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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 m^3 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.

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 km^2 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 km^2). 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 km^2 (10,000 mi^2), or one a year for each 6047 km^2, 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 km^2 (mean = 8.51 km^2). 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 km^2 imply ground disturbance of about 4250 m^2 yr^{-1} (for reference, the total land area of Polk County and adjacent areas affected by the same tornadoes is about 2500 km^2).

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

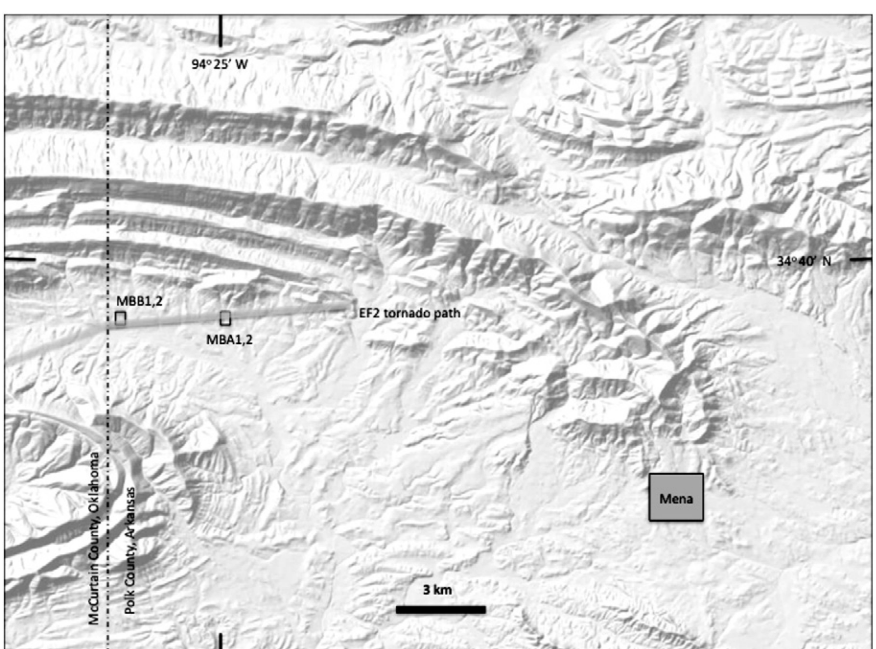

Fig. 1. Study areas (MBA transects 1 and 2; MBB transects 1 and 2) shown in relation to regional topography and path of the tornado responsible for the blowdowns.