



Geomorphological impacts of a tornado disturbance in a subtropical forest



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ABSTRACT

We studied tree uprooting associated with an EF2 tornado that touched down in portions of the Ouachita Mountains in western Arkansas in 2009. In the severe blowdown areas all trees in the mixed shortleaf pine–hardwood forest were uprooted or broken, with no relationship between tree species or size and whether uprooting or breakage occurred. There was also no significant relationship between tree species and amount of soil displaced, and only a weak relationship between tree size and rootwad size. Uprooting resulted in a mean bioturbation rate of $205 \text{ m}^3 \text{ ha}^{-1}$ (about 240 t ha^{-1}). Direct transfer of wind energy via tree uprooting to geomorphic work of soil displacement was about 75 to 190 J m^{-2} . Given the infrequency of tornadoes, this energy subsidy is minor with respect to the long-term energetics of pedogenesis and landscape evolution. However, it does represent a highly significant pulse of geomorphically-significant energy relative to other mechanical processes. Tornadoes such as that of April, 2009—not atypical for the region—are disturbances causing severe, non-selective impacts within the affected area. At a broader, landscape scale, tornadoes are highly localized disturbances, and occur infrequently within any given landform element or forest stand. Only about a third of the uproots revealed root penetration of bedrock, compared to about 90% in other areas of the Ouachita Mountains. This is attributable to the thicker colluvial soils at the study site, and is consistent with the idea that root–bedrock interaction is more likely in thinner regolith covers.

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1. Introduction

Meteorological events such as tornadoes, tropical cyclones, and ice storms are important disturbances in forests and other ecosystems. The effects of such events—such as tree uprooting—on soils and landforms, as well as on vegetation and ecological dynamics, are increasingly acknowledged as critical on a variety of timescales. The purpose of this paper is to explore the geomorphic impacts of a tornado blowdown event that occurred in western Arkansas, USA, in 2009.

Geomorphic and pedologic impacts of a 2006 tornado in the same general region were examined in a previous paper (Phillips et al., 2008a). In this paper we add to the database on the effects of tornadoes and other large wind events on forest environments. Contrasts in topographic setting, soil cover, and forest vegetation structure in comparison with the earlier study also enable a more detailed investigation of the

interactions among soil, landform, and ecological factors. In addition, this paper takes a more detailed look at the effects of this event in the context of the energy subsidies and of the role of meteorological disturbances in geomorphology.

In recent years there have been several attempts to develop a more explicit incorporation of the biological energy “subsidy” to pedological and geomorphological processes. Volobuyev (1964, 1974) made important early contributions, but these were largely ignored until recently (c.f. Rasmussen et al., 2005, 2011; Rasmussen and Tabor, 2007; Minasny et al., 2008; Phillips, 2009a). Geomorphologists have also increasingly recognized the important biomechanical effects of vegetation. Effects of organisms on soils and geomorphic processes have long been recognized, but the emphasis was on biological and chemical effects on pedogenesis, and the relationship between vegetation cover and surface erosion. More recently, however, soils and regoliths have come to be regarded as more or less continually mixed biomantles, and geomorphologists have emphasized the direct and active (vs. indirect and passive) geomorphic roles of biota (see reviews by Wilkinson et al., 2009; Pawlik, 2013). This paper is specifically concerned with the role of disturbance events in bioturbation.

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2. Background

2.1. Tornado climatology

North America experiences far more tornadoes than any other continent, and these generally small but intense cyclonic storms are not uncommon in Arkansas. The study area (Fig. 1) is covered by two radar stations, at Little Rock and Fort Smith, AR. The Little Rock coverage area has averaged 36 tornadoes per year since 1980 (National Weather Service, 2007). The Little Rock and Fort Smith coverage areas have return intervals of 1954 and 1853 years, respectively, ranking 13th and 10th out of the 141 radar coverage areas within the conterminous United States in the probability of tornadoes per year, both with respect to any tornado, and severe (enhanced Fujita scale of EF2 or greater) tornadoes (National Weather Service, 2007). Note that the return intervals apply to any given 40 km² grid within the radar area; probabilities of occurrence somewhere within the region are much higher.

In April the probability of a tornado occurring on a given day somewhere in the 90°–106° W longitudinal belt of North America that includes the study area is 39%, and 68% in May, the two most active months (Barrett and Gensini, 2013), with likelihoods varying according to phases of the Madden–Julian oscillation. According to Brooks' (2003) analysis of data for 1980–1999, any given location in the Ouachita Mountain region experienced an average of one day per year where a tornado touchdown occurred within a 40 km radius (an area of 5027 km²). Data from 1921 to 1995 indicates 20 to 25 days per century with tornadoes of severity F2 (Fujita scale) or greater, indicating wind velocities > 180 km h⁻¹ (Brooks, 2003). Arkansas as a whole has an annual mean of 4.3 tornadoes per 26,000 km² (10,000 mi²), or one a year for each 6047 km², according to data for 1953–2004 (NCDC, 2006).

Polk County, which includes the study area, experienced 27 tornado touchdowns from 1980 to 2012, according to the U.S. Storm Prediction Center database (<http://www.spc.noaa.gov/wcm/#data>). Multiple tornadoes are sometimes associated with a single outbreak, so the record includes 18 days with tornadoes, including three on 9 April 2009. Ten of the 27 tornadoes were rated F2 or EF2. Those had estimated widths ranging from 27 to 732 m (mean = 261 m), and path lengths of 0.8 to 67.6 km (mean = 33 km). This implies ground influence areas of 0.02 to 27.21 km² (mean = 8.51 km²). However, these must be taken as

maximum estimates, as tornadoes do not always maintain continuous contact with the land surface. The tornado responsible for the forest damage studied in this project was rated EF2, and is recorded in the U.S. National Severe Storms Laboratory database as having a length of 10.7 miles (17.2 km) and a width of 800 yards (732 m).

An estimated recurrence interval for an EF2 tornado of about 2000 years (National Weather Service, 2007), and a mean influence area of 8.51 km² imply ground disturbance of about 4250 m² yr⁻¹ (for reference, the total land area of Polk County and adjacent areas affected by the same tornadoes is about 2500 km²).

In addition to uncertainties in the tornado data (see Brooks, 2003) these estimates do not account for climate and vegetation change, magnitude/frequency relationships between storm intensity and influence area, or local variations in tornado strike probabilities within Arkansas or the Ouachita Mountains. However, the estimates are conservative, due both to the under-reporting of tornadoes in thinly populated areas (and before widespread use of radar technology), and to the fact that EF2 storms represent only 37% of tornadoes in the study area in the database.

2.2. Tree vulnerability to tornado damage

Ice storms and other factors may cause uprootings, but wind is the most common cause. Peterson (2007) focused specifically on tornadoes, including data from nine North American blowdown sites. Consistently positive relationships were found between tree diameter and the likelihood of blowdown, and uprooting was found to be more common than trunk breakage.

Interspecific variations in wood strength, rooting habit, branch and leaf architecture and other factors can lead to differences in vulnerability to uprooting and wind damage, as illustrated by the pronounced differences in tornado damage for two species of oak (*Quercus stellata*, *Quercus marilandica*) in the Cross Timbers area of Oklahoma (Fumiko et al., 2006). Hurricane wind damage in east Texas revealed that only nine of 27 canopy species had a statistically significant positive relationship between mortality and diameter, and one had a negative relationship (Harcombe et al., 2009). Xi et al. (2008) found that tree damage risk factors vary with spatial scale in North and South Carolina forests. Based on damage from one tornado and two hurricanes, they found that tree

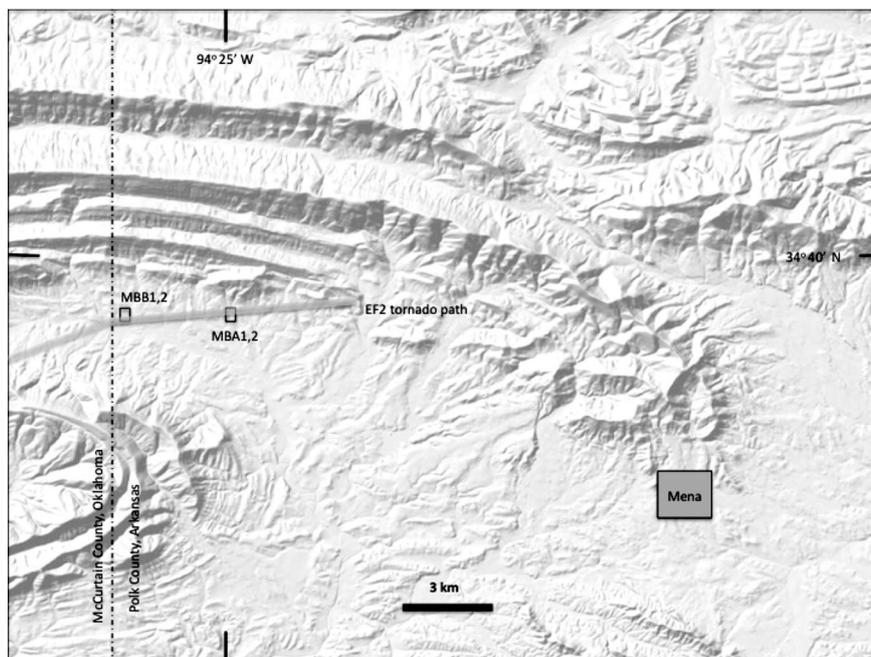


Fig. 1. Study areas (MBA transects 1 and 2; MBB transects 1 and 2) shown in relation to regional topography and path of the tornado responsible for the blowdowns.

size and species are most important at the stand scale, while topography and site characteristics are the dominant explanatory factors at the landscape scale. At a regional scale, meteorological factors such as the size, intensity, path, and duration of the storm are most important. Further, they found that differences between species exist, but that these were not consistent among studies (Xi et al., 2008).

2.3. Conifers vs. hardwoods

Mixed pine–hardwood forests dominate in the Ouachita Mountain study area, so contrasts between conifers and hardwoods in susceptibility to wind damage is of particular interest. Peterson's (2007) synthesis shows some tendency for conifers to be more vulnerable than deciduous trees, though the relationship is weak. Xi et al. (2008) found that *Pinus taeda* had high damage risk in a tornado study, but low damage levels in several hurricane studies. Tornadoic winds are both stronger, with much greater shear, and have substantially less duration than hurricane and other straight-line winds. The flexibility of pine boles may allow them to bend in hurricanes, but break in the abrupt wind shear of tornadoes. Deciduous trees, by contrast, may more readily absorb drag force by extended hurricane winds (Xi et al., 2008). Note that tropical cyclones systems such as hurricanes may also generate tornadoes, and that assessment of hurricane wind damage in forests may not distinguish between them.

In coastal plain environments pines may be less susceptible to uprooting than hardwoods due to the tendency of deeper *Pinus* taproots to favor breakage rather than tree throw. However, in shallow soils this relative advantage is negated. In the present study area all common trees have a taproot-style root architecture, and rooting depth of all trees tends to be limited by soil thickness (Phillips and Marion, 2006).

In their study in the Ouachitas, Phillips et al. (2008a) found that all uprooted trees were shortleaf pine (*Pinus echinata*), while all trees left standing in the most severe blowdown areas were hardwoods. Trunk breakage included both pines and deciduous hardwoods, but 70% of severely damaged trees were uprooted as opposed to suffering broken trunks. The characteristic diameters of the surviving deciduous trees were similar to that of the uprooted pines. Phillips et al. (2008a) speculated that due to the late fall timing of the storm the greater leaf area of the pines may have played a role in the disparity, but the explanation based on trunk flexibility proposed by Xi et al. (2008) also seems plausible.

2.4. Turnover time

Forest blowdowns may be quite localized, and the frequency and areal coverage of tree uprootings due to wind vary widely. However, uprooting by wind is significant over long time scales in many forest environments. The estimated turnover time for canopy destruction (the mean time period in which an area equivalent to the entire canopy would be destroyed by uprooting) varies over at least an order of magnitude (about 100 to 2500 years) in various studies in North America, Europe, Asia, and New Zealand (e.g., Šamonil et al., 2013; Schatzel et al., 1989; Ulanova, 2000; Vasenev and Targul'yan, 1995). This suggests the need to couple measurements of pedologic and topographic effects of treethrow with consideration of the climatology of blowdown events. Scatena and Lugo (1995) took this approach in their study of uprootings from a hurricane in Puerto Rico, estimating the forest turnover period due to hurricane blowdowns as 380 years.

With respect to tornadoes, the limited spatial extent must also be considered. In western Arkansas, the probability of a tornado occurrence within a 40 km radius of any given location was combined with the mean "footprint" or diameter of the storm and mean path length by Phillips et al. (2008a), to estimate a mean influence area based on the tornado climatology of Brooks (2004). This suggests that any given point would be disturbed by a tornado, on average, once every 14.4 ka.

2.5. Pedogeomorphic effects

Šamonil et al. (2010a,b) and Pawlik (2013) reviewed the pedological and geomorphological effects of uprooting. Wind damage to trees includes trunk breakage as well as uprooting, and less severe damage that may result in tree mortality within a year or two. The tree damage in turn has pedological and geomorphological impacts due to the bioturbation and topographic modifications associated with uprooting and infilling of stumpholes. Studies of biomechanical effects of trees on soil and geomorphology have focused almost exclusively on uprooting, though mass displacement by tree growth and infilling of pits created by decay or burning of dead trees and stumps are also significant (Phillips and Marion, 2006). The latter is certainly relevant to tornado-damaged forests.

Uprooting is in general more likely in shallower and wetter soils, or where restrictive horizons limit root penetration (Mueller and Cline, 1959; Schatzel et al., 1989, 1990; Ulanova, 2000). However, the size of trees seems to be more important than soil characteristics with respect to both the likelihood of uprooting and the amount of soil disturbed (Mueller and Cline, 1959; Peterson, 2007). In the previous Ouachita tornado study, tree diameter explained about half the variation in the amount of soil uprooted (Phillips et al., 2008a).

Vasenev and Targul'yan (1995) suggested that following uprooting-related perturbations in soils, pedogenesis in some cases returned to the pre-existing background soil, but in other cases the changes persisted. Ulanova (2000) related this difference to the depth of uprooting. When uprooting is shallow, soils may approach the morphology of undisturbed soils in less than 200 yr. Deeper uprootings, however, result in semi-permanent changes in soil morphology (Ulanova, 2000). Pawlik's (2013) review showed that severe wind events may, through uprooting, disrupt regolith sufficiently to obscure signatures of earlier pedologic and geomorphic regimes, and Šamonil et al. (2011) and Valtera et al. (2013) directly linked forest disturbances such as wind storms to soil spatial patterns. These studies thus indicate that uprooting can result in persistent pedological signatures. Treethrow microtopography can persist in some cases for up to 6 ka (Šamonil et al., 2013), suggesting that associated pedologic impacts can persist for comparable periods. Spatial patterns of soil that reflect forest disturbances (e.g., Šamonil et al., 2011; Valtera et al., 2013), suggest either pedological memory of disturbance effects, or disturbance recurrence intervals less than pedological relaxation times.

Uprootings provide an opportunity to observe tree root interactions with underlying regolith and bedrock. Biogeomorphic effects of trees are closely related to root penetration of bedrock at the base of the regolith, which facilitates weathering and regolith formation, and also "mining" of bedrock by uprooting (Cochran and Berner, 1996; Frazier and Graham, 2000; Lutz, 1958; Ollier and Pain, 1996; Phillips et al., 2008b; Rossi and Graham, 2010; Stone and Comerford, 1994; Vepraskas et al., 1991). Root penetration of bedrock is an important indicator of soil/regolith deepening by a combination of biomechanical and biochemical activity (c.f. Johnson, 1985; Phillips et al., 2005), as well as an indication of the likelihood that the effects of uprooting on soil morphology are likely to persist (Ulanova, 2000). The rootwads of trees uprooted in the 2006 tornado showed that in 93% the roots penetrated bedrock and "mined" bedrock fragments during uprooting (Phillips et al., 2008a).

3. Study area and methods

3.1. Environmental setting

Study sites are 15 to 21 km WNW of Mena, AR and within the Ouachita National Forest, which covers much of the Ouachita Mountains of western Arkansas and eastern Oklahoma (Fig. 1). The Ouachitas are a series of roughly parallel, east–west trending ridges with intermontane basins. The blowdown sites used are generally along the side of one of

the major valleys. The climate is humid subtropical. Mean annual precipitation in Mena is 1350 mm, occurring primarily as rain during warm-season thunderstorms or fall and winter frontal events. Precipitation occurs throughout the year, with the maximum usually occurring in the spring.

Geology is characterized by extensively faulted and folded Paleozoic sedimentary rocks (Stone and Bush, 1984). The strata are typically alternating layers of sandstone and shale (Jordan et al., 1991), with lesser amounts of quartzite, novaculite, and chert. Sample sites are underlain by the Mississippian Stanley Formation. Exposed shales are deeply weathered and highly erodible, whereas the sandstones are noticeably less altered and more durable. Ridgetops are composed of the more resistant sandstones, quartzites, and novaculites. Side slopes are often underlain by shale, with sandstone outcrops common. Soils in the region are predominantly Hapludults, generally characterized by loam to sandy loam A horizons overlying silty clay loam or finer B horizons. Rock fragment contents are often high.

The vegetation cover of the blowdown sites was a mixed shortleaf pine (*P. echinata*) and hardwood forest, which is common in the region. The larger pines generally had a diameter at breast height (DBH) of 30 to 40 cm, with a few >50 cm. The hardwoods are dominated by oaks (*Quercus* spp.) but include a variety of species. The largest hardwoods have DBH > 40 cm.

3.2. April 2009 tornado

Tornadoes struck a number of locations in the south-central and southeastern U.S. on 9–10 April 2009. The storm system spawned 85 confirmed tornadoes in Arkansas and 10 other states. According to the synoptic storm report (National Weather Service, 2009), on 9 April a low pressure system approached western Arkansas, with a strong dryline (air mass boundary characterized by a strong humidity contrast). The system approached as the atmosphere destabilized due to local convection in the heat of the afternoon, triggering thunderstorms along the dryline in eastern Oklahoma. Storms became more numerous as the system entered Arkansas, and encountered a strong mesoscale wind system. This created strong wind shear, creating mesocyclones which spawned isolated tornadoes.

An EF2 tornado affected forest areas north and west of Mena, and a stronger storm (EF3) tracked through Mena. The first, which occurred at about 19:30 local time, had a path length of about 17 km. The storm path of the EF2 tornado relative to the study sites is shown in Fig. 1. Trace amounts of rain were recorded in Mena on 5 and 9 April, but the last significant precipitation (13 mm) occurred a week earlier. Thus soils were not unusually wet at the time of the storm.

3.3. Methods

Ouachita National Forest personnel assessed forest damage soon after the storm, and produced a spatial dataset with the locations and the areas of tornado blowdown on National Forest land. No aerial photography was conducted, but we reconnoitered the blowdown areas in the field. From these observations, two areas were selected as typical of the severe blowdown areas, designated MBA and MBB (Mena Blowdown areas A and B). Within these, two transects each were established. For each transect a random starting point was selected. The transect line was then oriented from that starting point to cross the middle of the blowdown area, and continued across the entire severe blowdown area. One exception was transect MBB1, where length was limited by the time available for the field work. Both transect endpoints were mapped using a global positioning system receiver.

Along each transect, the rootwad of any uprooted tree (Fig. 2) was examined if any part of the rootwad fell within 5 m of the transect centerline. Thus the transects were 10 m wide. Following earlier practice (Phillips et al., 2008a) rootwad size was measured using a folding ruler and/or measuring tape to determine the mean length and width



Fig. 2. Typical rootwad along transect MBA2.

of the original soil surface area, and the mean thickness of the uprooted material (Fig. 3). This was accomplished by taking several measurements and computing and recording a mean value in the field. The number of measurements varied according to the complexity of the rootwad geometry. From these the surface area (mean length times mean width) of soil disturbed and total volume (surface area times mean thickness) of soil moved was estimated. The maximum depth of coarse (diameter > 1 cm) root penetration was also determined. Soils were classified to the series level in the field based on soil morphology observed in the rootwads and pits. The presence of fresh, apparently unweathered bedrock displaced by uprooting, and whether any apparent root turning had occurred, was determined following procedures described previously (Phillips et al., 2008a). The parent material or underlying material was recorded from observations of the uprooting pit, or from excavations into the pit bottom using a soil auger.

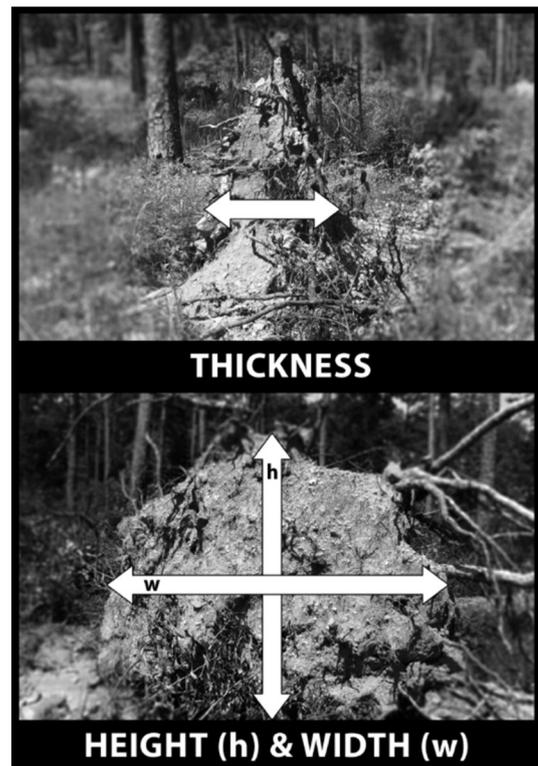


Fig. 3. Illustration of rootwad measurements.

All trees whose rootwads were sampled, and those where any part of the trunk fell within the 10-m wide sample swath, were identified to the species level. Trunk diameters were measured using a dendrological tape about 1.37 m (4.5 ft) above the tree base (DBH).

4. Results

4.1. Uprooting, breakage, and tree species

A total of 248 trees with DBH ≥ 10 cm had part of their fallen or broken trunk and/or rootwads intersecting the sample transects. No trees of this size on the transects escaped damaged by uprooting or trunk breakage. Of these, 156 (65.3%) were shortleaf pine (*P. echinata*), and 43 (22.6%) were oaks (*Quercus* spp.), principally white oak (*Quercus alba*). Other trees, all hardwoods, comprised in total slightly more than 13% of the sampled trees. These include hickory, elm, red maple, and sweetgum (*Carya* spp., *Ulmus* spp., *Acer rubrum*, and *Liquidambar styraciflua*, respectively).

Of the 248 affected trees, almost 77% were uprooted (190). Most of these had rootwads outside the sample transects, with the uprooted trunks falling across the transects. Fifty-two trees (27%) had rootwads within the transect. The remainder were broken (58 trees; 23.4%). In most cases breakage occurred <2 m above the ground surface.

The prevalence of shortleaf pine among the uprooted trees is slightly higher, and the proportion among broken trees slightly lower than for the sampled trees as a group (Table 1), but a chi-square test indicates that this difference is not statistically significant ($p > 0.05$). There was also virtually no difference in size (DBH) between the uprooted vs. broken trees.

4.2. Bioturbation

A total of 52 rootwads were examined along the four transects, as summarized in Table 2. Overall, surface areas of uprooted soil represented a mean of $247 \text{ m}^2 \text{ ha}^{-1}$, or slightly less than 2.5% of the surface area. The area disturbed was relatively consistent among transects, ranging from 205 to $265 \text{ m}^2 \text{ ha}^{-1}$ (Table 2). This represents a minimum disturbance area, as the resulting mound-pit topography often occupies an area up to about twice the surface area of the uprooted soil mass.

Bioturbated volume was more variable among transects, ranging from 90 to $474 \text{ m}^3 \text{ ha}^{-1}$ (mean = $205 \text{ m}^3 \text{ ha}^{-1}$). Bulk density of regolith in the study area ranges from $>2 \text{ t m}^{-3}$ for weathered rock to about 1.2 t m^{-3} for some soil horizons (Olson, 2003). For purposes of rough calculations of mass based on volume we assumed a conservative soil bulk density of 1.2 t m^{-3} . This amounts to about 240 t ha^{-1} of bioturbated mass (ranging from 108 to 569 t ha^{-1} in individual transects).

Though statistically significant, the dependence of rootwad size on tree diameter is not as strong as might be expected (Fig. 4). The relationship is stronger for surface area than for rootwad volume or maximum depth of coarse roots. This suggests that the depth of rooting is strongly influenced by factors other than tree size. Data represented in Fig. 4 are not normally distributed, and the regression lines shown are to assist visual interpretation. Spearman's Rho correlation coefficient, a non-parametric statistic suitable for non-normal distributions, was computed for the relationships between tree size (DBH) and rootwad surface area, volume, and maximum penetration of coarse roots. The values

Table 1
Tree types and diameter at breast height (DBH) of uprooted trees sampled.

	Total	Uprooted	Broken
Shortleaf pine	156 (62.9%)	124 (65.3%)	32 (55.0%)
Oak (e.g., white oak)	59 (23.8%)	43 (22.6%)	16 (27.6%)
Other	33 (13.3%)	24 (12.6%)	10 (17.2%)
DBH mean (cm)	31.9	31.9	32.0
DBH standard deviation (cm)	13.7	13.2	15.4

Table 2
Summary of sampled uprooted tree rootwads.

	MBA1	MBA2	MBB1	MBB2	Total	2006 ^a
Transect area (m^2)	1310	770	670	600	3350	
Total rootwads	16	10	11	15	52	
Uproots ha^{-1}	122	129	164	250	155	120
Rootwad surface area (m^2)	33.72	15.78	31.76	12.32	83.68	
Rootwad volume (m^3)	31.86	13.77	17.78	5.38	68.79	
Mean surface area (m^2)	2.11	1.58	2.89	0.82	1.59	3.18
Mean volume (m^3)	1.99	1.38	1.62	0.36	1.32	2.06
Density ($\text{m}^2 \text{ ha}^{-1}$)	257	205	265	205	247	380
Density ($\text{m}^3 \text{ ha}^{-1}$)	243	179	474	90	205	243
Bioturbated mass ^b (t ha^{-1})	365	268	711	134	240	365

^a Results from study of 2006 tornado blowdown (Phillips et al., 2008a).

^b Assuming bulk density of uprooted soil of 1.2 t m^{-3} .

are 0.68, 0.52, and 0.51, respectively. These are statistically significant at $p < 0.001$, and indicate a positive association between tree size and rootwad area and volume and maximum coarse root depth. However, as Fig. 4 shows, significant variation in rootwad size is not explained by DBH.

As indicated earlier, uprooted trees included both *P. echinata* and deciduous hardwoods, particularly oaks (*Quercus* spp.). Of the 52 uprooted trees where the rootwads were examined in detail, 12 were hardwoods. These generally had slightly smaller diameters than the pines (mean DBH = 33.4 vs. 36.2 cm), and slightly larger rootwad surface areas and volumes (means of 2.0 m^2 and 1.7 m^3 , respectively, vs. 1.7 m^2 and 1.2 m^3 for pines). The hardwoods also had an average maximum rootwad depth of 100.5 cm, as opposed to 89.3 cm for pines. However, Mann-Whitney U-tests showed that none of these differences are statistically significant ($p > 0.05$).

There is no obvious explanation for the five outliers that appear in all three plots in Fig. 4 (and are most apparent in Fig. 4b). Three of the outliers are shortleaf pine and two are oaks. All are found in soils formed in colluvial or old alluvial soils overlying shale, which potentially facilitates deeper rooting compared to thinner soils over bedrock. However, this also applies to many of the non-outliers. The outliers are apparently associated with greater rootwad thickness—they represent five of the six samples where rootwad thickness is >1 m.

4.3. Soils

Soils observed at the field sites are listed in Table 3. Soils at both ends of transect MBA1 were residual soils derived from weathering of underlying, mainly shale bedrock (Bengal series, or a Bengal/Bismarck/Nashoba complex or intergrade). The other soils ($>70\%$ of the transect) were of the Mena series, which is formed in old terrace alluvium. While the topographic setting does not make the terrace origin obvious, the presence of abundant rounded gravels in these soils attests to an alluvial or at least slopewash source. MBA2 was also dominated by soils formed from old alluvium; the Wilburton series (60% of the transect). As compared to the Mena series, the Wilburton is slightly coarser in texture, and the non-alluvial bedrock is deeper below the surface. Other soils on this transect included the Octavia and Bengal series.

Transect MBB1 was entirely residual soils, mainly formed from weathered shale or interbedded shale and sandstone. Series, in order of importance, were Sherless, Carnasaw, Bonnderdale, Littlefir, and Clebit. The Sallisaw series, another soil formed in old terrace alluvium (again identified by rounded gravels), was the only series observed on MBB2.

4.4. Root penetration

The average maximum depth of root penetration for MBA1 was about 115 cm (range: 55 to 188 cm; standard deviation: 42.8 cm). Only one of 17 rootwads along this transect indicated root penetration to intact bedrock. In six cases roots exposed by uprooting penetrated a

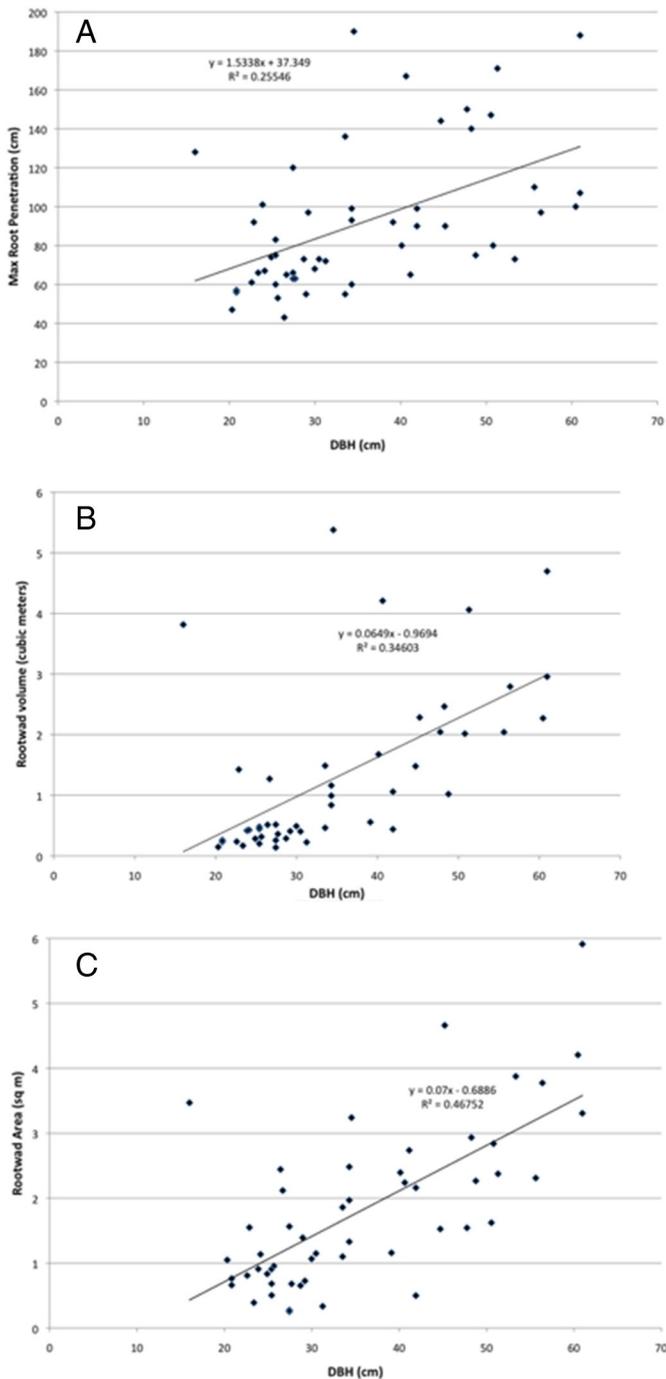


Fig. 4. Relationships between tree diameter at breast height (DBH) and rootwad size: A, thickness or maximum coarse root penetration; B, surface area; and C, volume. Regression relationships are shown to facilitate visual interpretation only, as the data are not normally distributed.

weathered shale horizon (Cr), and in the other 10 instances only a B horizon was exposed. Maximum depths ranged from 47 to 190 cm in MBA2 (mean = 88; standard deviation = 43.8). Of the 10 uprooted trees along MBA2, rootwads exposed one R (bedrock) horizon, one Cr, and one C horizon. In the other seven maximum coarse root penetration was to a Bt horizon.

In transect MBB1, the depth of maximum coarse root penetration based on observations of the rootwads ranged from 43 to 144 cm, with a mean of 85 cm ($N = 11$; standard deviation = 30.5 cm). In six cases coarse roots extended into a Cr horizon, in two cases bedrock (R horizon), and in three others a C horizon. No root penetration to intact

bedrock was observed in rootwads along MBB2. In 13 of 16 MBB2 cases maximum coarse root penetration was to a Bt horizon, in the others it was to a C or Cr. Mean depth of root penetration and variability were both lower on this transect than on the other three (mean = 75 cm; standard deviation = 13.0 cm).

On both MBB transects, where maximum coarse root penetration extended only into B horizons, the soils were those formed in colluvial or alluvial parent material (Sallislaw, Mena, and Wilburton series). In most cases root penetration into a Cr horizon (and all four into an R horizon) was on soils formed in weathered bedrock (as opposed to colluvium or alluvium). However, a few of the rootwads in the Mena and Sallisaw series also had coarse roots to weathered bedrock.

Evidence of root turning due to unfractured bedrock was rare, with only two cases observed, neither involving the entire root plate.

4.5. Energy subsidy

The total soil mass displaced by tornado blowdown amounts to a conservatively estimated mean of 240 t ha^{-1} , or 24 kg m^{-2} . Mean thickness of the rootwads is 0.65 m, implying a mean vertical mass displacement (assumed to be half the subsurface to surface movement) of 0.32 m. Considering also the mean displacement above the surface, given by half the rootwad width of 1.03 m, adds another 0.51 m.

Potential energy is given by

$$PE = mgh, \quad (1)$$

where m is the mass, g the gravity constant, and h the height or elevation above a base or reference level. Thus the potential energy associated with displacing 24 kg a distance of 0.32 m amounts to 75 J m^{-2} , and a distance of 0.83 m (considering both subsurface to surface movement, plus mean height above the surface) to 190 J m^{-2} . This represents a transfer of tornadic energy directly into mass displacement.

5. Discussion

5.1. Disturbance

Some ecological and geomorphological disturbance events are selective, while others are indiscriminate. Windthrow in forests due to all but the strongest straight-line wind events is selective, resulting in uprooting (or breakage) of the most vulnerable trees, and sparing others. Vulnerability is affected by tree species, size, and health, topography, and soil characteristics. Tornado windthrow is often indiscriminate, as in the severe blowdown study areas, with many or all (as in this case) trees damaged within the core of the tornado touchdown zone. On the other hand, hurricanes and other large cyclonic storm systems influence much larger areas, but are more selective in that fewer trees per unit affected area are damaged (Harcombe et al., 2009; Peterson, 2007; Phillips et al., 2008a,b; Scatena and Lugo, 1995; Ulanova, 2000). Thus tornadoes, as opposed to other wind storms, are smaller in terms of spatial extent but more intense in terms of forest (and associated geomorphic and pedological) impacts per unit area.

Geomorphic disturbances can be assessed in terms of frequency, magnitude, duration, areal extent, speed of onset, spatial dispersion, and temporal spacing, based on White's (1974) framework for analysis of natural hazards, and adapted to geomorphological disturbances by Gares et al. (1994) and Phillips (2009b). This framework is applied to tornadic and straight-line wind disturbances in Table 5. In general, tornado disturbances are rarer, shorter duration, and more localized than other windthrow events. While there are clear commonalities in the mechanics and impacts of tree uprooting or breakage regardless of the cause, it is clear that tornadoes are distinctly different types of disturbance from other wind-driven uprooting events. Further studies linking geomorphic disturbances to disturbance climatology would likely

Table 3
Soil types observed at field sites.

Soil series ^a	Taxonomy ^a	Comments
Bengal	Typic Hapludults	Colluvium overlying weathered shale
Bengal/Bismarck/Nashoba	Typic Dystrudepts/Typic Hapludults intergrade	At field sites, appears to be derived from a complex mixture of lithologies
Bonnerdale	Aquic Hapludults	Somewhat poorly drained; formed from interbedded shale/sandstone
Carnasaw	Typic Hapludults	Residual, formed from weathered shale
Clebit	Lithic Dystrudepts	Shallow, overlying sandstone
Littlefir	Oxyaquic Hapludults	Formed from tilted, fractured, folded strata of various lithologies; somewhat poorly drained
Mena	Aquic Paleudults	Formed in old alluvium
Octavia	Typic Paleudults	Colluvium overlying weathered shale
Sallisaw	Typic Paleudalfs	Formed in old alluvium
Sherless	Typic Hapludults	Residual, formed from interbedded shale/sandstone
Wilburton	Ultic Hapludalfs	Colluvial/alluvial parent material

^a U.S. Soil Taxonomy.

provide further distinctions among various synoptic types of meteorological disturbance.

In the Mena area study sites, all trees were damaged, regardless of size, species, or substrate. Thus, while the tornado disturbance was localized at the landscape scale, impacts on trees were non-selective within the severe blowdown areas.

5.2. Biogeomorphic interactions

Only relatively weak relationships were found between tree size and the amount of regolith displaced. This may be partially due to a relatively small range of sizes within the study area (10 to 60 cm DBH); a broader sample encompassing a larger range might reveal a stronger relationship. The fact that the relationship is stronger between DBH and rootwad surface area (original ground surface) than between DBH and rootwad volume, and that the major outliers in the latter relationship comprise the thickest rootwads suggests that variations in rooting depth account for the differences. That is, variations in size as indicated by DBH are more strongly reflected in the areal extent than in the depth of roots within the study area.

Despite commonalities in the general size range and species distribution between transects, significant variation in soil displacement rates by uprooting were noted. Stem density or basal area can be ruled out as a major control of these differences, as the transect with (by far) the smallest amount of bioturbation (MBB2) had (by far) the largest number of uproots per unit area. The major difference between MBB2 and the other transects is that, while the surficial soil was formed in valley fill deposits, it is almost entirely underlain by sandstone, with little of the shale that is common at the other sites. This is at least broadly consistent with earlier studies that found generally shallower rooting depths in sandstone vs. shale in the region (Mehlhope, 2013; Phillips, 2008; Phillips et al., 2008a). However, rootwad surface areas as well as thicknesses are also lowest on this transect (Table 2). This suggests

the need for further research on the relationships between rooting habits, soil/regolith properties, and bioturbation.

In terms of root–rock interactions, results here are consistent with studies of the 2006 tornado blowdown in that few instances of root turning (lateral deflection of roots due to inability to penetrate vertically) were noted. However, nearly 90% of the rootwads examined by Phillips et al. (2008a) showed that roots contacted or penetrated underlying bedrock, and in all of those cases uprooting “mined” unweathered bedrock. In the present study only about 33% of the rootwads indicated root penetration of weathered or unweathered bedrock. This largely reflects the soils in the Mena study areas being formed primarily from colluvial or alluvial deposits, rather than the somewhat thinner, predominantly residual soils in the 2006 blowdown sites. Overall, results are broadly consistent with the idea that root penetration of bedrock is not common if the regolith is sufficiently thick. Results also confirm that ease of entry is a significant factor, with root penetration of rock more common in the softer, more easily weathered shales than in sandstone.

5.3. Energy and memory

Soil displacement by uprooting in the 2009 tornado blowdown represents a transfer of about 75 to 190 J m⁻² of meteorological (solar) energy directly to geomorphic work via vegetation. This is a transfer of tectonic energy directly into biomechanical effects.

Applying the same methods to data from the 2006 tornado blowdown event (Phillips et al., 2008a) gives a higher value of 257 J m⁻² (for the subsurface-to-surface component only). This vertical displacement includes only one aspect of the geomorphological, pedological, and ecological work accomplished by the tornado. Wind velocities of about 50 m s⁻¹ represent kinetic energy ($=mV^2/2$, where V is velocity) of about 37,500 J, assuming a 30 m relevant height and an air density of 1 kg m⁻³. Not all of this energy produces environmental effects, but tree

Table 4
Energy inputs to selected geomorphological and pedological processes.

Phenomenon	Amount (J m ⁻²)	Source
Soil displacement by uprooting, single tornado event	75 to 190	This study
Soil displacement by uprooting, single tornado event ^a	257	Phillips et al. (2008a)
Energy expenditure, individual large floods, per unit drainage area, Narmada River, India ^a	0.0004 to 0.0015	Kale (2008)
Energy expenditure by river flow during monsoon, per unit drainage area, Narmada River, India ^a	0.0004 to 0.0038	Kale (2008)
Energy expenditure, stream channel, with specific stream power of 10 W m ⁻²	864,000 per day	This study
Geological uplift (areas of active tectonic uplift)	7.791 to 260 per year; 0.0213 to 0.7118 per day	Phillips (2009a)
Denudation rates (areas of active erosion)	3.776 to 130 per year; 0.0103 to 0.3559 per day	Phillips (2009a)
Net primary productivity, vegetated areas	>3300 per day	Phillips (2009a)
Effective energy & mass transfer from solar radiation & precipitation inputs (EEMT)	>30,000 per day	Rasmussen and Tabor (2007)
Median EEMT	>5500 per day	Rasmussen et al. (2011)

^a Calculated from data in the source publication.

Table 5

Comparison of disturbance parameters for tornadoes and straight-line wind events. Tornado parameters refer to western Arkansas, based on tornado climatology in Section 2.1, and results of this study and Phillips et al. (2008a).

Parameter ^a	Tornado	Straight-line winds $\geq 33 \text{ m s}^{-1}$
Frequency (recurrence interval)	>10 ka	<10 yr in areas subject to frequent tropical cyclones to >100 yr in midlatitude temperate forests
Magnitude (tree damage & associated soil & regolith impacts)	Severe	Minor to severe
Duration	<1 h	1 to 24 h
Areal extent	<10 km ²	>100 km ²
Speed of onset	Rapid	Rapid
Spatial dispersion	Locally concentrated	Diffused over large area
Temporal spacing	Irregular	Irregular, but with seasonal & interannual patterns

^a See White (1974), Gares et al. (1994) or Phillips (2009b) for explanation of terms.

and limb breakage, leaf removal, and transport of sediment and organic debris do occur in addition to uprooting.

To put the energy associated with soil displacement by uprooting in perspective, energy associated with geological uplift and with denudation rates, even in tectonically and erosively active areas, amount to $<1 \text{ J m}^{-2} \text{ day}^{-1}$. On the other hand, these processes are constantly or intermittently active, with total energy inputs of 3.8 to $260 \text{ J m}^{-2} \text{ yr}^{-1}$ (Table 4). Thus the tornado soil displacement energy is quite significant, in the range of total annual tectonic and denudation energy in active areas. If energy expenditures of river flow are averaged over the area of the entire drainage basin, as in the example in Table 4, the amount is at least five orders of magnitude less than the tornado effects. On the other hand, energy dissipation within a stream channel at only moderate levels of stream power are several orders of magnitude higher than that of the soil displacement by uprooting (Table 4).

Table 4 also shows typical values of net primary productivity and effective energy and mass transfer. The latter was developed by Rasmussen et al. (2005) to estimate energy and mass transfers potentially relevant to soil processes associated with solar radiation, biological energy transformations, heat flow, and precipitation. While not all of this energy input to soil and ecological processes is geomorphologically significant, even if only a small fraction of it is, it still exceeds the tornado uprooting energy.

Overall then, energy inputs from the tornado blowdown event are minor in terms of overall energy inputs driving weathering, organic matter and nutrient dynamics, and mass translocations within soil. However, they represent quite significant energy inputs with respect to bioturbation and soil displacement.

In an unmanaged or natural forest, geomorphological memory of a blowdown event of any type via pit-and-mound topography; resulting direct effects on weathering, pedogenesis and surface mass fluxes; and indirect effects via ecological impacts would be quite strong, though the longevity of such effects is variable (c.f. Cremeans and Kalisz, 1988; Schaeztl and Follmer, 1990; Meyers and McSweeney, 1995; Phillips and Marion, 2004; Šamonil et al., 2010a, 2013; Pawlik, 2013; Pawlik et al., 2013; Valtera et al., 2013). However, the study area was subject to salvage logging (as were the 2006 blowdown sites). Salvage logging is always implemented on National Forest land as soon as possible after extensive blowdown damage occurs, with downed trees being sawed off as close to the base as possible. This can cause the uplifted rootwad to settle back into the pit, as was the case at the present study sites. Thus the rootwad displacement can be temporary and sporadic where this occurs, and the pit-and-mound pairs might not form. The salvage logging, incidentally, was a key factor limiting our ability to sample. This is an example of how forest management practices can inadvertently influence geomorphological processes.

6. Conclusions

An EF2 tornado touched down in portions of the Ouachita Mountains in western Arkansas in 2009. In the severe blowdown areas the storm resulted in uprooting or breakage of all trees. There was no relationship between tree species or size and whether uprooting or breakage occurred. Uprooting resulted in a mean bioturbation rate of $205 \text{ m}^3 \text{ ha}^{-1}$ (about 240 t ha^{-1}). Direct transfer of wind energy via tree uprooting to geomorphic work of soil displacement amounts to about 75 to 190 J m^{-2} . There was no significant relationship between tree species and amount of soil displaced, and only a weak relationship between tree size and rootwad size.

The tornado of April, 2009—not atypical for the region—is a disturbance marked by severe, non-selective impacts within the blowdown area. At a broader, landscape scale, tornadoes differ from windthrow events associated with larger storms and straight-line winds: Tornadoes are highly localized, have shorter durations, affect smaller areas, and occur much less frequently with respect to any given landform element or forest stand.

Only about a third of the blowdown rootwads revealed root penetration of bedrock, compared to about 90% in other areas of the Ouachita Mountains (Mehlhope, 2013; Phillips et al., 2008a). This is attributable to the thicker colluvial soils at the study site, and is consistent with the idea that root–bedrock interaction is more likely in thinner regolith covers.

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