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Estimating Wind Speeds of Convective Storms from Tree Damage

LEE E. FRELICH
Center for Forest Ecology, University of Minnesota, Saint Paul, Minnesota

ERNEST J. OSTUNO
NOAA/National Weather Service Forecast Office, Grand Rapids, Michigan

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ABSTRACT

In much of the central and eastern United States, tree damage is typically the most common damage indicator available to National Weather Service meteorologists estimating wind speeds from convective storms. Unfortunately, most meteorologists have little or no formal training in the susceptibility of trees to high winds, and the Enhanced Fujita scale does not address many of the various factors that affect the wind tolerance of trees. This study attempts to describe these factors and to provide a strategy for integrating them when estimating wind speeds based on tree damage. Several case studies are used to illustrate the problems and possibilities in deriving a more detailed damage scale than currently exists.

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1. Introduction

Windthrow (uprooting or snapping of trees during high wind events) is an important ecological process, a common type of damage from severe weather due to trees falling on cars, houses and power lines, and an indicator used in post-storm assessment of storm severity. In 2007, the National Weather Service adopted the enhanced Fujita (EF) scale (McDonald et al. 2006) to replace the original damage scale developed by Fujita (1971). The new scale provides guidelines for estimating wind speeds based on damage to trees as well as structures. Trees, as part of a group of 28 damage indicators (DIs), were divided into two groups: hardwoods and softwoods. Table 1 shows wind speed estimates for degrees of damage (DoD) to each group derived through the expert elicitation process used by the EF project. Damage to hardwoods was attributed to slightly higher wind speeds than the corresponding damage done to softwoods. However, studies by forestry researchers have revealed a number of reasons

why the values in Table 1 may not work in a variety of field settings. We touch briefly on these reasons in the Introduction to set the stage for detailed consideration in sections 2 and 3 of the paper.

Rich et al. (2007) and Webb (1999) suggest that hardwood and softwood tree species vary significantly in susceptibility to windthrow due to factors such as age and size. Moreover, research has found some species of softwoods to be more wind-tolerant than some species of hardwoods (Canham et al. 2001, Buseng et al. 2009), and even closely related species of hardwoods and softwoods have shown a wide range of wind tolerance (Fumiko et al. 2006; Johnsen et al. 2009).

Potentially important factors in determining DoD include site characteristics such as topography and exposure to wind (Kupfer et al. 2008; Ruel, 2000), soil type and rooting conditions (Nicoll et al. 2006; Elie and Ruel 2005), and physical characteristics of trees such as crown size and shape (Eloy 2011; James et al. 2006; Kane et al. 2008).

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Corresponding author address: Lee E. Frelich, 1530 Cleveland Ave., St. Paul, MN 55108, E-mail: freli001@umn.edu

Table 1: Degrees of damage (DOD) for a) hardwood trees b) softwood trees, and the range of wind speeds (in mph) estimated to cause the damage. From McDonald et al. (2006).

A. DOD	Trees: Hardwood (oak, maple, birch, ash)	Expected	Lower Bound	Upper Bound
1	Small Limbs	60	48	72
2	Large Branches	74	61	88
3	Trees Uprooted	91	76	118
4	Trunks Snapped	110	93	134
5	Debarked, only stubs of largest branches	143	123	167
B. DOD	Trees: Softwood (pine, spruce, fir, hemlock, cedar, redwood, cypress)	Expected	Lower Bound	Upper Bound
1	Small Limbs	60	48	72
2	Large Branches	75	62	88
3	Trees Uprooted	87	73	113
4	Trunks Snapped	104	88	128
5	Debarked, only stubs of largest branches	131	112	153

In addition, trees can be weakened by various agents such as disease, insects and improper nursery planting techniques, while still appearing healthy to the untrained eye, particularly in urban and suburban settings (Jim and Liu 1997; Johnson et al. 1999).

The structural integrity of trees can be considered analogous to that of other DIs. For structures, failure in high winds occurs primarily at areas that are weakly connected, such as walls not well anchored to foundations or roofs weakly attached to walls. In trees, rotted limb joints or shallow roots are common failure points. Signs of decay or shallow roots should lead to a lower-bound wind speed assessment. Dead or rotted trees should not be used as DIs since failure could occur at much lower wind speeds than the lower bounds.

Some trees, especially in urban or suburban areas, may exhibit stem girdling roots (Johnson and Hauer 2000) which compress the trunk of the tree near the soil line and may lead to trunk breakage in high winds. These roots are often below ground and may not be detectable except under close examination of the break point.

Seasonal variation in wind tolerance exists for deciduous trees, which catch more of the drag force of wind when leafed out (Koizumi et al. 2010).

Wind duration, along with intensity, can be important in determining the DoD to various tree species. For example, Xi et al. (2008) found that loblolly pine (*Pinus taeda*) was less susceptible to damage than some hardwood species in hurricanes, yet more susceptible in a tornado. They surmised that the flexible trunks of that species could bend more readily in hurricane wind gusts while snapping in the more sudden and intense tornado winds.

The density of wood may determine whether a tree is uprooted or snapped (Asner and Goldstein 1997); therefore, the different wind speeds seen in Table 1 for snapping trunks versus uprooting are not warranted. As for debarking, wind-driven debris is an important factor. Debarking occurs when large amounts of debris strike a tree at high speeds, combined with bending of limbs and trunks.

The objective of this study is to review what is known about stability of trees in high winds in both forest and urban settings, present some illustrative case studies of windthrow, and assess the current state of knowledge and possibilities for future improvements to the EF scale for tree-based DIs.

2. Overview of tree mortality and wind Disturbance

Structural failure of trees during wind storms will occur if the critical turning moment or force necessary to topple a tree occurs. The weakest part of the tree determines the critical turning (or bending) moment. Generally either the stem will snap or the tree will uproot. A number of studies have measured the force necessary to mechanically uproot or snap trees, producing equations that can be used to model the forces necessary for tree failure, which are then compared to the force exerted on a tree by the wind [Eqs. (1)–(3) below]. The critical bending moment for stem breakage ($M_{crit\ break}$, in Newton meters; Gardiner et al. 2000; 2008) is:

$$M_{crit\ break} = \pi/32\ \text{MOR}\ \text{dbh}^3 \qquad (1)$$

where MOR is the modulus of rupture (Pa) for wood of the given tree species, and dbh is the trunk diameter at 1.4 m AGL.

The critical moment for overturning a tree ($M_{crit,\ over}$ N m) is:

$$M_{crit,\ over} = C_{reg}\ Sw \qquad (2)$$

where Sw = Stem weight and C_{reg} is a regression constant from empirical studies of tree uprooting by pulling with heavy machinery. The constant reflects the total weight of the roots and soil in the root plate as well as other factors that are hard to quantify such as soil strength. A factor expressing the additional downwards gravitational force exerted when a tree is bent by the wind also is included sometimes (e.g. Peltola 2006).

The force exerted by the wind (F_w) is:

$$F_w = \tfrac{1}{2}\ C_D\ \rho\ AU^2 \qquad (3)$$

where C_D is the drag coefficient (dimensionless), ρ is the density of air (1.225 kg m^{-3} at sea level and temperature of 15°C), A is the projected crown area of the tree (trunk and crown) against which the wind acts (m^2) and U is wind speed (m s^{-1}).

If the force exerted by the wind exceeds either of these critical moments, then the tree either will snap or be uprooted. Typically force is based on measured canopy-top wind speed, and wind speeds for 1-m height segments throughout the canopy profile then are modeled, based on what little is known about wind speed profiles in the forest. A more complete review of these equations and various modifications are provided by Gardiner et al. (2008).

The following two subsections explore how various factors such as species, size, architecture, health, location and wind speed influence the factors in Eqs. (1)–(3), and therefore, the probability of a tree toppling.

a. Mechanisms for surviving wind

Strategies for surviving wind include streamlining, shedding branches, strong and/or flexible wood, short stature, low center of gravity, and buttress roots. Streamlining refers to the ability of trees to align leaves, twigs, and progressively larger branches in the direction of the wind as speed increases, such that the profile of the tree crown impacted by the wind [A in Eq. (3)] is reduced in size as wind speed increases, leading to a reduced drag coefficient (Mayhead 1973; Hedden et al. 1995; Rudnicki et al. 2004).

Wind-tunnel studies for a variety of species show that streamlining can reduce frontal area to 20–40% of its initial area for hardwood species and 45–65% for conifer species as wind speed goes from 0–20 m s^{-1} (0–45 mph) (Rudnicki et al. 2004; Volsinger et al. 2005). Trees can increase streamlining, reducing frontal area and mortality up to a variety of wind speeds ranging from 27–53 m s^{-1} (60–118 mph), depending on species and height of tree (Mayhead 1973, Hedden et al. 1995). Beyond a certain wind speed, trees are streamlined to the maximum possible extent, and force on the tree increases more steeply with increasing wind speed, bringing most trees (even healthy ones with strong wood that are firmly rooted) to their limit for structural failure by 45–49 m s^{-1} (100–110 mph) (Hedden et al. 1995). All of the studies cited above in this paragraph were conducted in wind tunnels with relatively uniform speeds through the height of the trees and for the duration of the experiment, or were modeled mathematically. No data are available to illuminate how trees interact with type of storm (e.g., tornado, derecho, or hurricane), duration and gustiness in wind speed during a storm, and roughness of the surrounding landscape and forest canopy in a field setting. Also, how the trees have been pruned, shedding branches during the storm to create less area for the wind to push, and other factors discussed below, can alter the conclusions with regard to maximum wind speeds at which total tree failure occurs.

Prior to reaching the maximum degree of streamlining with minimum frontal area, drag on trees is proportional to the product of the square of wind speed and the wind speed specific frontal area. Because the latter decreases with wind speed, the force of the wind on a tree increases at a rate less than the square of wind speed up to the point of maximum streamlining. After that, further increases in wind speed increase the pressure on the tree at a much faster rate—hence the high frequency of toppling reported for trees when winds reach 45–49 m s^{-1} (100–110 mph).

Height-to-diameter ratio (H:D) is an important factor in tree stability. Open grown trees, trees growing on edges of woodlands or water bodies for a long time, and sometimes very large trees that emerge from the canopy of a forest (so that their crowns are well above all surrounding trees) have adaptive growth strategies. Those result in features such as buttressing and lower center of gravity, and shorter heights compared to a tree of the same diameter in a high-density interior forest setting surrounded with other trees of similar height. Such trees are less likely to blow down than trees with higher (H:D), and higher centers of gravity, due to "artists paintbrush" or "ball on a stick" growth form with the large weight of the crown at the top of the tree (Hedden et al. 1995; Rich et al. 2007). Trees along forest edges recently created by cutting a portion of the forest, or trees in a recently thinned forest, can be very susceptible to wind damage due to their tall, thin interior forest growth form being suddenly exposed to more extreme wind conditions (Mitchell et al. 2001). However, such trees can adjust to their new conditions by changing the allocation of new growth, lowering their H:D over a period of several years (Mitchell 2000).

Large-diameter trees sometimes acquire new flexibility by becoming hollow as they age, and may also live for some time, at least until the hollow to radius ratio is >0.7 (Mattheck et al. 1993). As large trees continue to grow, once their crown has reached its maximum size, the amount of wood the tree can manufacture each year remains relatively constant, so that similar annual basal area increment (the cross sectional area of the doughnut formed by each new ring) is added each year. However, as the diameter increases, the width of the ring with equal basal area increment decreases, and eventually the rate at which the hollow in the interior of the tree increases outpaces the rate of increase of the tree's radius, so the wall of wood becomes thinner over time until the buckling limit of 70% hollow is reached, making the tree susceptible to the next windstorm.

Large old trees commonly have a number of branches that are more susceptible to breakage than the base of the trunk, thus allowing older trees to shed branches during a high wind event and reduce the probability of windthrow (Niklas 2000). Some old trees have lost many branches over the years and sometimes actually become shorter as they enter old age, with relatively little 'sail' for the wind to push, and may live for many years, eventually falling to pieces due to rot. Large trees of species such as cottonwood (*Populus deltoides*), yellow birch (*Betula alleghaniensis*), loblolly pine (*Pinus taeda*) and white pine (*P. strobus*) with relatively inflexible trunks often survive high winds (as well as heavy wet snow and icing) by shedding branches during the storm, thus lessening their crown area. They then grow new branches over the next few years (Frelich, personal observation). One study reported that loblolly pine trees could have mortality reduced by as much as 60% in winds of 49 m s^{-1} (110 mph) if 50% of the crown were removed (Hedden et al. 1995).

There does not seem to be any one property of trees that leads to stability during high wind events—each species arrives at its characteristic degree of stability by a unique combination of traits (wood strength, compressibility, flexibility, H:D ratio, decay resistance, shedding branches during high winds, etc.). Northern white cedar (*Thuja occidentalis*) trees have relatively weak wood compared to their coexisting species, and yet were found by Rich et al. (2007) to be among the least susceptible species in a major derecho, presumably due to their relatively short stature and low H:D ratios. Red maple, on the other hand, also was found to be among the least susceptible species to wind, with much different traits—it has much higher H:D ratios than cedar, which is compensated for by much stronger wood.

Height-to-diameter ratios vary not only among species growing on identical sites, but also within species growing on different sites. For example, H:D ratios are greater on higher quality soils, but higher quality soils often occur in valley bottoms where exposure to wind is not as great as hilltops. Trees growing in warm and

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wet climates also have higher H:D ratios than in cold and dry climates. Many species of trees in the eastern U.S. have ranges that span 10° of latitude from Maine and Minnesota to Georgia, such as white pine (*Pinus strobus*), red oak (*Quercus rubra*), and sugar maple (*Acer saccharum*), and their H:D ratios are much higher in the south than the north. For example, white pine reaches maximum heights of 60.9 m (139 ft) in Minnesota and 90.8 m (207 ft) in North Carolina, but the diameters of these tall trees are almost the same (Frelich and Reich 2003); thus, white pines in the south have higher H:D ratios, and are more susceptible to blowdown.

b. Effects of wind on trees and forests

A vertical cylinder of wood has a buckling limit—a height for a given diameter at which the weight of the wood would cause the base to split and topple the tree. Trees in an experiment that were staked so they could not sway in the wind fell over immediately when unstaked, having grown close to the buckling height so that ordinary wind caused buckling (Jacobs 1954). In nature, however, with sway from winds, most trees alter their growth form by allocating more growth to the lower trunk than they would in a windless environment, and never grow anywhere close to the buckling height. Sheltered trees in valleys and forest understory environments grow somewhat closer to the buckling limit than open grown trees, which have low H:D (McMahon 1973, King 1986).

Many studies report that trees of larger diameter are more susceptible to wind due to stiffening of the trunk, which does not allow bending that would more evenly distribute force, higher likelihood of decay at the base of the tree, and higher windspeeds on top of the crown for taller trees (King 1986; Canham et al. 2001; Fumiko et al. 2006; Peterson 2007; Rich et al. 2007; Xi et al. 2008).

Rich et al. (2007) categorized species into three groups: high susceptibility across all diameters, low susceptibility and changing susceptibility with size (Fig. 1).

These groups seem to break down along lines of successional status of the tree species in nature. For example, of nine tree species in the "Big Blowdown" of 4 July 1999 in northern Minnesota, the study found that early successional species [i.e., aspen (*Populus* *tremuloides*) and jack pine (*Pinus banksiana*), Fig. 1, group 1] were much more susceptible than late successional [i.e. white cedar (*Thuja occidentalis*) and red maple (*Acer rubrum*), Fig. 1, group 3] species of the same diameter, sometimes regardless of hardwood/softwood status. The changing susceptibility group included balsam fir (*Abies balsamea*) and black spruce (*Picea mariana*), two species which have branches touching the ground as saplings, but look like a Christmas tree on top of a flag pole when mature, thus going from low susceptibility to high susceptibility relative to other species as they grow in size (Fig. 1, group 2).
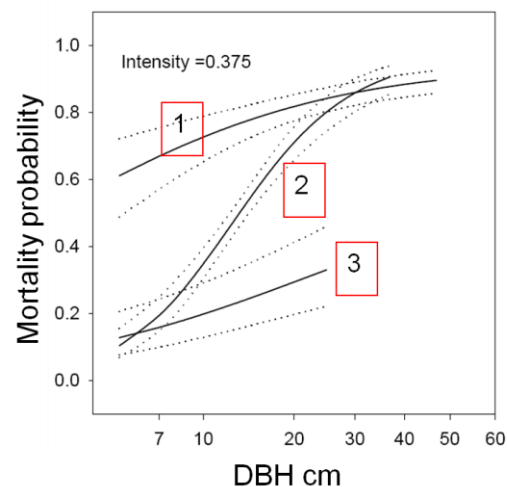
Figure 1: Probability of tree mortality by dbh (trunk diameter at 1.4 m AGL) of tree species and group. These curves show differential mortality among tree species on sites with moderate intensity of winds during the "Big Blowdown" of 1999 in northern Minnesota (wind intensity = 0.375 on a scale from 0–1). Species groups: 1) high susceptibility; 2) changing susceptibility with tree size; and 3) low susceptibility. Dotted lines show 95% confidence limits about each of the 3 regression lines. See text for details.

Early successional species have evolved a 'grow fast—die young' strategy, while late successional species invest more in mechanical stability because their strategy is to be around longer (King 1986). Early successional species also invest relatively little in containing decay after injuries. Relatively few studies have been done that standardize for storm severity and examine the proportion of trees that died by size class, compared to the number of trees that existed in each size class prior to the storm. One

study that did so (Peterson 2007) found much weaker evidence for higher susceptibility among early successional species, but that study examined tornadoes rather than derechos, and perhaps that also makes a difference. Therefore, whether this pattern by successional status holds up as a general pattern will remain to be seen in future studies.

Soil texture and rooting depth play important roles in tree stability. Shallow depths to bedrock, the water table, and hardpans formed by deposition of certain minerals that produce an impenetrable layer where soil particles are cemented together below the soil surface, can restrict rooting depth, potentially leading to increased susceptibility to wind. Because roots need some oxygen, rooting depths can be restricted even when there is no physical barrier to roots; rooting depths are shallowest with soils containing a lot of clay, and roots go progressively deeper in well drained silty and sandy soils. In one study the force necessary to pull trees over was measured for sitka spruce (*Picea sitchensis*) and Douglas-fir (*Pseudotsuga menziesii*) trees; sandy, silty, and clay soils had the highest, medium and lowest resistance to uprooting, respectively (Fraser 1962). In addition, sandy soils maintain their ability to provide stability when wet, while silty and clayey soils have less cohesion, making uprooting more likely in saturated soils (Mergen 1954). Thus, trees growing on soils that are normally not saturated, but that become so during prolonged rainfall followed by high winds, have a higher likelihood of being toppled. This effect is larger on loamy, silty and clayey soils than on sandy soils. Saturation-related toppling can be exaggerated further if soils are shallow to bedrock or a hardpan, so that less rainfall is required to saturate the rooting zone.

The situation with regard to windfirmness is complex in swamp and river bottomland forests where soils are usually saturated. For example, bald cypress (*Taxodium distichium*) trees have sinker roots that are adapted to the low oxygen levels of soils in the swamp. Such roots provide great stability, allowing long lifespans of centuries even in a region where hurricanes occur (Putz and Sharitz 1991). Black spruce root systems in northern swamps are often interwoven with each other so that they have a relatively low susceptibility to being toppled by wind, as was observed for the 1938 New England Hurricane (Foster and Boose 1992).

Strong-wooded species with deep rooting on well drained soils (i.e., white oak (*Quercus alba*), bur oak (*Q. macrocarpa*), hickories (*Carya* spp.), sugar maple (*Acer saccharum*), and trees of smaller diameter in good health are the least susceptible trees to blowdown. Nonetheless, as wind speed increases, differences among trees of different sizes and species become smaller (Rich et al. 2007). At a certain wind speed, all trees would be damaged. Virtually all mature trees are felled or have most branches stripped off by EF3 winds, and therefore the proportion of heavily damaged trees is of little diagnostic value in differentiating among EF3, 4 and 5 winds.

Often, in both forest and urban settings, there are more small and medium sized trees than large, old trees, so that even if the smaller trees have a lower chance of mortality in a given wind event, the absolute number of them toppled may be higher than for large trees. This gives the misleading impression that small trees are more susceptible. Of course, the relatively few large trees downed in a storm may create a large proportion of damage as they fall due to their large height and weight (analogous to the rarity of EF4–5 tornadoes that nevertheless cause most of the damage).

Season of wind makes a difference in the relative susceptibility of deciduous and evergreen trees. During winter there is much less area for wind to push on deciduous trees (Koizumi et al. 2010). Furthermore, in mixed forests, the deciduous trees don't protect evergreens by blocking wind as much. Some hardwoods such as live oak (*Quercus virginiana*) are evergreen and that some oaks such as pin oak (*Quercus ellipsoidalis* and *Q. palustris*) also retain dead leaves—known as marcescent leaves—through winter. In addition, some softwood conifers such as larch (*Larix laricina*) are deciduous. Thus, these seasonal differences do not break down strictly by hardwood and softwood categories.

Season also can make a difference in northern locations, where frozen soil makes uprooting of conifers less likely, in spite of exposure to high wind of intense extratropical cyclones and extra weight of snow and ice on branches (Peltola et al. 1999).

A few studies have shown that long duration of winds, such as that during midlatitude cyclones and hurricanes, can weaken trees

gradually by loosening the soil and by breaking small and moderately sized roots each time a gust jerks the tree. This way, fewer roots bear the remaining force, until the entire root system fails (Oliver and Mayhead 1974; Blackburn et al. 1988). Similarly, the trunk of the tree may sustain gradually increasing cracking until it snaps (Mergen 1954). Also, the longer the duration of a wind event, the higher the probability that a strong momentary gust will hit a given tree, and/or that a strong gust will align with the periodicity of a tree's sway, producing a force that exceeds the minimum necessary to uproot or snap the trunk (Blackburn et al. 1988). We are unaware of any studies comparing low-duration wind events of similar speed such as tornadoes lasting a minute or less to moderate-duration events, such as derechos that may last from 5–20 min, or to long-duration events such as hurricanes.

A complex interaction exists among tree species, tree size, wind disturbance history, and susceptibility to damage. For example, if two windstorms of given strength occur one month apart, at the second event, few trees will blow down, because most of those susceptible at that wind speed would have gone down in the first event. But, a few trees that were partially damaged in the first event or were in a different topographic location relative to wind direction may go down. If the second event had substantially stronger winds, then a number of additional trees would go down, but not nearly as many as in a single event with similar wind speeds.

Thus, the history of severe wind events in recent years is of considerable importance in determining the size of the "crop" of trees susceptible to being blown down at any given wind speed (Runkle 1982). This phenomenon was clearly evident in a study of treefall mortality, reconstructed over a period of more than a century from tree-ring analyses, in old-growth hemlock and sugar maple forests in Michigan (Frelich and Lorimer 1991). Forest stands that had suffered high mortality from thunderstorm downburst winds often had a period of several decades where little additional tree fall mortality was detected. Importantly, in the absence of any extreme wind, trees still will fall over eventually; they will decay to the point that a lower wind speed will take them down, or as observed by senior author Frelich on many occasions, they may fall over on a calm day.

Urban trees face a variety of environmental conditions that may increase their susceptibility to windthrow. Proper planting, pruning and care of trees could prevent a lot of damage caused by falling trees in urban areas. In cities, injuries at the base of trees caused by lawn mowers, snowplows, weed eaters, and other mechanical equipment (Fig. 2), often lead to entrance of decay organisms into the base of the tree, leading to failure during wind storms many years later. Thus, maintaining a layer of mulch around the base of a tree that prevents lawn mowers from knocking off chunks of bark can improve tree lifespan and stability during high wind events. Cutting roots for sidewalk and street construction, or killing roots through soil compaction by heavy construction equipment, leads immediately to structural instability and/or declining health of trees.

Figure 2: Mechanical damage to the base of a tree leading to rot within the trunk and increased susceptibility to wind. Photo by Eric Berg, Nebraska Forest Service. *Click image to enlarge.*

Improper planting of trees is common in cities. The two most common mistakes are planting too deep, which can lead to rot at the base of the trunk (Fig. 3) and planting with girdling roots, which later expand and choke off the base of the trunk, creating a compression point below ground where the trunk breaks (Fig. 4). These were the most common causes of total failure of the ubiquitous urban trees green ash and little leaf linden during a 1998 derecho in the Minneapolis-Saint Paul, MN metro area (Johnson et al. 1999). The planting situation with regard to depth, girdling roots, adequate soil area, and mechanical injuries to the base of trees probably overrides species and size as factors determining susceptibility to wind damage in cities (Fig. 5).

Figure 3: A small tree that has been planted too deep, a situation that could lead to failure at the base of the trunk many years later. Photo by Eric Berg, Nebraska Forest Service. *Click image to enlarge.*

Forest-grown trees are part of a stand, with susceptibility to wind changing as the stand matures. After a major disturbance such as tornado, clearcutting, or severe fire, forest stands go through four stages of structural development (Frelich 2002). The first stage is initiation, in which all of the trees are seedlings and saplings, with very little susceptibility to windthrow because small trees are not very tall and are able to bend when exposed to wind.

The stem exclusion stage follows, with mature, even-aged trees. At this stage there are many tall trees in a dense stand, maximizing susceptibility to wind. Many forests are in this stage of development due to extensive disturbance across the landscape by European settlers in North America during the late 1800s to early 1900s, as well as ongoing clear-cutting of forests for fiber and lumber production. A widely distributed, current example of this stage across the Midwest and eastern sections of the United States is the red pine (*Pinus resinosa*) plots planted by Civilian Conservation Corps workers in the 1930s.   These very dense stands of tall and evenly-sized trees have been observed to sustain heavy damage in high wind events (see Fig. 13).

Figure 4: Girdling roots that will choke off the base of the trunk progressively as they grow. Photo by Eric Berg, Nebraska Forest Service. *Click image to enlarge.*

Figure 5: Upper, a downed tree with base of trunk pinched off underground by large girdling roots. Lower, a maple tree that failed during a wind storm, likely because it was planted too deep. Photos courtesy NOAA/NWS. *Click images to enlarge.*

Next is transition to uneven aged condition, as the stand becomes a mixture of tree ages, and finally the multi-aged stage of development with trees of many age classes mixed together. If a

severe wind storm hits such a multi-aged forest, it is likely that the large trees will be more heavily impacted, but unlikely that even a very high wind would completely level the stand, since a sizable proportion would be occupied by small and medium sized trees that are less susceptible to blowdown. In these multi-aged forests, the susceptibility of large old trees probably varies greatly over time—high susceptibility for an individual tree immediately after its neighbors die, and, if the tree survives, lower susceptibility a few decades later as the tree's growth strategy allows it to adapt to the relatively large crown exposure.

Sometimes succession (change in species composition) accompanies stand development (Frelich 2002). In such cases, changes in tree species over time might lead to more or less susceptibility to future wind events, although succession leading to less susceptibility is more likely since late successional species generally are thought to be less susceptible to wind damage (Frelich 2002; Rich et al. 2007). Windstorms can aid succession by releasing saplings of later successional species present in the forest understory (Webb and Scanga 2001). In some cases where the early successional species are large individuals of very susceptible species, with small individuals of less susceptible species growing in the understory, extreme differences in mortality can result. In effect, the storm pushes succession ahead by selectively weeding out the early successional species while also reducing the overall stature of the forest (Rich et al. 2007).

Table 2: DoD 1–5 for a) one or two family residences and b) metal buildings. Speeds in mph. From McDonald, et al (2006).

A. DOD	One or Two Family Residences (1000–5000 ft^2)	Expected	Lower Bound	Upper Bound
1	Threshold of visible damage	65	53	80
2	Loss of roof covering material (<20%), gutters and/or awning	79	63	97
3	Broken glass in doors and windows	96	79	114
4	Uplift of roof deck and loss of significant roof covering material (>20%)	97	81	116
5	Entire house shifts off foundation	121	103	141

B. DOD	Metal Building Systems	Expected	Lower Bound	Upper Bound
1	Threshold of visible damage	67	54	83
2	Inward or outward collapse of overhead doors	89	75	108
3	Metal roof or wall panels pulled from the building	95	78	120
4	Column anchorage failed	117	96	135
5	Buckling of roof purlins	118	95	138

### 3. Field observations of wind disturbance

Surveys of tree damage from convective wind events of varying intensity and duration are described below. These events were chosen to illustrate some of the factors affecting wind tolerance of individual trees and forest stands described in section 2. In some cases, tree damage was noted in close proximity to other EF-scale DIs, so wind estimates derived from DoD to each could be cross referenced.

a. 4 July 2003

This event consisted of winds in the 20–25 m s^{-1} (45–55-mph) range as a gust front from a weakening line of thunderstorms moved through Grand Rapids and the surrounding Kent County, MI area. A peak wind gust of 21.5 m s^{-1} (48 mph) was measured by the Grand Rapids Automated Surface Observing System with a maximum 2-min average wind speed of 17 m s^{-1} (38 mph). Figure 6 shows that the 0.5° elevation angle radar-indicated winds within 150 m (500 ft) of the ground were near 22 m s^{-1} (50 mph). A 24.6 m s^{-1} (55-mph) peak wind gust was recorded about 8 km (5 mi) northwest of Grand Rapids by a rooftop anemometer.

About a dozen trees or large limbs were snapped and one was uprooted. Their locations are plotted in Fig. 6 along with available measured peak wind speeds. Only one of the trees did not show signs of rot. The tree that was uprooted was shallow-rooted (Fig. 7). All of the tree species were hardwoods. No damage to other DIs was observed.

A storm survey found a red oak (*Quercus rubra*) that was extensively rotted (Fig. 8) and a large limb that broke off a sugar maple (*Acer saccharum*) had termite damage (Fig. 9). Several other trees lost large limbs, and inspection of the break points showed the wood to be rotted. A white ash (*Fraxinus Americana*) was the only healthy tree that had snapped (Fig. 10). This tree was near the western edge of a stand of hardwoods and was exposed to the wind. Winds may have been in the 24.6–27 m s^{-1} (55–60 mph) range in this area, judging from radar data and a recorded wind gust of 24.6 m s^{-1} (55 mph) <3.2 km (2 mi) away. No other significant tree damage was seen near this tree, with only twigs and leaves noted on the surrounding ground.
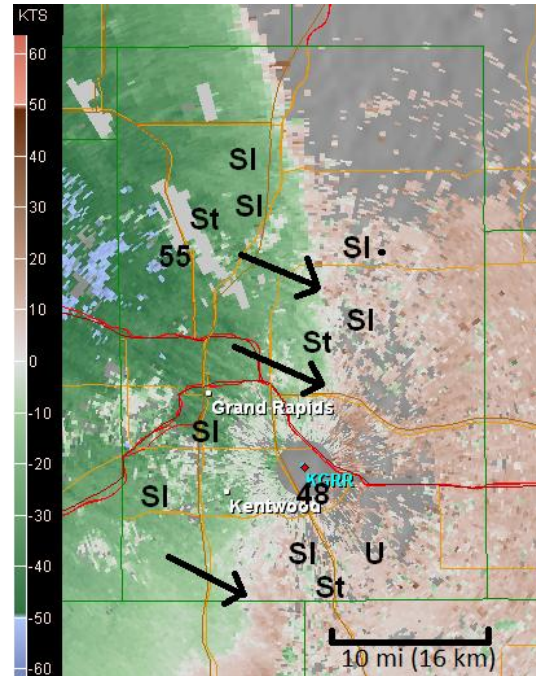
Figure 6: 0.5° radar base velocity image showing a gust front moving across Grand Rapids, MI. Location of tree damage is noted by Sl for snapped limbs and St for snapped trunk. U means uprooted. Peak wind gusts (mph) at two locations are plotted. Color coded wind scale is in knots. The arrows show the prevailing wind direction at the leading edge of the gust front.


Figure 7: Shallow-rooted tree blown over. The trunk can be seen at top. Note the saturated soil. Photo courtesy NOAA/NWS. *Click image to enlarge.*

Figure 8: The rotten and partially hollow core of a red oak. Note the thin wall of healthy, light-colored wood. Photo courtesy NOAA/NWS. *Click image to enlarge.*

Figure 9: A large limb shed by a sugar maple. The discolored wood is rotted. Photo courtesy NOAA/NWS. *Click image to enlarge.*
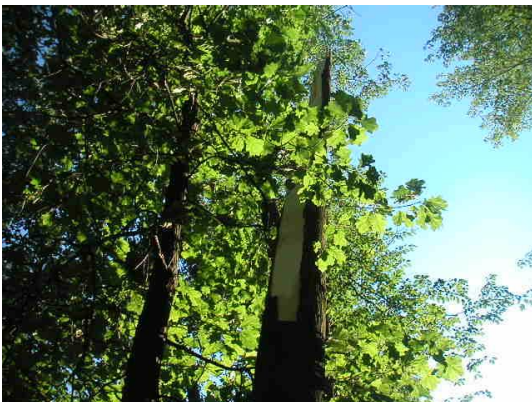
Figure 10: The snapped trunk of an apparently healthy ash tree. Photo courtesy NOAA/NWS.

Figure 11: a) A home sustaining extensive roof damage. Note uprooted tree in foreground. The tornado moved from left to right of this view. b) Trees snapped and uprooted adjacent and downwind of the home in (a). Photos courtesy NOAA/NWS. *Click images to enlarge.*

b. 21 August 2003

A tornado occurred in Ingham County, MI about 135 km (85 mi) southeast of Grand Rapids, with a damage path >6.5 km (4 mi) long and ≤0.8 km (0.5 mi) wide. The forward speed of the tornado was estimated to be 9 m s^{-1} (20 mph) with damaging winds persisting for about 90 s for the DIs in the center of the path.

There were several areas where damage to homes and trees occurred in close proximity (e.g., Fig. 11). Roof damage in Fig. 11a is consistent with a DoD of 4 for the one- or two-family residence (FR12) DI (Table 2), implying an expected wind speed of 43 m s^{-1} (97 mph) according to the EF scale. Several apparently healthy hardwood trees near the house were uprooted or snapped. This corresponds to a DoD of 3 and 4 (see Table 1a.), indicating expected winds from 41–49 m s^{-1} (91–110 mph). In this case, the DoD from two different DIs yielded

wind speeds that were in general agreement, in the upper EF1 range.
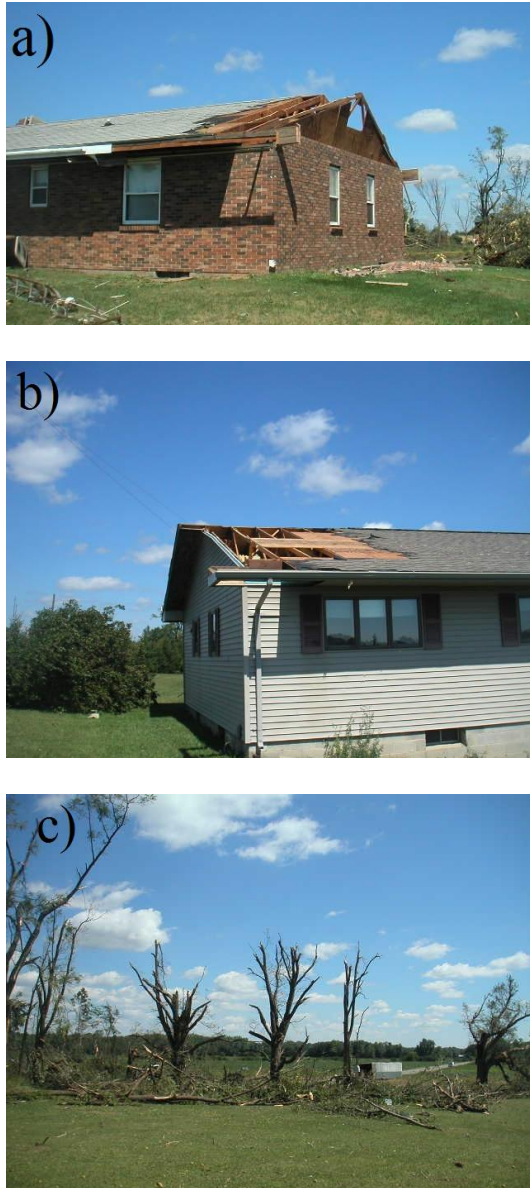
Figure 12: a) Roof damage to a home about 50 m (164 ft) from b) similar roof damage to the home in (a).   c) Large branches shed from hardwood trees near the homes in (a) and (b). Photos courtesy NOAA/NWS. *Click images to enlarge.*

The same two DIs can be compared elsewhere along the path. Figure 12 shows roof damage to two homes that would indicate a DoD of 2 and damage to hardwood trees <50 m (164 ft) away that appear to be consistent with a DoD of 2. This yields expected wind speeds of

35 m s^{-1} (79 mph) for the homes and 33 m s^{-1} (74 mph) for the trees. The DoD from these DIs were in general agreement in the upper EF0 range.

There are some problems with this classification, however. A careful examination of the DIs shows that the roof damage was close to the 20% threshold used to delineate DoD 2 from DoD 4. No broken glass was noted in windows or doors of the houses, which defines DoD 3. Looking at the hardwood trees, all the large limbs were broken, suggesting that winds may have been higher than DoD 2. There were also several hardwood trees snapped and uprooted near the homes (not shown) that would indicate DoD 3 and 4.

Figure 13: a) Damage to a stand of even-aged red pine. b) Another view of the pine stand and surrounding area. Smaller deciduous trees fared better in surviving the strong winds. Photos courtesy NOAA/NWS. *Click images to enlarge.*

c. 29 May 2011

A narrow but intense swath of damaging winds struck southern sections of Battle Creek and surrounding suburban and rural areas of Calhoun County, MI. The winds were associated with a mesocyclone embedded in a derecho. A wind sensor at Battle Creek Airport, about 3 km (2 mi) north of the path of heaviest wind damage, recorded a peak wind gust (3-s average) of 24 m s^{-1} (53 mph), and winds over 18 m s^{-1} (40 mph) persisted for 10 min. Winds were estimated to be in the EF1 range based on damage south and east of the airport.

An area of extensive tree damage occurred in Kimball Pines County Park on the southeast side of Battle Creek (Fig. 13). Only minor damage to metal outbuildings was noted in this area, suggesting EF0 winds based on DoD 1 to the metal building system (MBS) DI (Table 3).

Tree damage included both snapping and uprooting of hardwoods and softwoods. The greatest damage was to an even-aged red pine plantation, which suffered significantly higher mortality than nearby deciduous trees of varying ages. This is consistent with damage that has occurred to other red pine plantations during severe winds and suggests that damage to these trees, and perhaps other species in an even-aged stand, would rate at the lower bound for DoD 3 and 4.

d. 1 July 2011

Several areas of damaging downburst winds occurred along the path of a bowing line of thunderstorms across northern Wisconsin. Estimated peak winds and damage were similar to the 29 May 2011 event in Michigan with widespread damage to trees but only minor damage to structures. Figure 14 shows a stand of trees with high mortality as most trees were toppled, both uprooted and snapped. Large trees along the edge of the stand withstood the winds better than trees in the interior, as did a row of open-grown spruce trees and smaller trees in the interior of the stand.

One nearby building was damaged by a falling tree; otherwise no substantial structural damage was observed. The extent of damage to the stand of trees in Fig. 14 would suggest at least EF1 winds. However, the lack of damage to buildings, the survival of many trees along the edge of the stand, and the intact stand of spruce trees in close proximity, suggest lower-bound EF1. This appears to be a case of significant damage to an even-aged, early successional stand of trees.

4. Conclusions, best practices and possibilities for future study

Many factors affect the susceptibility of trees to wind, from the forest scale down to the individual tree. Accounting for the effects of these variables is challenging and requires some basic knowledge of forest-stand dynamics, tree morphology and health, and assessing site characteristics such as exposure (especially recent changes in exposure) and soils.

Figure 14: Forest stand blown down in Burnett, County, WI. Note the many surviving trees at the edge of the stand. Photo courtesy NOAA/NWS. *Click image to enlarge.*

Damage to healthy trees usually begins around 24.6–27 m s^{-1} (55–60 mph), slightly below the lower end of EF0 winds. The percentage of trees snapped and uprooted increases through the EF1 range with most trees downed by EF2 winds. Virtually all mature trees can be expected to be downed by EF3 winds. Several cases studies presented here have shown that both snapping and uprooting of trees occurs during high wind events, and there is no evidence that stronger winds are required to snap a tree rather than uproot it. The higher wind speeds assigned to DoD 4 (snapping of trunks) compared to DoD 3 (trees uprooted) appears to be unwarranted.

Trees in urban and suburban areas can be highly susceptible to winds due to injury or improper planting techniques. Signs of injury at or near the breakpoint or stem girdling roots should be noted by damage surveyors. These signs should result in, at most, a lower-bound wind speed being assigned. If no healthy trees or limbs were downed, no EF-scale rating should be assigned.

In forests, even-aged stands, especially monocultures such as red pine plantations, are susceptible to wind damage and could be given lower-bound wind speed estimates. Even a complete blowdown of such a stand may not be indicative of EF1 winds, especially if other species and sizes of trees present in or near the stand suffer much less damage.

Forests composed of large, early successional species such as aspen (*Populus tremuloides*) are also susceptible to widespread wind damage and would rate a lower-bound wind speed. Conversely, forests composed of later successional species such as beech (*Fagus grandiflora*) or forests that had suffered large scale wind disturbance within the past several years could rate a higher-bound wind speed.

When possible, EF-scale ratings of tree damage should be correlated to nearby structural damage. Large discrepancies between expected wind speeds for observed DoDs of trees and nearby structures should be noted and an attempt made to resolve them. This, in turn, must be done while assessing the construction standards of buildings as well as the factors affecting the susceptibility to wind by forest stands and individual trees.

The large variation in wind tolerance among various species of both hardwoods and softwoods, and the relatively small differences in the estimated winds assigned to DoDs of hardwoods and softwoods, suggest that only one DI for trees is necessary in the EF-scale rather than separate DIs for softwoods and hardwoods. An average of the original estimated wind speeds that resulted from the expert elicitation process for DIs 27 and 28 would suffice.

During the course of researching past studies of wind mortality to trees, the authors noted a lack of research assessing wind duration as a factor in the magnitude of tree damage. Some general information regarding the fact that damage can build up to the point that a tree may fail during long-duration events was uncovered, but there were no quantitative analyses of similar windspeeds with varying duration. Tornadoes, derechoes, hurricanes and powerful extratropical cyclones all produce wind damage of highly varying intensity and duration, yet only one paper was noted in the literature that briefly addressed differences in damage characteristics between forests hit by tornadoes and hurricanes. Further research is needed for better understanding of wind-duration effects on the effort to assign wind speeds based on tree damage.

ACKNOWLEDGMENTS

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REVIEWER COMMENTS

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[Authors' responses in *blue italics.*]

REVIEWER A (Kevin Laws):

Initial Review:

Recommendation: Accept with minor revisions.

Substantive specific comments:
Page 6 – last 2 full paragraphs – Is this mainly based on observations? Where exactly did this come from?

Of these two paragraphs, the first one introduces the topic and the second provides information with references. That single high-mortality wind storm events create a period of resistance to future winds, and that all trees eventually fall to the ground even if there is no wind, is common knowledge among foresters, it doesn't seem necessary to provide any more citations, and the Frelich and Lorimer reference is pretty comprehensive. We did, however, slightly reorganize the flow of ideas in the second paragraph to make it clearer.

Page 9 – last sentence of last paragraph – Is this your opinion here? I think this is a critical point, as the winds are at the severe thunderstorm critical threshold. So, one healthy tree snapped = 60 mph? I think that needs to be clear one way or the other.

The sentence is: "Winds may have been in the 55 to 60 mph range in this area judging from radar data and a recorded wind gust of 55 mph less than 3.2 km (2 mi) away." Unfortunately, no definitive statement can be made based on this event due to lack of a wind measurement in close proximity. Radar sampling of winds indicated maximum speeds around 50 knots, but these were sampled 900 feet AGL. Of course, in the NWS we put an arbitrary importance on winds less than or greater than 58 mph for warning verification, but in nature the spectrum of damage is quite blurry and it would probably take a large number of surveys to establish if we can expect a healthy tree to be snapped during a 60 mph wind event. I added a sentence to note that no other significant tree damage occurred near this tree with only leaves and twigs seen down in the area.

Page 13 – 2nd paragraph – Can we separate out the DoDs and/or DIs with variability in species, rot, age, etc.? Admirable goal, in my opinion…

Separating out species would be difficult since the same species may have significantly different susceptibility to different types of wind events, i.e., derecho versus tornado. Age may be a better indicator, but again there may be too many caveats to use this effectively. I would suggest that rotted trees, even partially rotted, should not be used when assigning wind speeds. The exception could be when many rotted trees have come down along with small healthy limbs to suggest winds approaching severe levels.

[Minor comments omitted...]

REVIEWER B (Timothy P. Marshall)

Initial Review:

Recommendation: Accept with minor revisions.

General Comments

WIND SPEEDS: Wind speeds mentioned in the paper must be defined as to the height, duration, and exposure/roughness. For example, the following paragraph on page 3 mentioned various wind speeds, but it remains unclear whether these are comparing the same type winds.

example from page 3: "Wind tunnel studies for a variety of species show that streamlining can reduce frontal area to 20–40% of its initial area for hardwood species and 45–65% for conifer species as wind speed goes from 0–45 mph (Rudnicki et al 2004, Volsinger et al 2005). Trees can increase streamlining, reducing frontal area and mortality up to a variety of wind speeds ranging from 60–118 mph, depending on species and height of tree (Mayhead 1973, Hedden et al 1995). Beyond a certain wind speed, trees are streamlined to the maximum possible extent, and force on the tree increases as the square of wind speed, bringing most trees (even healthy ones with strong wood that are firmly rooted) to their limit for structural failure by 100–110 mph (Hedden et al 1995)."

We have changed the first paragraph on page 4 of the revised manuscript to make the points that much of the data comes from wind tunnel studies, and that there are virtually no field measurements for certain aspects of tree damage: "All of the studies cited above in this paragraph were conducted in wind tunnels with relatively uniform speeds through the height of the trees and for the duration of the experiment, or were modeled mathematically. No data are available to illuminate how trees interact with type of storm (tornado, derecho, hurricane), duration and gustiness in wind speed during a storm, and roughness of the surrounding landscape and forest canopy in a field setting."

[Minor comments omitted...]

REVIEWER C (Chris Peterson):

Initial Review:

Reviewer recommendation: Accept with minor revisions.

Specific (Substantive) Comments

1 - My most fundamental concern lies with the general premise of using the wind velocities in Table 1 to estimate wind velocities in actual storms. Neither Frelich or I really believe that the numbers in Table 1 are robust; indeed, the authors spell out in the first paragraphs of the Introduction several factors that influence tree stability, making the simplistic classification in Table 1 uncertain. But if that's the case, then whence the remainder of the manuscript? Perhaps the way forward is for the authors to insert some additional qualifying language in the manuscript explicitly spelling out to readers that all the conclusions and inferences in this paper are contingent on Table 1, in which some of us have limited confidence.

We have changed wording at the end of the first paragraph to accommodate this concern: "However, studies by forestry researchers have revealed a number of reasons why the values in Table 1 may not work in a variety of field settings. We touch briefly on these reasons in the Introduction to set the stage for detailed consideration in sections 2 and 3 of the paper." In addition, the conclusions section has a number of recommendations for improving the ways that tree damage is used in assessing wind speeds.

2 - I am also a bit concerned about consistency in interpretation. Figure 11b is confusing—the caption says it shows trees in the yard of the home in Figure 6a, but Figure 6a is the radar image. I presume the caption should say "the home in 11a"??? But there are still some problems here: the authors conclude in the text on page 10 that the home and the trees in Fig. 11 are roughly consistent in suggesting a wind velocity of 91–110 mph. But on page 3, lower right column, the authors assert that wind velocities in this range should destroy most. Surely Figure 11b shows that a majority of the trees are still standing, even if some are snapped or uprooted. This example clearly illustrates the limitation of the DoDs given in Table 1—a few of the Fig. 11b trees are indeed snapped or uprooted, but many are still standing.I would argue that this indicates something less than a level 4 DoD.

Fixed typo: "6a" was changed to "11a" in the caption to Figure 11b. Inserted some new language on page 3 (paragraph continuing onto page 4 of revised ms), to point out that shedding branches and other factors discussed later on can change the relationship of wind and tree failure. Clearly most of the standing trees in Fig. 11b have shed branches.

3 - The authors also perhaps should have some qualifying language in the soil texture & moisture paragraph in the lower right column of page 5. I believe that both Foster & Boose (1992), and Putz and Sharitz (1991) concluded that wet soils do not necessarily lead to greater uprooting because often the spp growing on these soils are hydrophilic and have mechanisms to allow deeper rooting in saturated and anoxic soils. The more succinct way to s tate the authors' point is that when normally unsaturated soils BECOME saturated (as might happen in the torrential rains of a hurricane), the loss of soil cohesion can indeed lead to much more uprooting.

Good point. We broke the paragraph into two, adding more detail and references requested by the reviewer. The first paragraph covers upland soils, and the second now discusses permanently saturated soils, where trees have mechanisms to compensate for the saturation, as suggested by the reviewer. This suggestion strengthens the paper (last partial paragraph of column 1 on page 6, continuing to column 2 of revised manuscript).

[Minor comments omitted…]

[Editor's Note: Revisions were satisfactory such that the manuscript was not reviewed substantively in Round 2.]