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Pedologic and geomorphic impacts of a tornado blowdown event in a mixed pine-hardwood forest

Jonathan D. Phillips [a,*], Daniel A. Marion [b,a], Alice V. Turkington [a]

[a] Tobacco Road Research Team, Department of Geography, University of Kentucky, Lexington, KY 40506-0027, United States
[b] USDA Forest Service, Southern Research Station, P.O. Box 1280, Hot Springs, AR 71902, United States

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ABSTRACT

Biomechanical effects of trees on soils and surface processes may be extensive in forest environments. Two blowdown sites caused by a November 2005 tornado in the Ouachita National Forest, Arkansas allowed a case study examination of bioturbation associated with a specific forest blowdown event, as well as detailed examination of relationships between tree root systems, soils, and underlying bedrock. The sites occur within mixed shortleaf pine and hardwood forests. More than 95% of trees in the severe blowdown areas were either uprooted or suffered trunk break, with uprooting more common than breakage. Within the most heavily damaged areas all uprooted trees were pines, while all trees left standing were hardwoods. Root wads of uprooted trees had a mean surface area of about 3 m^2 and volume of about 2 m^3, though individual sizes were quite variable. Nearly 4% of the ground surface area was affected by uprootings, with a soil volume equivalent to a disturbance of the entire surface area to a depth of 2.4 cm. Tree size (as measured by diameter at breast height) was significantly related to the area and volume of root wads (R^2=0.55, 0.71, respectively), with volume of uprooted soil varying as diameter to the ~3 power, suggesting that the timing of blowdown events relative to tree age or growth stage significantly influences the area of disturbance and the mass and volume of material involved. In 93% of cases the roots of the uprooted trees contacted or penetrated the underlying bedrock, and in all those cases bedrock was quarried by uprooting. Only 11% of the tree throws showed evidence of general lateral root turning at the soil–bedrock interface; in most cases roots penetrated bedrock along joints. The propensity for tree roots to penetrate bedrock joints, facilitate weathering, and excavate bedrock during uprooting supports the idea that tree roots play a predominant role in locally deepening soils.

1. Introduction

The effects of vegetation on soils and geomorphic processes have long been recognized, but studies of these effects have traditionally emphasized biological and chemical effects on pedogenesis and the relationship between vegetation cover and surface erosion. More recently, however, pedologists have increasingly come to view soils and regoliths as more or less continually mixed biomantles, and geomorphologists have emphasized the direct and active (rather than indirect and passive) geomorphic roles of biota. This study examines a localized but severe forest disturbance event in the Ouachita Mountains, Arkansas, to gain insight into soil and geomorphic disturbance by tree uprooting, and the interrelationships between tree growth, pedogenesis, and bedrock weathering.

Scientists such as Nathaniel Shaler and Charles Darwin recognized and wrote about biomechanical effects of organisms in the 19th century, but until recently studies of biological effects on soils have concentrated on biochemical, edaphic, and ecological influences. Increasingly, however, biomechanical effects have been found to be significant, and sometimes of comparable or even greater importance than other biological effects (e.g., Schaetzl et al., 1990; Johnson, 1993; 2002; Johnson et al., 2005; Butler, 1995; Balek, 2002; Van Nest, 2002; Gabet et al., 2003; Meysman et al., 2006).

Tree uprooting (tree throw or tree tip) is a pervasive source of bioturbation in forests, with significant direct effects on soils, as well as indirect effects on pedogenesis and sediment transport (Stephens, 1956; Veneman et al., 1984; Beatty and Stone, 1986; Schaetzl, 1990; Schaetzl et al., 1990; Small et al., 1990; Meyers and McSweeney, 1995; Scatena and Lugo, 1995; Vasenev and Targul'yan, 1995; Kabrick et al., 1997; Gabet et al., 2003). The direct effects include soil mixing, soil profile inversion, local redistribution of sediment mass, and the creation of characteristic pit-mound topography. Indirect effects include exposure of unprotected sediment to erosion and mass wasting, and creation of microscale differences in weathering, moisture flux, organic matter dynamics, and microclimate in the pit-mound topography.

In the Ouachita Mountains of west central Arkansas, USA, studies of the coevolution of and interactions among soils, landforms, and vegetation in upland forests found that biomechanical effects of trees are a major driving force in weathering and regolith evolution and

* Corresponding author.
E-mail address: jdp@uky.edu (J.D. Phillips).

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soil development, and a major contributor to soil spatial variability (Phillips and Marion, 2004, 2005; Phillips et al., 2005a,b). Biomechanical effects on soils go well beyond effects of uprooting, but uprooting is the single most intense and effective process of bioturbation in the region (Phillips and Marion, 2006). These studies suggested that individual trees locally deepen soils by root penetration into bedrock joints and bedding plains, which facilitates biochemical weathering and moisture flux; and by “mining” of bedrock fragments during uprooting. Further, these effects may be self-reinforcing due to preferential reoccupation of the same microsites. Subsequent work confirmed that tree roots systematically penetrate joints in fresh, unweathered bedrock and facilitate weathering thereof (Phillips et al., 2008), and that depth to bedrock is systematically greater under trees than in immediately adjacent sites (Phillips, 2008).

Fieldwork conducted in 2001 and 2002 measured the uprooted soil mass (root wads) of a number of uprooted trees, most of which apparently occurred during an ice storm in 2000, and which mainly involved scattered individual trees in a variety of microsites. That inventory also included other tree throws of unknown timing and origin (Phillips and Marion, 2005; Phillips et al., 2005a). This study expands on that work by examining a number of uprooted trees in close proximity, of known and common timing and cause, and allowing for a dense set of spatial observations of root/soil/rock relationships. The current study is based on several tornado touchdowns in the Ouachita National Forest in November, 2005.

1.1. Tree uprooting and windthrow

Tree uprooting has important influences on forest ecology, and implications for forest management. The extensive literature on the ecological and silvicultural aspects of uprooting is reviewed by Schaetzl et al. (1989), Ulanova (2000), and Peterson (2007). Ice storms and other factors may cause uprootings, but wind is the most common cause.

Peterson (2007) specifically focused on tornado blowdowns, based on a literature review and data from nine North American sites. In general, consistent positive relationships exist between tree diameter and blowdown risk, and uprooting is substantially more common than trunk breakage. Vulnerability to uprooting and wind damage varies among species, related to wood strength, rooting habit, and other factors. Shallow rooting increases wind throw vulnerability, and Peterson's (2007) synthesis shows a tendency for conifers to be more vulnerable than deciduous trees, though the relationship is weak. The blowdowns studied by Peterson (2007) ranged from 20 to 97% of trees toppled; the Georgia tornado blowdown sites examined by Harrington and Bluhm (2001) also fall within this range.

While individual blowdowns may be quite localized, and the frequency and areal coverage of tree uprootings due to wind varies widely, uprootings by wind is significant over long time scales in many forest environments. In forests of northern Eurasia, Vasenev and Targul'yan (1995) and Ulanova (2000) estimate that any given patch of the forest floor has been influenced by uprooting pits or decomposing logs 10 to 20 times during the Holocene, on average. The estimated disturbance cycles for canopy destruction (the mean time period in which an area equivalent to the entire canopy would be destroyed by uprooting) for North American and New Zealand forests presented by Schaetzl et al. (1989) ranges from as little as 100 to 280 years in New Zealand to 12.5 to 25 ka for some Michigan forests. In one forest type alone, the estimated range is an order of magnitude (220 to 2439 years; Schaetzl et al., 1989, p. 6). Greenberg and McNab (1998) did not give quantitative estimates, but based on their study of blowdown by hurricane-related wind downbursts in western North Carolina (which disturbed 1.6 to 4.3% of the ground surface area in a single event), suggested that episodic high-intensity blowdown events caused by wind are not uncommon in the region. These events have significant impacts on forest structure, species composition, gap succession, and microtopography.

1.2. Geomorphic and pedologic impacts of uprooting

A comprehensive review of the pedologic impacts of uprooting was provided by Schaetzl et al. (1990). Since then significant advances have occurred, particularly in discovering the role of uprooting in the formation of podzolized forest soils (e.g. Schaetzl, 1990; Vasenev and Targul'yan, 1995; Ulanova, 2000), effects of uprooting on the distribution of gravel and rock fragments (e.g. Small et al., 1990; Phillips et al., 2005a; Osterkamp et al., 2006), and the key role of biomechanical effects of trees, including uprooting, on local and microscale soil variability (e.g. Kabrick et al., 1997; Ulanova, 2000; Phillips and Marion, 2005; Scharenbroch and Bockheim, 2007).

Appreciation of the critical role of bioturbation in pedologic and geomorphic processes has grown in recent years (e.g. Johnson, 2002; Johnson et al., 2005; Meysman et al., 2006). An extensive review of bioturbation influences on soil processes and sediment transport, with some emphasis on tree uprooting, is given by Gabet et al. (2003). Since that review additional progress has been made, particularly regarding the interaction of uprooting with other processes such as karst dissolution, bedrock weathering, and weathering of uprooted clasts (e.g. Embleton-Hamann, 2004; Phillips et al., 2005a,b; Osterkamp et al., 2006).

Impacts of uprooting on soil, geomorphic processes, and topography include the direct impacts of soil mixing and profile inversion, and the indirect effects associated with pit-mound (or cradle-knoll) topography created at uprooting sites (e.g., Veneman et al., 1984; Beatty and Stone, 1986; Cremeans and Kalisz, 1988; Schaetzl, 1990; Meyers and McSweeney, 1995; Kabrick et al., 1997). A coarse index of the importance or intensity of these effects is the “turnover time” (time required for an area equivalent to 100% of the ground surface to be uprooted), or the portion of the ground surface at a given time occupied by tree throw pits and mounds.

In the Cumberland Plateau area of Kentucky, Cremeans and Kalisz (1988) found that less than 2.5% of the surface area was occupied by pits and mounds. In Russian and Ukrainian forests, pit-mound surface coverage is typically 7 to 12%, but 15 to 25% in areas showing effects of severe windthrow events (Ulanova 2000). Data compiled by Schaetzl et al. (1989) from 14 different forested sites around the world found surface coverage ranging from <1 to nearly 50%, but >10% in 11 of 14 cases. The areal coverage, however, depends not only on the size of the features and frequency of uprooting, but also on the longevity of tree throw microtopography, which depends on, among other things, slope gradients and erosion rates (Schaetzl and Follmer, 1990).

In Puerto Rico, Scatena and Lugo (1995) showed that the area influenced by uprootings from a hurricane varied by topographic position, ranging from 2.6% on ridges to 11.9% in riparian valleys (drainage basin mean 2.8%). They estimated the forest turnover period due to hurricane blowdowns as 380 years for stems >10 cm in diameter (Scatena and Lugo, 1995). In the Ouachita Mountains, Arkansas, Phillips and Marion (2006) estimated a turnover time for soil surface disturbance due to tree uprootings caused primarily by ice storms to be >11 ka.

Vasenev and Targul'yan (1995) suggested that following uprooting-related changes in soils, pedogenesis in some cases returned to the preexisting 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 years. Deeper uprootings, however, result in semi-permanent changes in soil morphology (Ulanova, 2000).

Uprooting is in general more likely in shallower and wetter soils, or where restrictive horizons limit root penetration (Mueller and Cline, 1959; Schaetzl 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).

The persistence of recognizable microscale biomechanical effects of trees on soil depends in large measure on the tendency for trees to repeatedly reoccupy the same microsites (Phillips and Marion, 2004; Phillips, 2008), and the extent to which tree roots interact with underlying weathered and unweathered bedrock. The latter is discussed below.

1.3. Root–bedrock interactions

Lutz and Griswold (1939) presented one of the first comprehensive discussions of the effects of tree roots on soil morphology, including both uprooting and root penetration of bedrock. The latter was more specifically addressed by Lutz (1958), who noted the importance of rock structure to soil development due to the penetration of roots, especially by trees. In shallow soils, he noted joints, bedding planes, and fractures “often compensate in part for the physical shallowness of the soil” (Lutz, 1958, p. 77).

The 1990s saw increasing attention to biological activity below the solum and to whole-regolith pedology (e.g. Graham and Tice, 1994; Stone and Comerford, 1994; Richter and Markewitz, 1995), and thus to phenomena such as root penetration of bedrock. While roots can penetrate saprolite and highly-weathered rock, entry into fresh or lightly-weathered rock requires a pre-existing opening such as a fracture or bedding plane (Lutz, 1958; Stone and Comerford, 1994; Zwieniecki and Newton, 1995). Roots encountering unweathered rock with no joints or openings are turned laterally (parallel to the rock surface). Ecological evidence suggests feedback effects. Root growth responds most vigorously to nutrient concentrations. Thus, at the bedrock interface, openings previously occupied by roots and containing nutrients associated with decaying organic matter, are likely to better support new roots (Stout, 1956; Zwieniecki and Newton, 1995; Casper et al., 2003).

Once roots enter a rock opening, chemical weathering is enhanced by channeling of moisture along the roots, formation of organic acids, chelation, and hosting of microbial activity (Graham and Tice, 1994; Stone and Comerford, 1994). Vepraskas et al. (1991) noted the importance of roots for moisture flux in saprolites. They found that foliation and shear planes, if not occupied by roots, became plugged with clay and ferro-manganese oxides. The most important moisture conduits were roots themselves, and a network of channels whose geometry and size indicate an origin as root channels (Vepraskas et al., 1991). Roots rather than surficial litter are also the major supplier of organic matter to weathered rock (Graham and Tice, 1994).

A key issue is the extent to which roots occupy structural features already enlarged and weakened by weathering, as opposed to penetrating relatively fresh joints, etc., and facilitating weathering. In the Ouachita area, studies on recently exposed bedrock benches indicate rapid root occupation of fresh fractures (Phillips et al., 2008). Thus the extent to which roots are observed to enter bedrock and to uproot bedrock fragments is an important indicator of soil/regolith deepening by a combination of biomechanical and biochemical activity (c.f. Johnson, 1985; Phillips et al., 2005b), as well as an indication of the likelihood that effects of uprooting on soil morphology are likely to persist (Ulanova, 2000).

2. Study area

2.1. Environmental setting

The Ouachita National Forest is in the Ouachita Mountains of western Arkansas and eastern Oklahoma (Fig. 1). The Ouachitas are parallel, east-west trending ridges with intermontane basins. Local

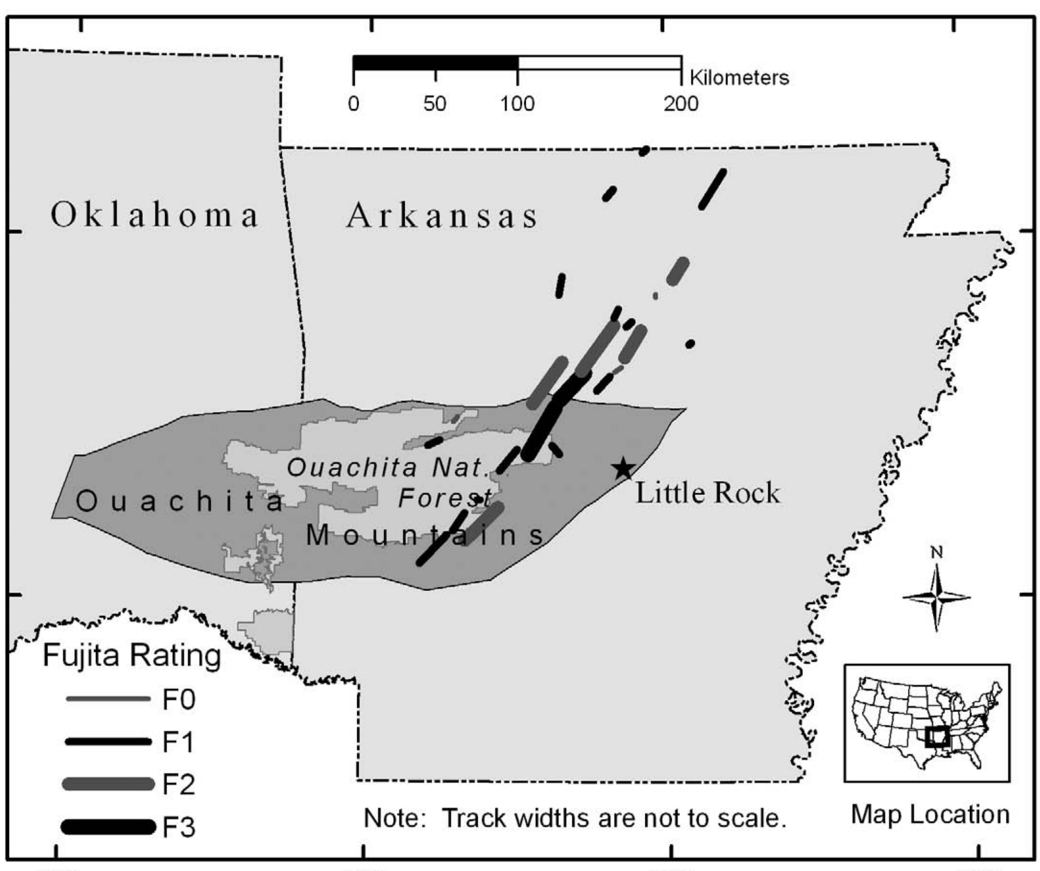

Fig. 1. Tornado occurrences in Arkansas, late November, 2005. General location of Ouachita Mountains and Ouachita National Forest is also shown.

relief varies from 75–530 m, generally increasing from east to west. The climate is humid subtropical. Mean annual precipitation is 1300–1400 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.

The geologic setting 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 within the Stanley Shale, Jackfork Sandstone, and Atoka Formation lithologic units. All three are common in the Ouachita Mountains, and are similar in that they all consist of steeply dipping, extensively faulted, intermixed beds of fine- to medium-grained sandstones and fine-grained shales. The formations differ in age and in the relative proportions of each rock type (Jordan et al., 1991; McFarland, 1998). 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 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, with rock fragments frequently comprising >35% of soil volume, and stone zones with >70% rock fragments being common (Phillips et al., 2005a). Soils are formed by a combination of weathering of underlying bedrock and downslope mass movement of sandstone fragments from resistant ridgetop outcrops. The weathering of the sandstone clasts creates surficial horizons with significant sand content, even when weathering of the underlying shale produces clayey residua. Sandstone clasts are found throughout many soil profiles even where there is no sandstone in the underlying rock, indicating soil mixing, predominantly due to uprooting and to rock fragment transport into stump holes (Phillips et al., 2005a). At the landscape scale general relationships exist between soil thickness and topography, with thin soils or rock outcrops on ridgecrests, and thicker soils along toeslopes and in valley bottoms. At a local scale, however, thickness is highly variable and unrelated to topography (Phillips et al., 2005b). The major controls on these local variations in thickness are local lithological and structural variations in the underlying rock, local soil deepening under individual trees, and the tendency of trees to reoccupy the same microsites over multiple generations of forest (Phillips and Marion 2004, 2005; Phillips et al., 2005b; Phillips, 2008). The deepening processes associated with trees are believed to include root penetration into bedrock joints and associated weathering therein, the infilling of holes created by stump rot, and the quarrying of bedrock fragments by uprooting (Phillips and Marion, 2006; Phillips, 2008; Phillips et al., 2008).

The vegetation cover of the blowdown sites was a mixed shortleaf pine (*Pinus echinata)* and hardwood forest, which is common in the region. The larger pines generally had a diameter at breast height

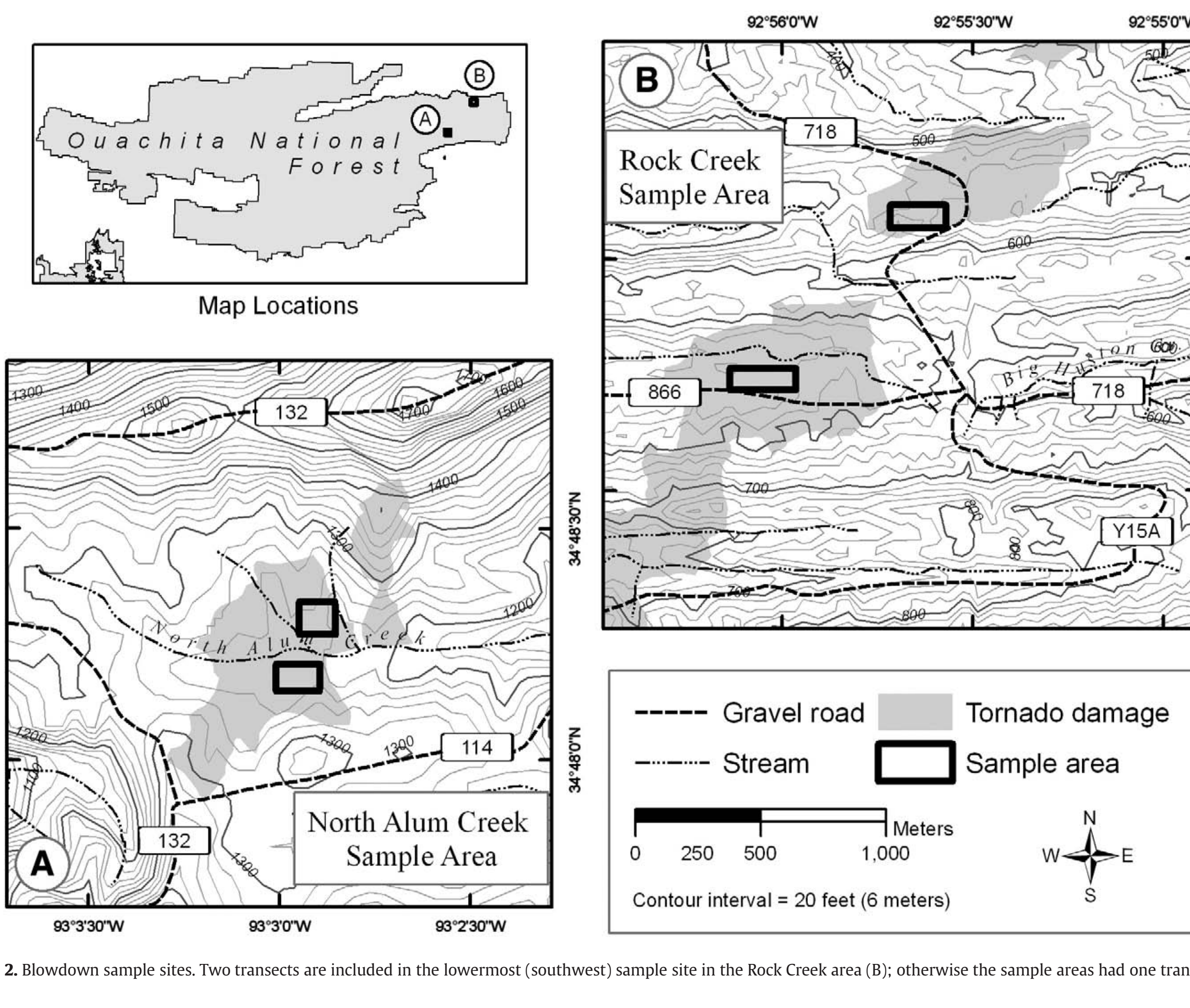

Fig. 2. Blowdown sample sites. Two transects are included in the lowermost (southwest) sample site in the Rock Creek area (B); otherwise the sample areas had one transect each.

(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.

2.2. Tornadoes of November, 2005

Tornadoes are not uncommon in Arkansas. The Little Rock Radar Coverage Area, which encompasses nearly all of the state, has averaged 36 tornadoes per year since 1980. The Area ranks 39th out of the 141 coverage areas within the conterminous United States in the average number of tornadoes per year (F0 or greater on the Fujita intensity scale), and 6th in the average number of severe (F2 or greater) tornadoes per year (National Weather Service, 2007a). Even so, the storm event of 27 November 2005 was particularly extensive and powerful. During this event, 24 confirmed tornadoes occurred throughout central and north-central Arkansas, with intensities ranging from F0 to F3 (Fig. 1) (National Weather Service, 2007b). Several tornadoes touched down within the Ouachita National Forest during this storm, causing extensive blowdown, and affecting a total Forest area of almost 450 ha. Fig. 2 shows the extent of damage to the Forest in the vicinities of our study sites. The damage shown in map A of Fig. 2 was caused by a tornado that was rated an F1 with wind speeds estimated at 145 km/h (National Weather Service, 2005a). The damage shown in map B was from an F3 tornado with estimated wind speeds of 258 km/h (National Weather Service, 2005b).

3. Methods

After examining the blowdown sites in the field and from aerial photography, two general severe blowdown areas in the North Alum Creek area and three in the Rock Creek area were selected which appeared to be typical, based on the photography and conversations with USDA Forest Service personnel familiar with the sites. Within these general areas specific transect lines were randomly selected across the damage area, approximately perpendicular to the storm path. The number of transects which could be measured was limited by the fact that salvage logging of downed timber was already occurring. Beyond the general ground disturbance of the logging activities, removal of the trunks caused many of the rootwads to resettle into the uprooting pits, making our measurements impossible.

The transects were 10 m in width (5 m either side of the center line), with lengths ranging from about 50 to 100 m, determined by the extent of the area of severe damage. Along each transect, any uprooted or broken tree was included if any part of the trunk (when the tree was still in growth position) or root wad was within the 10 m swath. Trees which uprooted or broke outside the transect and fell into it were not included. Topography of the transect was measured with a laser level and prism.

Fig. 3. Underside of rootwad of uprooted shortleaf pine showing sandstone bedrock fragments.

Table 1
Uprooted trees and root wads within sample transects at the North Alum (NAC) and Rock Creek (RC) study sites

Transect	N[a]	Diameter[b] (cm)			Area[c] (m^2)			Volume[d] (m^3)		
		Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
NAC 1	15	24	39	30.7	1.03	5.55	2.80	0.42	3.94	1.55
NAC 2	9	30	51	40.2	0.97	11.78	2.83	0.63	6.01	1.24
RC 1	12	30	51	39.6	1.54	6.10	3.08	0.81	4.88	2.49
RC 2	3	35	53	44.3	4.22	5.50	4.78	1.62	2.92	2.15
RC 3	6	16	37	32.0	0.52	6.51	2.95	0.11	2.34	1.38
Total	45	16	53	34.1	0.52	11.78	3.18	0.11	6.01	2.06

[a] Number of uprooted trees.
[b] Tree diameter at breast height.
[c] Surface area of root wads.
[d] Volume of uprooted soil.

For uprooted trees the trunk diameter was measured 1.37 m (4.5 ft) above the root crown using a dendrological tape, and the type of tree (pine vs. hardwood) recorded. The size of the root wad was measured using a folding ruler and/or measuring tape to determine the mean length and width of the original soil surface area, and the mean depth of the uprooted material. 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 root wad 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.

In all cases uprooted soil included material below the solum, with the latter defined as all soil above a C horizon. The lowermost (relative to the pre-uprooting position) material was assessed as representing C, Cr, or R horizons or layers. R horizons (bedrock) included dominantly intact bedrock which lacked weathering features except locally along rock joints. Cr horizons (weathered bedrock) contained a mixture of weathered and unweathered rock. C horizons consisted chiefly of highly weathered rock, with relatively small amounts of soil and unweathered rock fragments. Weathering features assessed included discolorations (such as iron staining), weathering rinds, solutional pits and etching on clast surfaces, and presence of secondary minerals as observed in the field.

The type of bedrock was observed in most cases directly from the uprooting pit, or from excavations into the pit bottom. In a few cases (in valley or swale settings) where this was not feasible, the underlying bedrock was inferred based on rock fragments in the root wad. The relationship between the roots and bedrock was observed, with particular attention to whether roots entered bedrock joints, the extent to which roots were turned laterally, parallel to the rock surface (indicating resistance to root penetration) at the soil–bedrock interface, and the presence of rock fragments excavated by uprooting. Lateral turning of roots was qualitatively assessed in three categories: Little or no turning; local turning associated with specific rock fragments or faces; and general turning where half or more of the lowermost portion of the root mat was flattened. The soundness of fragments apparently removed from bedrock (as opposed to the rock fragments which are commonly present throughout many soil profiles in the region; Phillips et al., 2005a) was tested by breaking at least six fragments with a geological hammer, based on the methods developed by Selby (1980, 1993).

Broken trunks where the fallen section's alignment was consistent with the blowdown pattern of the storm were assumed to have broken during the tornado. As with uprooted trees, the dbh was measured, and the general type recorded.

Table 2
Soil disturbance caused by tornado blowdown within sample transects at the North Alum (NAC) and Rock Creek (RC) study sites

Transect	Length (m)	Area[a] (m^2)	Uprooted trees per m^2	Disturbed[b] area (%)	Equivalent[c] depth (cm)
NAC 1	70.4	700.4	0.021	6.0	3.3
NAC 2	56.8	567.9	0.016	2.9	1.0
RC 1	102.0	1020.0	0.012	3.6	2.9
RC 2	55.0	550.0	0.005	2.6	1.2
RC 3	97.0	970.1	0.006	2.4	0.8
Total		3808.4	0.012	3.8	2.4

[a] Total transect area.
[b] Area of measured root wads relative to the surveyed area.
[c] Total root wad volume divided by surveyed area.

The relationship between the dbh of uprooted trees, and the mean depth, area, and volume of the root wads was assessed using regression. Linear, exponential, logarithmic, and power function relationships were applied, and the best-fit function (which turned out to be a power function in all three cases) was chosen based on the highest coefficient of determination (R^2).

4. Results

4.1. Uprooting and soil disturbance

Overall, 45 uprooted trees on five sample transects were measured. Of these, 33 were on sideslope or convex slope positions; the remainder in valley or swale topographic positions. In the latter settings soils were generally deeper. In the higher topographic positions, however, 91% (30 of 33) of uprooted trees were in contact with bedrock. In all cases where coarse roots were in contact with bedrock, the uprooting resulted in the mining or quarrying of bedrock fragments (Fig. 3).

The uprooted trees were all shortleaf pine. Trees left standing in the most severe blowdown sites were all hardwoods, while broken trunks included both pines and hardwoods. Uprooting was more common than breakage, with 18 broken trunks measured, or 29% of the total tornado-damaged trees sampled.

The individual root wads have areas of 0.52 to 11.78 m^2, with a mean of 3.18. Mean root wad volume is 2.06 m^3, with a range of 0.11 to 6.62. Data for the individual transects is shown in Table 1. The proportion of the area disturbed by uprooting was determined by dividing the total surface area of the root wads by the surveyed area. This was at least 2.4% in all transects, with a mean of 3.8% (Table 2). The total root wad volume was divided by surveyed area to determine the thickness of the uprooted soil if spread uniformly over the entire study site(s). The overall mean was 2.4 cm, as shown in the equivalent depth column of Table 2.

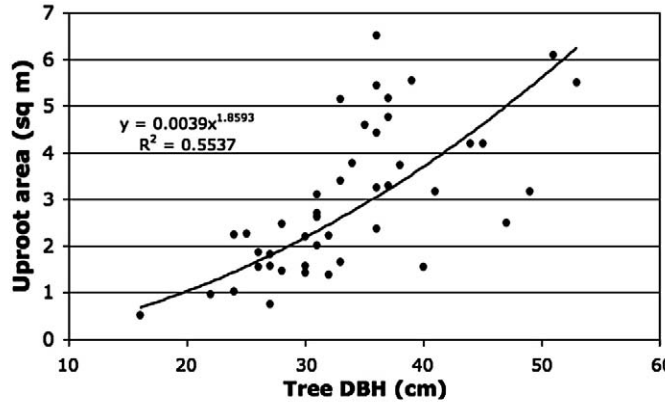

Fig. 5. Relationship between tree size (diameter at breast height) and surface area of uprooted soil masses.

Tree size, as represented by dbh, was weakly related with the depth (thickness) of uprooted root wads (R^2=0.44; Fig. 4) and with the surface area of uprooting disturbance (R^2=0.55; Fig. 5). The strongest relationship was between tree dbh and root wad volume (R^2=0.71; Fig. 6).

4.2. Root, rock, and regolith relationships

In 18 of the 45 uprooted trees measured, unweathered bedrock was evident within the root wad (R horizons). In another 23 cases Cr horizon material, including both weathered bedrock and fresh, unweathered rock, was uprooted. In only three cases (<7%) was the uprooted material entirely soil; in those instances C horizons that included some weathered but recognizable bedrock.

When tree roots growing downward encounter material they cannot penetrate, they are turned laterally (e.g., Wilson, 1967; Stone and Comerford, 1994; Zwieniecki and Newton, 1995). Local lateral turning of roots was widely observed in root wads of uprooted trees, often associated with a large intact rock fragment. However, a general lateral turning of the majority of roots was observed in only seven cases (16%). In two of these cases the roots penetrated bedrock via joints at the base of the regolith before turning laterally along bedding planes. In the other five cases the lateral turning occurred at the regolith–bedrock interface, though in two of these instances unweathered rock fragments were found in the rootwad, suggesting

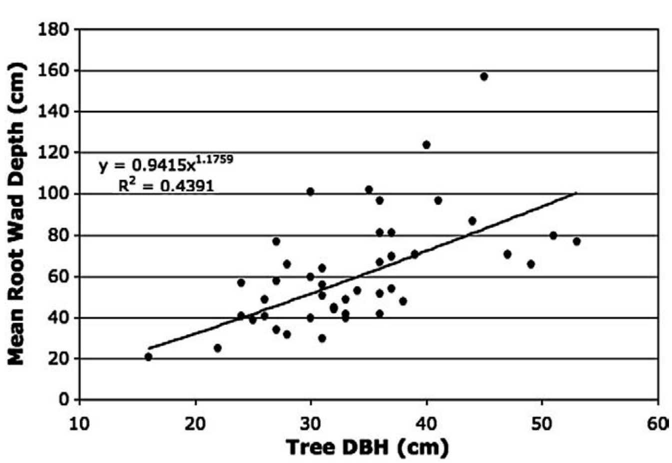

Fig. 4. Relationship between tree size (diameter at breast height) and depth (thickness) of uprooted soil masses.

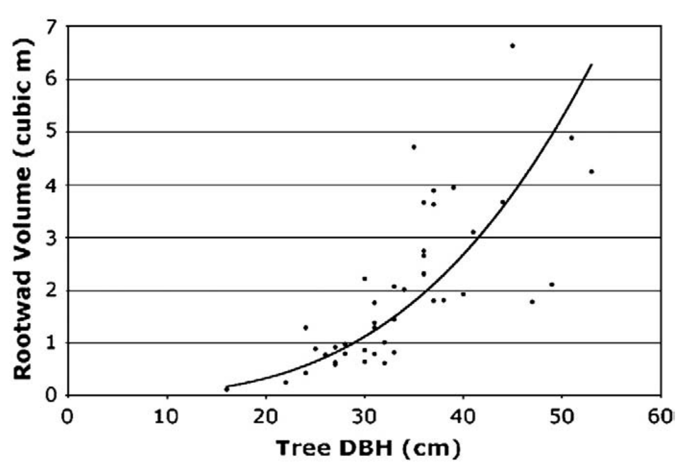

Fig. 6. Relationship between tree size (diameter at breast height) and volume of uprooted soil masses. The trendline equation is $y=0.0039\times^{3.04}$ (R^2=0.72).

Fig. 7. Rootwad of uprooted shortleaf pine showing root penetration into bedrock. Flat rock fragments visible in soil mass are extracted directly from bedrock bedding planes.

either minor penetration or adherence of underlying rock to overlying roots. Thus, in 89% of the samples, roots penetrated the bedrock interface, and in 93% bedrock material was uprooted. Some bedrock penetration by roots probably occurred in the other cases, but could not be conclusively proven. Sub-horizontal root penetration of bedrock occurred along joints of various kinds, primarily fractures and subhorizontal bedding planes (Figs. 7, 8).

The bedrock underlying the uprooted trees was sandstone in eight cases, and shale in 31. In the remaining six cases, intact interbedded shale and sandstone was present in the root wads. There were no apparent relationships between lithology, bedrock mining, and lateral root diversion, other than more instances of local (as opposed to general) root turning where large sandstone fragments were present.

5. Discussion

5.1. Bioturbation

Tree uprooting has long been known to be a significant process of soil bioturbation, and these results reinforce that notion. Evidence is strong that uprooting and other pedogeomorphic influences of trees are not uniformly or randomly distributed, even within a single stand or hillslope (Ulanova, 2000; Phillips and Marion, 2004, 2005, 2006; Peterson, 2007). However, consideration of bioturbation quantities as though they were distributed uniformly over area provides a basis for comparisons with other bioturbation studies, and with other geomorphic processes. In this case the volume of uprooted soil is equivalent to a depth of 2.4 cm over the severe blowdown area in a single event. With typical soil bulk densities of about 1.4 t m^{-3}, this is equivalent to 33.6 kg m^{-2}.

Tornado blowdowns are geographically localized and concentrated compared to tree uprooting associated with straight-line winds from tropical and other storms (not common in the study area but important elsewhere) or from ice storms. However, as these data illustrate, blowdown and associated bioturbation may be severe and intense. Data on tornado frequency and areal extent of touchdowns is not adequate to allow confident extrapolation of data from this study into long-term rates. However, knowledge of tornado climatology is sufficient to suggest that similar events are a regular occurrence in the region.

Data from 1980–1999 indicates that for any given location in the Ouachita Mountains region an average of one tornado/day per year occurs within a 40 km radius (5027 km^2) of any given point (Brooks, 2003). Analysis of data from 1921–1995 suggests 20 to 25 days per century with tornadoes of severity F2 (Fujita scale) or greater, indicating wind velocities > 180 km h^{-1} (Brooks, 2003). U.S. National Climatic Data Center data for 1953–2004 (NCDC, 2006) for Arkansas indicates an annual mean of 4.3 tornadoes per 26,000 km^2 (10,000 $miles^2$), or one a year for each 6047 km^2.

Brooks (2004) analyzed the relationship between tornado intensity and path length and width for U.S. tornadoes. F1 tornadoes have mean widths of 60 to 70 m and lengths of 4 to 5 km, with lengths and widths increasing with tornado severity. This suggests a typical influence area (width times path length) for F1 tornadoes of 0.24 to 0.35 km^2. If the frequency/area data cited above, which correspond to one tornado per 5027 to 6047 km^2 per year, are modified by the ground surface area affected, a rough estimate of the mean frequency of tornado disturbance for any given point can be estimated. For example, if the mean path length times width = 0.35 km^2, and the mean recurrence time indicates 1 tornado per 5027 km^{-2} $year^{-1}$, then a tornado influencing any given point would be expected once every 14,363 years. Mean F1 influence areas from Brooks (2004) cited above suggest that tornado blowdowns would influence an area equal to 100% of the forest every 14 to 25 ka. These are longer recurrence intervals than the 11.2 ka for uprooting estimated by Phillips and Marion (2006), based on a measurements of uprooted trees in the Ouachita Mountains in areas influenced by an ice storm in 2000, but not by severe windthrow.

Even discounting flaws in the tornado data (see Brooks, 2004) these estimates are merely suggestive, and do not account for climate and vegetation change, the magnitude/frequency relationships between storm intensity and influence area, or local geographical variations in tornado strike probabilities within Arkansas or the Ouachita Mountains. They do suggest, however, that over Quaternary geological time scales wholesale more-or-less instantaneous bioturbation in areas of 0.1 to 1.0 km^2 at a time could be occurring several times. It should also be noted that the estimates are quite 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 20% or more of tornadoes in the study area are of severity F2 or higher, with larger impact areas (Brooks, 2003, 2004).

Fig. 8. Rootwad of uprooted shortleaf pine showing area of root lateral turning at regolith/bedrock interface (rectangle) and area of root penetration into bedrock (circle).

While the rates estimated here are significant, they are much less than the uprooting disturbance estimated for higher-latitude forests by Vasenev and Targul'yan (1995) and Ulanova (2000). The latter suggest average disturbance of any point on the forest floor 10 to 20 times over the Holocene, as opposed to perhaps once by tornadoes as implied in this study. The recurrence interval for tropical storm wind damage in Puerto Rico (385 years; Scatena and Lugo, 1995) is also much greater than in this study.

In this study the area of root wads comprised, on average, 3.8% of the surface area of the surveyed transects. The transects were in severe blowdown areas where >95% of all trees were tornado damaged and 71% of those were uprooted. Even if the area of influence were doubled to account for the mounds as well as the pits, less than 8% of the surface area would be occupied by tree throw topography. Comparing our result to the data summarized in section 1.2, where many sites have more than 10% of the surface occupied by pit-mound topography, suggests that high densities of pit-mound pairs are likely to result from multiple uprooting events and persistence of the resulting topography.

Previous estimates of long-term rates of bioturbation and turnover time by uprooting have been based on a particular type of event (e.g., hurricanes, Scatena and Lugo, 1995) or are inevitably influenced by the most recent uprooting event in a given study area (e.g., ice storm, [Phillips and Marion, 2006]). The Ouachita study area is influenced by tornadoes, ice storms, and high-velocity straight-line winds (>60 km h^{-1}) associated with the passage of strong cold fronts. Multiple causes for uprooting are not atypical. Given the climatology of the region, for instance, the Georgia tornado blowdown site studied by Harrington and Bluhm (2001) would also be potentially subjected to the influences of tropical cyclones and ice storms. The possibility of multiple uprooting processes, along with the variations in and uncertainty about the persistence of tree throw topography, illustrates the difficulty in quantifying the long-term geomorphic and pedologic impacts of uprooting.

5.2. Influence of tree types

We did not expect such a strong disparity between pines and hardwoods with respect to their propensity to uproot during the November, 2005 tornadoes, but a general tendency for evergreen conifers to be more vulnerable to windthrow than deciduous trees has been noted in other studies (Peterson, 2007). Our results are also consistent with other studies of tornado blowdowns (e.g., Harrington and Bluhm, 2001; Peterson, 2007) in that uprooting is considerably more common than trunk breakage.

In southern U.S. Coastal Plain environments subject to uprooting due to tropical storm and midlatitude cyclone winds, pines may be less susceptible to uprooting than hardwoods, due to the tendency of deeper taproots of many southern pines to favor breakage rather than three throw. However, in relatively shallow soils this relative advantage is negated. In the study area all common trees have a taproot-style root architecture, and rooting depth of all trees tends to be limited by soil thickness. Because of the late November timing of the storm, deciduous hardwoods had either lost their leaves, or the dead leaves were likely quickly removed as wind velocity increased ahead of tornadic winds. Thus the increased surface area presented by the evergreen pines may have contributed to their uprooting. Other studies have found that size is a more important determinant of vulnerability to windthrow than species (Peterson, 2007), but at our study sites the diameter of the surviving hardwoods was similar to that of the uprooted pines.

5.3. Roots and regolith

Traditional concepts of soil and regolith thickness have been based on downward migration of the bedrock weathering front and surface mass fluxes due to erosion and/or deposition (see review by Humphreys and Wilkinson, 2007). Johnson (1985; Johnson et al., 2005) expanded this simplistic model to include, among other things, soil deepening due to bioturbation at the base of the regolith. Previous work suggests that removal of bedrock fragments by tree throw is an important deepening process in the Ouachita region (Phillips et al., 2005b), and the results of this study provide solid evidence that such "mining" is important.

Local deepening of soil under individual trees has also been attributed to root penetration of bedrock fractures and bedding plains, which facilitates weathering via organic acids, concentration of moisture flux, facilitation of microbial activity, and physical pressure (e.g., Lutz and Griswold, 1939; Lutz, 1958; Stone and Comerford, 1994; Casper et al., 2003; Phillips, 2008; Phillips et al., 2008). Additionally, infilling of rotting stump holes and tap root channels may contribute to local soil deepening (Phillips and Marion, 2006; Phillips, 2008). The results of this study also support these notions, particularly for relatively thin soils formed over weathered or weathering bedrock.

5.4. Forest management

Results suggest that while other factors influence the amount of uprooted soil associated with a tree throw, tree size is (not unexpectedly) an important influence on bioturbation volumes and masses. The relationship found here with root wad volume varying as roughly the third power of tree dbh within a dbh range of about 20 to 50 cm, suggests that the age and size of trees may have disproportionately large influences on bioturbation by tree uprooting. This in turn suggests that both forest management and the timing of disturbances relative to stand rotation and harvesting age may have signification influences on soil morphology. Harvesting must also influence the relative frequency of uprooting vs. stump creation and thus both the type and intensity of pedogeomorphic impacts.

The persistent pedologic and geomorphic impacts of the pit-mound pairs associated with tree throw (the uprooting pit and the mound eventually resulting from redepostion of the root wad) are well established (c.f. Schaetzl, 1990; Scatena and Lugo, 1995; Vasenev and Targul'yan, 1995; Kabrick et al., 1997; Ulanova, 2000). Our fieldwork was conducted on sites where salvage logging had not yet occurred, but where such operations were ongoing or recently completed nearby, allowing us to observe some short-term impacts. The salvage logging typically involved sawing the trunk within 1 m of the root crown. Removal of this trunk mass often caused the root wads to rotate back into the uprooting pit, thus approximately restoring the pre-tornado soil stratigraphy and foreclosing the development of pit-mound topography. Thus forestry practices, in addition to reducing the long-term frequency of uprooting, may also reduce the pedogeomorphic impacts of uprooting.

6. Conclusions

Analsysis of two tornado blowdown sites allowed a case study of a specific tree uprooting event in the Ouachita National Forest, Arkansas, and detailed examination of relationships between tree roots, soils, and underlying bedrock.

The sites occurred within mixed shortleaf pine and hardwood forests, but all uprooted trees on the study transects were pines. More than 95% of trees at the touchdown sites were either uprooted or suffered trunk break, with uprooting more common than breakage. Root wads of uprooted trees had a mean surface area of about 3 m^2 and volume of about 2 m^3, though individual sizes were quite variable. Nearly 4% of the ground surface area was affected by uprootings, with the volume equivalent to a disturbance of the entire surface area to a depth of 2.4 cm, and local mass redistributions equivalent to nearly 34 kg m^{-2}. Tree size (as measured by dbh) was significantly related to the area and volume of root wads (R^2=0.55, 0.71, respectively). The data suggest a steep nonlinear increase in root wad volume with tree size. The amount of bioturbation associated with the November, 2005 tornadoes, coupled with a consideration of tornado climatology of the region, suggests that similar events may be important long-term factors in pedogenesis and landscape evolution.

Analysis of root wads supports the notions of soil deepening by "mining" of bedrock fragments during uprooting, and by accelerated weathering associated with root penetration of joints. In about 90% of cases the roots of the uprooted trees contacted or penetrated the underlying bedrock, and in all those cases bedrock was quarried by uprooting. Only 11% of the tree throws showed evidence of general lateral root turning at the soil–bedrock interface; in most cases roots penetrated bedrock along joints.

More broadly, results support notions of close couplings between biota, landforms, and soils, and of the coevolution of landscapes and ecosystems.

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References

Balek, C.L., 2002. Buried artifacts in stable upland sites and the role of bioturbation: a review. Geoarchaeology 17, 41–51.
Beatty, S.W., Stone, E.L., 1986. The variety of soil microsites created by tree falls. Canadian Journal of Forest Research 16, 539–548.
Brooks, H.E., 2003. Severe Thunderstorm Climatology. U.S. National Severe Storms Laboratory. National Oceanic and Atmospheric Administration, Norman, OK. URL: http://www.nssl.noaa.gov/hazard/totalthreat.html.
Brooks, H.E., 2004. On the relationship of tornado path length and width to intensity. Weather and Forecasting 19, 310–319.
Butler, D.R., 1995. Zoogeomorphology. Animals as geomorphic agents. Cambridge University Press, New York.
Casper, B.B., Schenk, H.J., Jackson, R.B., 2003. Defining a plant's belowground zone of influence. Ecology 84, 2313–2321.
Cremeans, D.W., Kalisz, P.J., 1988. Distribution and characteristics of windthrow microtopography on the Cumberland Plateau of Kentucky. Soil Science Society of America Journal 52, 616–621.
Embleton-Hamann, C., 2004. Processes responsible for the development of a pit and mound microrelief. Catena 57, 175–188.
Gabet, E.J., Reichmann, O.J., Seabloom, E.W., 2003. The effects of bioturbation on soil processes and sediment transport. Annual Review of Earth and Planetary Sciences 31, 249–273.
Graham, R.C., Tice, K.R., 1994. The pedologic nature of weathered rock. Whole Regolith Pedology. Soil Science Society of America Special Publication, 34, pp. 21–40.
Greenberg, C.H., McNab, W.H., 1998. Forest disturbance in hurricane-related downbursts in the Appalachian mountains of North Carolina. Forest Ecology and Management 104, 179–191.
Harrington, T.B., Bluhm, A.A., 2001. Tree regeneration responses to microsite characteristics following a severe tornado in the Georgia Piedmont, USA. Forest Ecology and Management 140, 265–275.
Humphreys, G.S., Wilkinson, M.T., 2007. The soil production function: a brief history and its rediscovery. Geoderma 139, 73–78.
Johnson, D.L., 1985. Soil thickness processes. Catena suppl. 6, 29–40.
Johnson, D.L., 1993. Biomechanical processes and the Gaia paradigm in a unified pedogeomorphic and pedo-archaeologic framework: dynamic denudation. In: Foss, J.E., Timpson, M.E., Morris, M.W. (Eds.), Proceedings of the First International Conference on Pedo-Archaeology, pp. 93–103. University of Tennessee Agricultural Experiment Station Special Publication 93-03, Knoxville.
Johnson, D.L., 2002. Darwin would be proud: bioturbation, dynamic denudation, and the power of theory in science. Geoarchaeology 17, 7–40.
Johnson, D.L., Domier, J., Johnson, D.N., 2005. Animating the biodynamics of soil thickness using process vector analysis: a dynamic denudation approach to soil formation. Geomorphology 67, 23–46.
Jordan, D.W., Lowe, D.R., Slatt, R.M., Stone, C.G., 1991. Scales of geological heterogeneity of Pennsylvanian Jackfork Group, Ouachita Mountains, Arkansas: applications to field development and exploration for deep-water sandstones. American Association of Petroleum Geologists 1991 Annual Guidebook for the Dallas Geological Society field trip 3. Arkansas Geological Commission, Little Rock, pp. 1–20.
Kabrick, J.M., Clayton, M.K., McBratney, A.B., McSweeney, K., 1997. Cradle-knoll patterns and characteristics on drumlins in northeastern Wisconsin. Soil Science Society of America Journal 61, 595–603.
Lutz, H.J., 1958. Geology and soil in relation to forest vegetation. Proceedings, First North American Forest Soils Conference, pp. 75–85. East Lansing, MI.
Lutz, H.J., Griswold, F.S., 1939. The influence of tree roots on soil morphology. American Journal of Science 237, 389–400.
McFarland, J.D., 1998. Stratigraphic Summary of Arkansas. Arkansas Geological Commission Information Circular, 36. Little Rock.
Meyers, N.L., McSweeney, K., 1995. Influence of treethrow on soil properties in Northern Wisconsin. Soil Science Society of America Journal 59, 871–876.
Meysman, F.J.R., Middelburg, J.J., Heip, C.H.R., 2006. Bioturbation: a fresh look at Darwin's last idea. Trends in Ecology and Evolution 21, 688–695.
Mueller, O.P., Cline, M.G., 1959. Effects of mechanical soil barriers and soil wetness on rooting of trees and soil-mixing by blow-down in central New York. Soil Science 88, 107–111.
National Weather Service, 2005a. Public information statement [from National Weather Service Little Rock, AR, station issued at 3:00 PM CST 6 December 2005]. http://www.srh.noaa.gov/lzk/thml/pns112705btxt.htm. [Date accessed: January 10, 2008].
National Weather Service, 2005b. Public information statement [from National Weather Service Little Rock, AR, station issued at 8:00 PM CST 29 November 2005]. http://www.srh.noaa.gov/lzk/thml/pns112705btxt.htm. [Date accessed: January 10, 2008].
National Weather Service, 2007a. Online severe weather climatology: Little Rock, AR radar coverage area. http://www.spc.noaa.climo/online/rda/LZK.html. [Date accessed: January 11, 2008].
National Weather Service, 2007b. Severe weather on Nov 27 2005 (damage surveys). http://www.srh.noaa.gov/lzk/html/surveys112705yr.htm. [Date accessed: January 10, 2008].
NCDC (National Cimatic Data Center), 2006. Tornado Climatology. U.S. National Oceanic and Atmospheric Service, Asheville, NC. URL: http://www.ncdc.noaa.gov/oa/climate/severeweather/tornadoes.html#maps.
Osterkamp, W.R., Toy, T.J., Lenart, M.T., 2006. Development of partial rock veneers by root throw in a subalpine setting. Earth Surface Processes and Landforms 31, 1–14.
Peterson, C.J., 2007. Consistent influence of tree diameter and species on damage in nine eastern North America tornado blowdowns. Forest Ecology and Management 250, 96–106.
Phillips, J.D., 2008. Soil system modeling and generation of field hypotheses. Geoderma 145, 419–425.
Phillips, J.D., Marion, D.A., 2004. Pedological memory in forest soil development. Forest Ecology and Management 188, 363–380.
Phillips, J.D., Marion, D.A., 2005. Biomechanical effects, lithological variations, and local pedodiversity in some forest soils of Arkansas. Geoderma 124, 73–89.
Phillips, J.D., Marion, D.A., 2006. The biomechanical effects of trees on soils and regoliths: beyond treethrow. Annals of the Association of American Geographers 96, 233–247.
Phillips, J.D., Luckow, K., Marion, D.A., Adams, K.R., 2005a. Rock fragment distributions and regolith evolution in the Ouachita Mountains. Earth Surface Processes and Landforms 30, 429–442.
Phillips, J.D., Marion, D.A., Luckow, K., Adams, K.R., 2005b. Nonequilibrium regolith thickness in the Ouachita Mountains. Journal of Geology 113, 325–340.
Phillips, J.D., Turkington, A.V., Marion, D.A., 2008. Weathering and vegetation effects in early stages of soil formation. Catena 72, 21–28.
Richter, D.D., Markewitz, D., 1995. How deep is soil? BioScience 45, 600–609.
Scatena, F.N., Lugo, A.E., 1995. Geomorphology, disturbance, and the soil and vegetation of two subtropical wet steepland watersheds of Puerto Rico. In: Hupp Osterkamp, C.R., Osterkamp, W.R., Howard, A.D. (Eds.), Biogeomorphology, Terrestrial and Freshwater Systems. Elsevier, Amsterdam, pp. 199–214.
Schaetzl, R.J., 1990. Effects of treethrow microtopography on the characteristics and genesis of spodosols, Michigan, USA. Catena 17, 111–126.
Schaetzl, R.J., Follmer, L.R., 1990. Longevity of treethrow microtopography: implications for mass wasting. Geomorphology 3, 113–123.
Schaetzl, R.J., Burns, S.F., Johnson, D.L., Small, T.W., 1989. Tree uprooting — review of impacts on forest ecology. Vegetation 79, 165–176.
Schaetzl, R.J., Burns, S.F., Small, T.W., Johnson, D.L., 1990. Tree uprooting: review of types and patterns of soil disturbance. Physical Geography 11, 277–291.
Scharenbroch, B.C., Bockheim, J.G., 2007. Pedodiversity in an old-growth northern hardwood forest in the Huron Mountains, upper peninsula, Michigan. Canadian Journal of Forest Research 36, 1106–1117.
Selby, M.J., 1980. Hillslope Materials and Processes, 2nd Edition. Oxford University Press, New York.
Selby, M.J., 1993. Hillslope Materials and Processes, (2nd ed.). Oxford University Press, Oxford.
Small, T.W., Schaetzl, R.J., Brixie, J.M., 1990. Redistribution and mixing of soil gravels by tree uprooting. Professional Geographer 42, 445–457.
Stephens, E.P., 1956. The uprooting of trees—a forest process. Soil Science Society of America Proceedings 20, 113–116.
Stone, C.G., Bush, W.V., 1984. Summary of the geology of the Central and Southern Ouachita Mountains, Arkansas. In: Stone, C.G., Haley, B.R. (Eds.), A Guidebook To The Geology Of The Central And Southern Ouachita Mountains, Arkansas. Arkansas Geological Commission, Little Rock, pp. 65–75/.
Stone, E.L., Comerford, N.B., 1994. Plant and animal activity below the solum. Whole Regolith Pedology. Soil Science Society of America Special Publication, 34, pp. 57–74. Madison, WI.

Stout, B.B., 1956. Studies of the root systems of deciduous trees. Harvard Black Rock Forest Bulletin 15. Cambridge, MA, 45 pp.
Ulanova, N.G., 2000. The effects of windthrow on forests at different spatial scales: a review. Forest Ecology and Management 135, 155–167.
Van Nest, J., 2002. The good earthworm: how natural processes preserve upland archaic archaeological sites of western Illinois, U.S.A. Geoarchaeology 17, 53–90.
Vasenev, I.I., Targul'yan, V.O., 1995. A model for the development of sod-podzolic soils by windthrow. Eurasian Soil Science 27, 1–16.
Veneman, P.L.M., Jacke, P.V., Bodine, S.M., 1984. Soil formation as affected by pit and mound microrelief in Massachusetts, U.S.A. Geoderma. 33, 89–99.
Vepraskas, M.J., Jongmans, A.G., Hoover, M.T., Bouma, J., 1991. Hydraulic conductivity of saprolite as determined by channels and porous groundmass. Soil Science Society of American Journal 55, 932–938.
Wilson, B.F., 1967. Root growth around barriers. Botanical Gazette 128, 79–82.
Zwieniecki, M.A., Newton, M., 1995. Roots growing in rock fissures: their morphological adaptation. Plant and Soil 172, 181–187.