831 SIDE-BY-SIDE TREE AND HOUSE DAMAGE IN THE MAY 2013 MOORE, OK EF5 TORNADO: LESSONS FOR THE ENHANCED FUJITA SCALE

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1. INTRODUCTION

The ability to infer storm intensity is a vital component of severe weather research (Edwards et al. 2013). The absence of abundant in situ data within tornadic circulations, in part due to the extreme winds that destroy most meteorological observing platforms, necessitates an approach that infers near-surface wind velocities based on damage. Research and operational meteorologists use the enhanced Fujita (EF) scale (WSEC 2006) to categorize structural damage and infer near-surface wind velocities. The scale pairs 28 damage indicators (DIs), each with various degrees of damage (DoDs), to arrive at an estimate of the wind speed responsible for that damage. A robust characterization of wind speeds along the entire path of a tornado requires a large and spatially diverse sample of DIs. Otherwise, the evaluation of a tornado may end up relying on very few or even a single DI. An example of such an undersampled tornado is the EF4 that occurred on 27 April 2011 in the Great Smoky Mountains National Park. A National Weather Service employee rated the tornado on the basis of a single collapsed metal truss electrical transmission tower. Ironically, the observed degree of damage for this particular DI corresponds with a rating of EF3, so the final rating of EF4 remains puzzling. Trees are the only other DI that the tornado struck along its entire 18-mile path. Similarly, a damage survey team that included one of the present authors relied solely on tree damage to assign a rating of EF1 to another tornado that occurred on 13 June 2013 in the Great Smoky Mountains National Park. In other less extreme cases, rural tornadoes strike far more trees than structures (Blanchard 2013). This underscores the importance of a robust and reliable set of metrics for tree-focused DIs if meteorologists wish to assign the most realistic wind speed estimates along a tornado track.

The DIs that form the basis for EF-scale ratings remain heavily biased toward structures. The only exception is the two hardwood and softwood tree DIs out of the 28 possible DIs. This bias is understandable given the societal concerns with damage to structures, such as buildings and homes, rather than to naturally-occurring objects. Trees, however, provide a wealth of abundant, easily visible, and potentially useful natural objects that are significantly impacted by strong winds (Frelich and Ostuno 2012) . Table 1 shows the two tree-focused EF-scale DIs and their associated DoDs and inferred wind speeds. Note that the present DoDs for tree-focused DIs offer no guidance to differentiate moderate EF4- or EF5-level wind damage from that of EF3, since the DoDs reach their maximum in the EF3 wind speed range. However, there is currently much discussion among field inspectors regarding the possibility that the highest DoD descriptions (associated with EF2 to EF3 wind speeds) might actually indicate EF4 or EF5-level damage, despite the guidelines presented in WSEC (2006) and replicated in Table 1.

2. EXISTING TREE DI LIMITATIONS

The present EF scale formulation contains several potential limitations to the tree-focused DIs. These limitations include the fact that 1) the wind speeds associated with the present DoDs are based on an expert elicitation process (WSEC 2006) rather than objective data; 2) there exists no empirical evidence that snapped and uprooted trees should correspond with different degrees of damage; 3) the existing DIs do not consider tree size or tree species, yet both measures strongly influence tree strength and windfirmness (Everham and Brokaw 1996; Peltola 2006; Nicoll et al. 2006; Peterson and Claassen 2013); 4) debarking and stubbed branches are only observed at more extreme wind speeds than those corresponding to a rating of EF3; and 5) the distinction between hardwoods and softwoods on the EF scale remains too general to capture the variability in tree strength across species. These five limitations could easily lead to flawed estimates of tornadic winds, an incorrect understanding of tornado dynamics, and inconsistencies in damage surveys. Improvements to the tree-focused DIs based on quantitative empirical data could address each of these shortcomings. Therefore, the central goal of the small project described here is to outline a way to improve the tree-focused DIs using side-by-side comparisons of tornado damage to one-or two-family residences (FR12) with damage to hardwood (TH) and softwood (TS) trees.

Previous research efforts by the authors highlight the shortcomings of the current tree-focused DIs. Despite more than two decades of extensive research into tree damage from tornadoes in forested contexts, the similarities in damage processes and patterns between forest

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trees and residential neighborhood trees remain uncertain. However, an extensive forest tree damage database collected to date yields several very clear patterns that strongly support the above concerns about the existing EF-scale criteria (Peterson 2007). For example, in an exceedingly unusual juxtaposition of events, two tornadoes passed through the same old-growth beech-hemlock forest in northwestern Pennsylvania. One tornado occurred in 1985 (the infamous F4 Kane tornado) and one occurred in 1994, both located in the Tionesta Scenic and Research Natural Areas within the Allegheny National Forest. The damaged areas sampled after each event were only a few kilometers apart and thus contain nearly identical tree species composition, tree sizes, management history, climate, topography, and soil types. A rigorous comparison between the sites is easily justifiable, since the only major difference between the sites is the behavior of the individual tornadoes (Peterson 2000). The 1985 F4 tornado created a damage swath with a maximum width in excess of 800 m and caused nearly complete canopy destruction. In contrast, the 1994 F1 tornado left a damage swath with a maximum width of only about 75 m and destroyed only about 40% of the forest canopy. The two tornadoes therefore differ substantially in intensity, but the forest composition in each of the resulting damage swaths differs very little. Fig. 1 shows the proportions of downed trees that suffered trunk breakage versus uprooting. Despite the large differences in storm intensity, the most striking aspect of this plot is that the two sites exhibited nearly identical ratios of trunk breakage versus uprooting. Such a pattern is clearly inconsistent with the distinct wind speeds inferred by snapping and uprooting in the existing EF-scale DoDs for trees. This result implies that large differences in storm intensity do not in fact yield significant differences in the proportion of trees that suffer from trunk breakage versus uprooting.

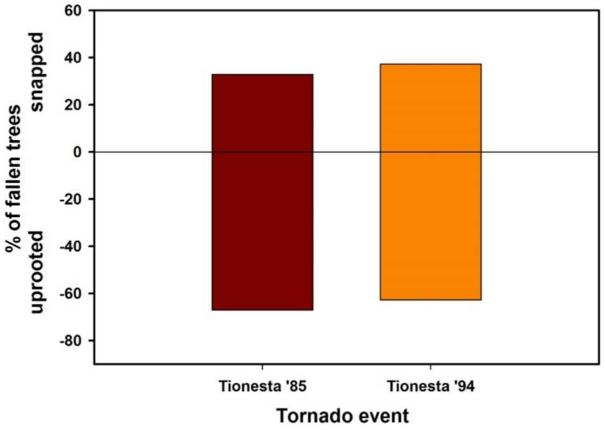

FIG. 1. Percentage of fallen trees suffering trunk breakage (snapped) and uprooting (uprooted) in two tornado events near Tionesta, PA in the Allegheny National Forest.

Two other tornadoes that passed through forested areas in Pennsylvania and Tennessee provide another example of the fallibility of the present tree-focused EF-scale DoDs. An F2 tornado passed near Blooming Grove in northeastern Pennsylvania in 1998 and another F2 occurred near Beech Grove in central Tennessee in 2002. Figs. 2 and 3 show the observed percentage of all sampled trees that were snapped or uprooted, separated according to species, within each of these tornado tracks. While the differences in tree fate between species are noticeable in Fig. 2, those differences are dramatic in Fig. 3. Here, observed tree fates range from nearly 70% uprooted for *Quercus rubra* (northern red oak) to 0% uprooted for *Juniperus virginiana* (eastern red cedar). Clearly, species identity is a major influence on the fates of trees that experience extreme winds. This fact must be built into any scheme that infers wind characteristics from tree damage (Peterson 2007).

Notably, the study site whose data are shown in Fig. 3 is one with deep soils and deeply-rooted trees, while the study sites shown in Figs. 1 and 2 have shallow soils that cause tree rooting to be restricted due to a subsurface hardpan (Tionesta) or a very shallow water table (Blooming Grove). The broad trend toward greater uprooting

TABLE 1. DIs 27 and 28 of the EF scale, their associated DoDs, inferred wind speeds, and EF-scale ratings. Hardwood examples include oak, maple, birch, and ash. Softwood examples include pine, spruce, fir, hemlock, cedar, redwood, and cypress.

DI 27: Hardwood Trees				
DoD	**Damage Description**	**Expected Wind (m.p.h.)**	**Range (m.p.h.)**	**EF**
1	Small limbs broken (up to 1” diam.)	60	48–72	EF0
2	Large branches broken (1”–3” diam.)	74	61–88	EF0–low EF1
3	Trees uprooted	91	76–118	EF0–low EF2
4	Trees snapped	110	93–134	High EF1–EF2
5	Debarked with only stubs of largest branches remaining	143	123–167	High EF2–EF4

DI 28: Softwood Trees				
DoD	**Damage Description**	**Expected Wind (m.p.h.)**	**Range (m.p.h.)**	**EF**
1	Small limbs broken (up to 1” diameter)	60	48–72	EF0
2	Large branches broken (1”–3” diameter)	75	62–88	EF0–low EF1
3	Trees uprooted	87	73–113	High EF0–EF2
4	Trees snapped	104	88–128	EF1–EF2
5	Trees debarked with only stubs of largest branches remaining	131	112–153	EF2–EF3

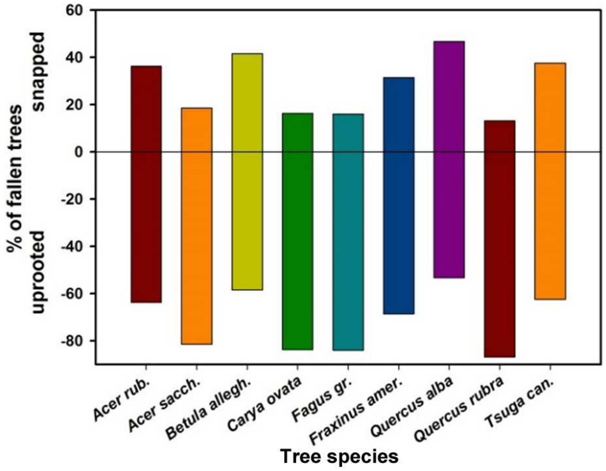

FIG. 2. Percentage of fallen trees suffering trunk breakage (snapped) and uprooting (uprooted) according to tree species in the Blooming Grove, PA F2 tornado.

in Figs. 1 and 2 may partially result from shallowly-rooted trees, whereas the much greater proportion of trunk breakage in two-thirds of the species in Fig. 3 may derive from deeper rooting that causes the trunk to be the weakest point in terms of windfirmness. These contrasting patterns suggest that site factors such as soil depth may have a substantial influence on the eventual condition of each fallen tree.

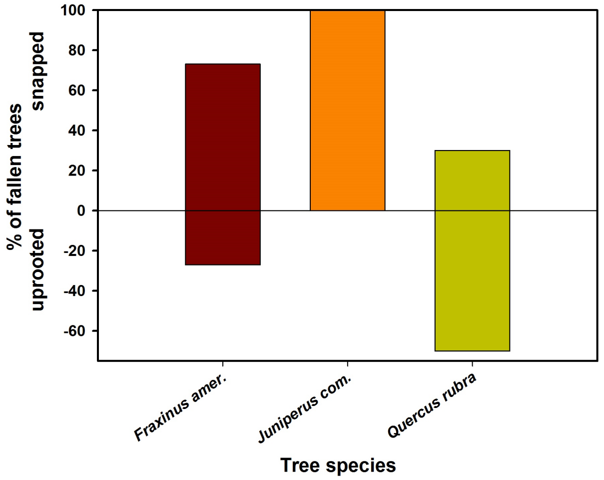

FIG. 3. Percentage of fallen trees suffering trunk breakage (snapped) and uprooting (uprooted) according to tree species in the Beech Grove, TN F2 tornado.

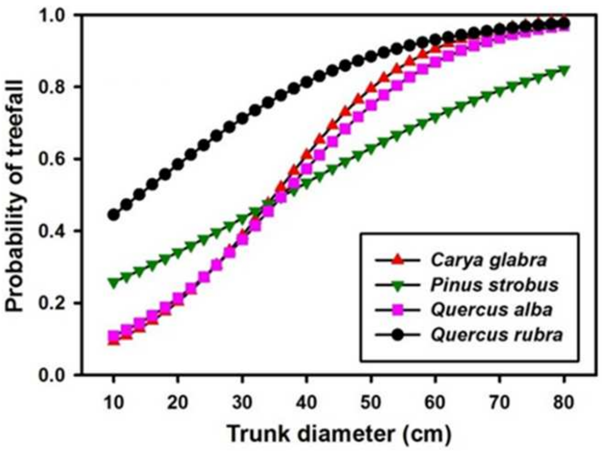

FIG. 4. The probability of treefall as a function of trunk diameter for a selection of trees sampled near Boggs Creek in the Chattahoochee National Forest in northeastern Georgia.

Fig. 4 shows the probability of treefall (either snapped or uprooted) as a function of tree diameter for a selection of trees sampled after an EF3 tornado passed through the Chattahoochee National Forest in northeastern Georgia on 27 April 2011. The plot shows the results of logistic regressions and is one of many that could be drawn from available data. Trunk diameters are measured at a standard height of 1.4 m above the ground level. This plot clearly indicates that the diameter of a tree tremendously influences its odds of being toppled by tornadic winds. Therefore, any tree-focused DI clearly must consider—even roughly—the tree diameter. Fig. 4 also indicates that different species have distinct relationships between diameter and the level of treefall risk. In the smaller size classes, *Quercus alba* (white oak) and *Carya glabra* (pignut hickory) exhibit the most resistance to treefall, but in larger size classes, *Pinus strobus* (eastern white pine) exhibits the most resistance. Once again, these results dramatically proclaim the importance of considering both tree size and species when assessing wind damage.

Fig. 5 shows the spatial coordinates and fate of several

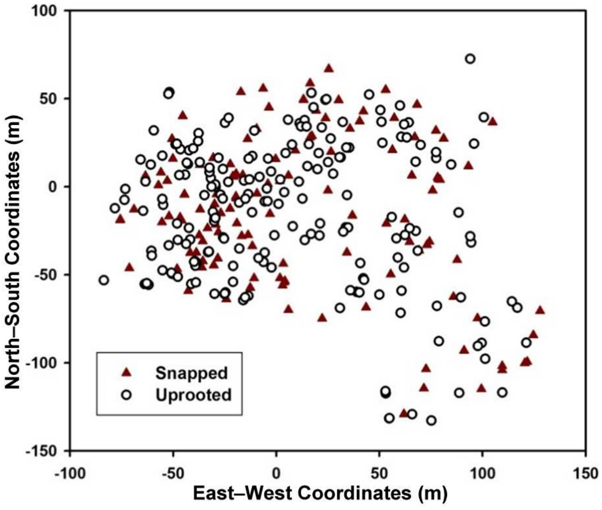

FIG. 5. Spatial coordinates (in meters) of *Acer rubrum* (red maple) trees in the Blooming Grove, PA tornado track showing locations of snapped and uprooted trees.

hundred *Acer rubrum* (red maple) trees that were blown down by the same 1998 Pennsylvania tornado discussed in Fig. 2. This figure shows only a single species (red maple was the most abundant species in the study site) to exclude species-by-species variation and to highlight the typical observation that types of treefall are spatially well-mixed. Although uprooting is about twice as common as snapping overall, both types of treefall are well-dispersed throughout the study area. In agreement with the observations of other authors (e.g., Frelich and Ostuno 2012), there exist no concentrated regions of snapping or uprooting in any particular location that would indicate that certain wind speeds produce a particular type of damage. This pattern of highly intermingled types of tree damage would not occur if snapping and uprooting were indicative of different wind speeds as asserted in the tree-focused DoDs of the current EF scale. If snapping and uprooting did correspond with different wind speeds, one would expect that certain areas would predominantly exhibit one or the other type of damage. Since areas along the right side of the forward-moving storm experience the sum of rotational and translational winds, for example, the right side should show more snapping. Such a pattern is not evident, despite the fact that the nearly 250 m shown in Fig. 5 spans almost the entire width of the tornado track.

3. DAMAGE COMPARISONS

The previous discussion summarizes key results from research on wind damage in forests. A limited counter-argument might be that such results represent only forests and therefore may not represent patterns of tree damage observed in residential neighborhoods. The following photographs of damage from recent tornadoes adequately refute this counter-argument. The images serve to reinforce the arguments outlined above and suggest that these concerns indeed hold true for trees in the immediate vicinity of residential houses.

Fig. 6 shows a house with damage that was rated EF2.

FIG. 6. House with EF2 damage.

FIG. 7. House with EF2 damage.

Note that on the EF scale, EF2 winds are expected to produce breakage of large branches, as well as snapping and uprooting of both hardwoods and softwoods (see Table 1). However, the photo shows two large hardwood trees in very close proximity to the house, yet they remain standing with most branches intact. Notably, the trees are both severely defoliated, suggesting that perhaps defoliation is an indicator of moderate winds within a tornado, yet defoliation is not currently considered within the DoDs for tree-focused DIs.

A similar situation is evident in Fig. 7. The damage to this house was rated EF2, yet the expected EF2 damage is clearly not evident on the large hardwood in the center of the photograph. In the case of either photo (Figs. 6 and 7), it is difficult to blame the discrepancy on the small-scale spatial variations within a tornadic circulation (and thus claim that the trees were far enough away that they were subjected to lower wind speeds), because in both cases aerial imagery shows that the trees are less than 5 m away from the houses. While the well-known small-scale variability within a tornado could certainly offer a plausible explanation in a minority of cases, it seems unlikely that the maximum wind speeds could vary over

FIG. 8. House with EF2 damage.

such small spatial scales in the majority of situations.

Finally, Fig. 8 shows the opposite pattern. In this situation, the house experienced EF2 damage, but the large tree to the far right, which is only 4 m from the corner of the house, was stubbed and partially debarked. These patterns of damage indicate EF3 winds given the DoDs in the EF scale. One notable observation is that debarking may be primarily a phenomenon of urban and residential areas. The authors have collectively examined thousands of trees across more than 15 tornado damage areas in forests and have rarely seen debarking.

The fact that the distinction between hardwoods and softwoods on the EF scale remains too general to capture the variability in tree strength across species is based on an extensive review that covered seven field studies encompassing 32 species and over 4000 inventoried trees (Peterson 2007). That review concluded that there exists some evidence that softwoods have greater vulnerability to wind than hardwoods, but that there is substantial overlap between the groups such that weaker hardwoods may well be more vulnerable than stronger softwoods. A separate line of evidence follows from recent results of a tree winching experiment on a softwood (loblolly pine) and a hardwood (tulip poplar) in central Georgia (Cannon et al. 2014). Winching generates the critical force at the base of a tree that is sufficient to cause either trunk breakage or uprooting. In this recent experiment, the critical turning moment for the softwood and hardwood trees was not significantly different. This is one of the only examples of a controlled experiment that demonstrates that the hardwood–softwood dichotomy may be overstated. Although averages across many species may produce group differences in trunk strength, the hardwood–softwood distinction offers little predictive ability for expected tree damage in any given location and for any individual storm. Most importantly, the distinction is not sufficiently well known to offer inferences of distinct wind speeds that would cause a particular degree of damage in the two groups.

Comparisons of tree damage with damage to one- and two-family residences (FR12) have the potential to address and mitigate all of the limitations to the existing tree-focused DIs discussed above. The plausibility of this approach stems from the fact that 1) these two objects often occur in close proximity, 2) both trees and houses are often abundant along tornado tracks, with dozens to hundreds of homes in a medium-sized tornado track and hundreds to tens of thousands of trees, and most importantly, 3) the engineering properties of homes are well understood, and while not infallible or perfect, meteorologists and engineers generally consider the EF-scale wind speeds inferred from FR12 damage to be robust.

4. METHODOLOGY

One method for accomplishing side-by-side comparisons of tornado damage to trees and to FR12 structures involves a detailed examination of ground photographs and remote imagery from multiple sources, along with damage assessments reported by National Weather Service (NWS) storm survey teams. The initial effort detailed here assesses home and nearby tree damage following the 20 May 2013 Moore, Oklahoma EF5 tornado. The approach for this tornado draws from five different types of imagery: 1) on-the-ground photographs from post-event damage assessments included with the National Weather Service Damage Assessment Toolkit (DAT), an experimental online application that contains detailed information on each damage point, including the DI and DoD for each; 2) oblique photographs from a helicopter commissioned by the NWS; 3) news media photographs available online, particularly those from USA Today; 4) Google Crisis Response maps, which include 15-cm resolution nadir aerial photographs acquired on 22 May 2013; and 5) pre-storm Google Maps Street View and Google Earth satellite imagery. Noting the EF-scale damage estimate and the geographic coordinates for selected FR12 structures available in the DAT, the authors gathered all relevant forms of imagery showing both the structure and nearby trees (e.g., in densely-packed residential neighborhoods, nearby trees might include the trees in the subject home's yard and adjacent yards). Inspection of the relevant imagery allows an assignment of tree damage levels into the following non-exclusive categories (i.e., a tree could exhibit more than one type of damage): defoliated, small branches broken (up to 1-in diameter), large branches broken (1–3-in diameter), trunk snapped, uprooted, debarked, and stubbed (i.e., all large branches removed leaving a trunk and stubs of major branches). A Google Earth pre-storm scene allows measurements of the minimum distance from the focal house to each focal tree.

5. PRELIMINARY ANALYSES

The following discussion illustrates the process of damage evaluation through an analysis of remote imagery. The large home shown in Fig. 9 is on South Olde Bridge Rd., just north of SE 4th Street in Moore, OK. This image captured from Google Earth shows the pre-storm condition of the structure. Figs. 9 and 10 have both been rotated 180° to match approximately the view of the newspaper photograph shown in Fig. 11. Note that the trees are quite visible in each image, including very small trees such as the two saplings just above the driveway (not numbered).

The image shown in Fig. 10 is a 15-cm resolution aerial nadir photograph obtained from the Google Crisis Response site. The extensive roof damage evident in this image led the NWS damage assessment team to rate the damage to this home as EF1 (i.e., uplift of roof deck and loss of significant roof covering material). The trees lying on the ground after snapping or uprooting show up clearly and their damage is readily apparent, but the fate of other trees (e.g., the small trees labeled 1 through 4

FIG. 9. Pre-storm image of a residential structure. Numbered labels refer to the individual trees listed in Table 2. Image source: Google Earth.

FIG. 10. The same structure shown in Fig. 9 captured from a 15-cm resolution aerial photograph. Image source: Google Crisis Response.

below the driveway) is more difficult to discern.

Fig. 11 shows a publicly-available photograph published by USA Today. This is an oblique image, looking roughly from the bottom and slightly to the right of the images shown in Figs. 9 and 10. Note that the disposition and condition of several of the trees are much more readily apparent in this image than in the post-storm aerial photograph shown in Fig. 10.

Table 2 shows an example of the key information acquired from an analysis of the imagery in Figs. 9 through 11. Note that several trees were stubbed, but not debarked, though the present EF-scale DoD presents these two types of damage together, thus not allowing them to be recorded separately. Note that while all of these trees are near the same FR12 structure that received a damage rating of EF1, the nearby trees exhibit a broad range of levels of damage.

FIG. 11. The same structure shown in Fig. 9 captured from a helicopter. Image source: USA Today.

Table 3 shows a summary of the information collected on 34 residential homes and 62 nearby trees (i.e., within 15 m) following the approach outlined above. Several trends immediately stand out in this modest sample. First, stubbed trees overwhelmingly appear in the vicinity of homes with damage rated EF4 and EF5 and not, as implied by the existing DIs, near homes with damage rated EF2 or EF3. The same trend exists for debarked trees, and although not apparent in Table 3, a number of trees were stubbed or debarked but not both, suggesting that these two types of damage occur independently from one another. Snapping of tree trunks was not observed at all near homes with damage rated less than EF3 and most of the uprooting is also seen near homes with a rating of EF3 or greater. The relative abundance of both snapping and uprooting as a mode of tree failure gives no indication that snapping results from higher wind speeds than uprooting. Puzzlingly, of the four trees near homes with damage rated EF5, none were either snapped or uprooted, though all were debarked and most were stubbed. If snapping and uprooting occur at lower wind speeds than stubbing and debarking, then the stubbed and debarked trees would not remain standing. This cursory analysis of a very modest sample size clearly indicates that 1) several of the DoDs for tree-focused DIs need modifications and 2) this approach does indeed provide a valid mechanism for accomplishing the specific goal of improving the tree-focused DIs.

6. DISCUSSION

The approach outlined here is fast, inexpensive, and relies upon easily-accessible data, though it suffers from two main shortcomings. First, limitations to photographic image resolution, focus, or the photographer's angle may limit the proportion of trees in a particular image that can actually be classified into damage categories [see Brown et al. (2012) for broader consideration of image resolution issues]. Sometimes, fewer than half of the trees in an image (e.g., three or four trees out of 10 in a particular image) can be classified into damage categories. Secondly, the remote imagery approach does not allow identification of tree species with high confidence and can be so limited that anything more than very coarse size classifications would be difficult (e.g., small trees versus large trees). A second potential approach involves on-site inspection and measurement of trees near tornado-damaged homes. This would allow far greater

TABLE 2. Sample damage classification of trees visible in Figs. 9–11. Damage categories are not mutually exclusive (e.g., a tree could be both stubbed and debarked). Note that damage to small and large branches is combined here to facilitate analysis.

Tree	Intact/Standing	Defoliated	Branches Broken	Uprooted	Snapped	Stubbed	Debarked
1						✓	
2						✓	
3						✓	
4						✓	
5		✓	✓				
6					✓		
7					✓		
8	✓						
9			✓				
10				✓			
11						✓	

accuracy in the identification of tree species, direct measurements of tree sizes, and inclusion of most or all of the potential study trees. This second approach is slower and more expensive than the first and is limited by concerns with safety and property access. However, employing these two approaches in combination could overcome most of these limitations and would allow for the development of a large database of trees and houses.

Together, these two data collection methods have the potential to tackle a variety of unanswered questions that, when answered satisfactorily, could facilitate updates and improvements to the tree-focused DIs of the EF scale as called for in Blanchard (2013) and Edwards et al. (2013). First, the data collection and analysis approach can document whether or not consistent and substantial differences exist between the observed damage to hardwood and softwood trees as implied by the current EF-scale DIs. If such differences do exist, then the present hardwood–softwood distinction on the EF scale will gain an objective, quantitative foundation for its continuance. Otherwise, this work would provide an unbiased basis for the discontinuation of this distinction in the EF scale. Second, this approach would allow statistical tests for, and identify the nature of putative differences in, DoD between tree sizes and between tree species. If future results indicate that such differences are substantial and robust, then such findings would provide the basis for the implementation of guidelines aimed toward the inclusion of tree size and species in revisions of the EF scale. Third, this approach could quantitatively document the range and distribution of DoDs for trees in close proximity to residential structures with known EF-scale damage ratings. This would allow a direct evaluation of the inferred wind speeds that produce particular levels of tree damage, but categorized by tree size and tree species.

An expanded analysis employing the methods described here could result in a consistent and objectively-defined set of DoDs for the tree-focused DIs of the EF scale. These would provide greater consistency across geographic regions and among NWS offices, as well as a more defensible basis for the EF-scale ratings obtained by damage assessment teams. Wider use of trees in storm surveys would greatly widen the spatial coverage of damage assessments and would invite greater use of remote imagery, thereby limiting in-person field surveys and yielding significant time and cost savings.

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TABLE 3. Number of trees assigned to each damage classification for trees in the path of the 20 May 2013 EF5 tornado in Moore, OK, grouped by corresponding level of damage to the nearby house. Note that damage categories are not mutually exclusive.

EF-Scale Rating (n)	Trees	Intact/Standing	Defoliated	Branches Broken	Uprooted	Snapped	Stubbed	Debarked
EF1 (5)	8	7	3	2	1	0	0	0
EF2 (5)	6	5	4	3	1	0	1	1
EF3 (8)	22	12	7	5	3	7	1	5
EF4 (14)	22	11	15	0	4	7	3	4
EF5 (2)	4	4	2	0	0	0	3	4

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