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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.

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 (Diffenbaugh 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