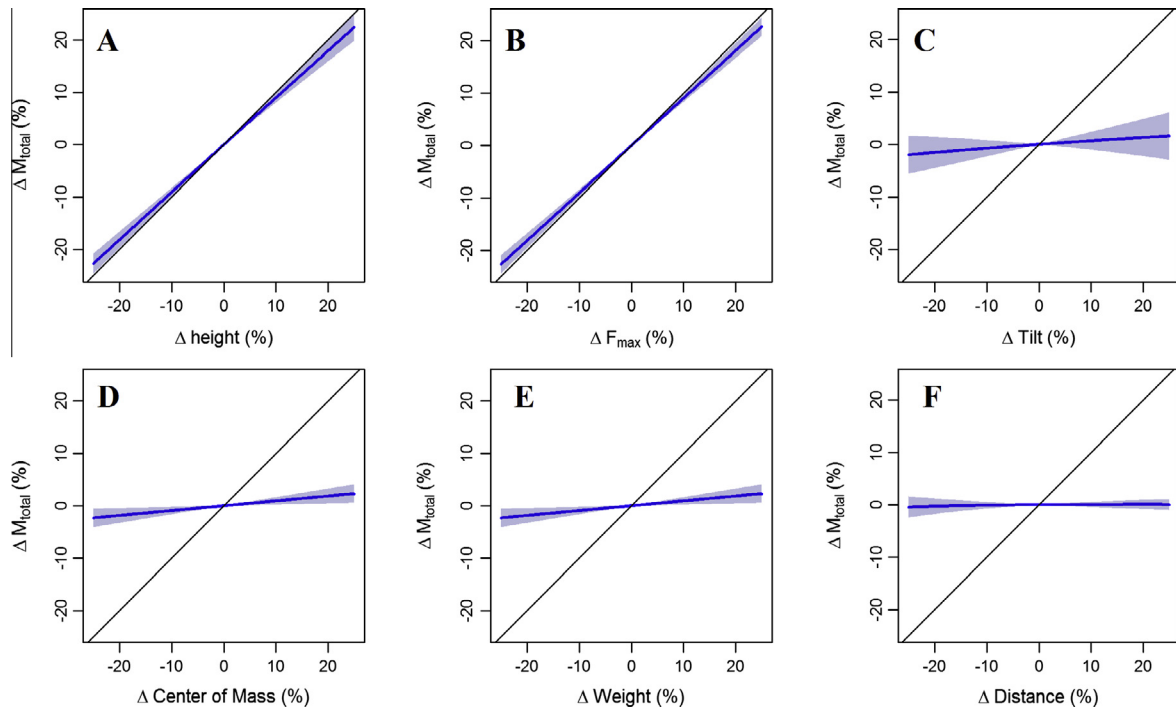


Fig. 4. Sensitivity analysis illustrating the effect of variation ($\pm 25\%$) in six field-measured parameters on calculation of $M_{critical}$. Parameters include (A) height of strap attachment, (B) maximum winching force, F_{max} , (C) tree tilt, (D) tree center of mass, (E) tree weight, and (F) distance between target and anchor tree. Blue line represents the average change in the $M_{critical}$ for a change in the given parameter. Blue polygons represent ± 2 standard deviations of the mean change in $M_{critical}$. Black lines represent one-to-one change. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

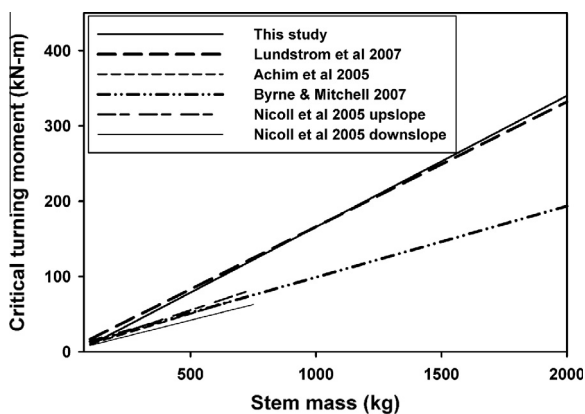


Fig. 5. Critical turning moment plotted against for data from selected studies. The regression line from Achim et al. (2005) is obscured by that of Byrne and Mitchell (2007) and extends only to a stem mass of 650 kg.

fire-scarred trees. Platt et al. (2002) found variation in hurricane damage to forests with differing fire regimes. Those authors speculated that faster tree growth after growing season fires predisposes trees to damage, but that study did not document such an effect. Further, Matlack et al. (1993) found that fire-scarred trees in a New Jersey oak–pine forest were more vulnerable to wind-storm damage. In their study, all 73 damaged trees snapped, with no incident of uprooting. The authors noted that incidence of fire-scarring in their study was strongly associated with fungal rot suggesting that fire and subsequent fungal rot likely compromised trunk strength causing these trees to snap.

Although we found a trend toward decreased tree stability in trees with larger fire scars, this trend was not significant, thus a direct link between fire-scarring and reduced tree stability was not rigorously demonstrated in our study. It should be noted,

however, that although our study compared 21 fire-scarred trees to 48 unscarred trees, the majority of fire-scarred trees (57%, 12 trees) had fire-scars that were very small, with a scar index ≤ 0.2 . The inclusion of fire-scarred trees in our study was fortuitous, but by including a greater number fire-scarred trees with a more even range of fire-scar sizes, future research may confirm or refute the hypothesis that fire-scars lead directly to reductions in tree stability.

We expected that fire-scarred trees in our study would have reduced trunk strength and thus an increased incidence of trunk breakage. Surprisingly, our expectation was not upheld, and in fact, fire-scarred trees showed a non-significant trend toward greater incidence of uprooting. This result suggests that fire may interact with wind in an indirect way. For example, greater uprooting after fire-scarring could be explained by considering that fire scars destroy cambium on one sector of the trunk (Smith and Sutherland, 1999), and therefore may result in death of one sector of the root system, resulting in an increase in likelihood of uprooting. Results from studies of tree girdling (which also damages tree cambium) suggest that damage to vascular tissue can substantially reduce root respiration (Anderson et al., 2005; Frey et al., 2006). For example, Högberg et al. (2001) found a 54% reduction in soil respiration that they attributed to loss of roots from girdled trees. Although fire scars are unlikely to have effects as severe as girdling, repeated fires may damage a substantial amount of cambium and lead to the death of both fine roots and structural roots making scarred trees more likely to uproot than break in wind damage.

If in reality there is a greater incidence of uprooting in post-fire stands, such an effect could have a multitude of ecological, edaphic, and geomorphological consequences (e.g. Sobhani et al., 2014) that would be less prevalent in stands that had not been recently burned. For example, during forest regeneration after windthrow, root plates offer refugia for tree seedlings from deer browsing (Long et al., 1998; Krueger and Peterson, 2006). Root pits have altered rates of carbon loss through soil respiration compared to nearby intact soil (Lindroth et al., 2009; Köster et al., 2011), and

formation of treefall root pits and mounds inhibits podzolization of soils (Ulanova, 2000). All of these phenomena could potentially be increased if a wind event strikes a previously burned stand with fire-scarred trees.

5. Conclusions and management implications

The results of this study shed light on several concerns relevant to forest management. First, this study supports the idea that tree size, rather than species differences, is the most important determinant of tree stability in upland sites. Differences in mechanical tree stability due to species or site differences are often small when detected. Thus, observed differences in tree damage between species or species groups (e.g., hardwood versus conifer) may be a less important factor governing vulnerability to wind compared to tree size, which we found strongly influenced tree strength. Second, our study echoes the findings of Peltola et al. (2000) uprooted trees have a lower critical turning moment than trunk broken trees.

Our study did not definitively support that fire-scarring increases tree vulnerability to wind damage. However, our study suggested a non-significant, but revealing trend that fire-scarred trees may be more likely to uproot rather than snap, especially when scarring is severe. Because uprooted trees have critical turning moments 17% lower than snapped trees, severe fire-scarring may indirectly lead to greater wind susceptibility. Depending on management objectives, failure of scarred trees may allow wind to penetrate into a stand and cause unwanted and widespread damage to un-scarred trees. However, other management objectives, such as the restoration of pine savannas, an increased vulnerability of fire-scarred trees may help accelerate the removal of fire-sensitive tree species. Management to minimize wind damage may therefore be more profitably directed at size structure of a stand rather than species composition.

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