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Estimating soil turnover rate from tree uprooting during hurricanes in Puerto Rico

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ABSTRACT

Soil turnover by tree uprooting in primary and secondary forests on the island of Puerto Rico was measured in 42 study plots in the months immediately after the passage of a Category 3 hurricane. Trunk basal area explained 61% of the variability of mound volume and 53% of the variability of mound area. The proportion of uprooted trees, the number of uprooted trees, or the proportion of uprooted basal area explained 84–85% of the variation in hurricane-created mound area. These same variables explain 79–85% of the variation in mound volume. The study indicates that the soil turnover period from tree uprooting by Puerto Rican hurricanes is between 1600 and 4800 years. These rates are faster than soil turnover by landslides and background treefall in the same area and provide a useful age constraint on soil profile development and soil carbon sequestration in these dynamic landscapes.

1. Introduction

The uprooting of trees reallocates soil, biomass, carbon, and nutrients in forested watersheds (Gabet et al., 2003). Uprooting may be the most pervasive form of soil bioturbation (Mitchell, 1988). Uprooted trees bring buried nutrients, clasts and soil organic carbon to the surface, exposing them to atmospheric and surficial processes. Treethrow may increase mineral weathering processes and nutrient availability (Foster, 1988). By exposing material to aeration and erosion, it can influence the storage of carbon in soils, which globally contain 75% of the carbon in the terrestrial organic carbon pool and double the amount of carbon found in the atmosphere (Prentice, 2001). Thus, better quantitative estimates of bioturbation rates are needed to achieve an understanding of long-term terrestrial carbon dynamics (Gabet et al., 2003).

An element of this type of disturbance is mound-and-pit microtopography, which has interested scientists for at least 70 years (Lutz, 1940) because of its potential influence on soil formation, nutrient cycling, soil morphology, sediment movement, drainage patterns and forest ecology (Schaetzl et al., 1989). Mound-and-pit microtopography can influence species distributions (Putz et al., 1983), with some species favoring pits for establishment (Walker, 2000), while others favors mounds (Kabrick et al., 1997).

These processes have implications for forest soil development and forest management. Knowledge of uprooting susceptibility, such as by tree type or species, can yield informed decisions regarding reforestation and afforestation projects, including under the reducing emissions from deforestation in developing nations (REDD) structure of the proposed international climate treaty. Estimates of soil disturbance across a range of sites could complement existing literature on the proportion of trees uprooted by a hurricane or other disturbance event.

Reported mean areas of mounds and pits range from 1.5 m^2 for pits in Kentucky (Cremeans and Kalisz, 1988) to 16 m^2 for combined mound/pit complexes on Barro Colorado Island in Panama (Putz, 1983), with other estimates including 11.9 m^2 for "soil disturbance" from 22 freshly uprooted maple and beech trees in Michigan (Brewer and Merritt, 1978); an average of 2.5 m^2 for pits of various ages ($n = 73$) in a forested subalpine area of Colorado (Osterkamp et al., 2006); 8.8 m^2 of "exposed soil and rock" per uprooted tree in the Luquillo Experimental Forest in Puerto Rico (Zimmerman et al., 1994); and 4.7–8 m^2, depending on treefall

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type, for mounds in central New York forests (Beatty and Stone, 1986). These studies of mound formation, however, are applicable only to specific sites and are limited in applications beyond that forest stand.

Establishing the frequency of individual uprooting events, required when assessing soil turnover rate from uprooting, is especially challenging in tropical forests. While tree-ring cores can be used to estimate uprooting dates of many temperate species, tree-ring dating of tropical trees is limited and typically requires isotopic analysis (Evans and Schrag, 2004). However, an understanding of the return rate of catastrophic windthrow events, such as hurricanes, can help fill the knowledge gap about soil turnover processes in both tropical and temperate regions in the hurricane zone (Lugo, 2008). Furthermore, ongoing climate change may increase the frequency of uprooting events and soil turnover in hurricane-prone forests, as warming sea surface temperatures create conditions that increase wind velocity of hurricanes when other atmospheric factors do not intervene (Emanuel, 2005; IPCC, 2007).

This study quantifies the volume and area of soil uplifted by trees disturbed by the passage of Hurricane Georges over the Caribbean island of Puerto Rico, 21–22 September 1998. Our analyses focused on these questions: (1) How do the analyzed variables of individual trees and stands, landforms, and hurricane properties influence tree uprooting at the plot level? (2) How do these variables influence the quantity of soil uplifted by individual trees and at the plot level? (3) How does the rate of hurricane-induced soil turnover in Puerto Rico compare to other types of disturbance? To seek first-order principles that have applications at a variety of sites, more attention was given to finding broad similarities across heterogeneous sites than discerning small differences within or among sites or individual samples.

2. Material and methods

2.1. Study area

Puerto Rico is a 890,000-ha tropical island in the Greater Antilles chain of the West Indies, centered on approximately 18.5° North and 67° West. Approximately 60% of island area is classified (by Holdridge, 1967) as moist forest (1000–2000 mm rainfall annually), 25% as wet forest (2000–4000 mm), and 14% as dry forest (<1000 mm, Ewel and Whitmore, 1973). Extensive clearing for agriculture had reduced the island's forest cover to a low of about 12% by the late 1940s (Koenig, 1953). Since then, closed forest cover has increased to about 41.6% of island area (Helmer et al., 2002). Outside of protected areas, much of this closed forest is fragmented in sections ≤1 ha (Lugo and Helmer, 200 4).

2.2. Data collection and analysis

On 22–23 September 1998, Hurricane Georges passed over Puerto Rico with maximum sustained winds of 185 km h^{-1} and gusts up to 241 km h^{-1} (Bennett and Mojica, 1998). From 23 September through 20 December 1998, detailed measurements on 72 freshly uprooted mounds were taken in 42 plots of 500 m^2 in a variety of stands across the island (Lenart, 2003). Stands were selected island-wide to cover a diversity of forest types and a range of locations relative to the track of the hurricane (Fig. 1). Forests across the island of Puerto Rico were sampled for this paper, including stands in the Bisley and El Verde sections of the protected Luquillo Experimental Forest (LEF) of the Caribbean National Forest, state forests in the island's interior, and natural and managed forest stands on private and municipal land (Table 1). While individual stands were partially chosen because of their accessibility, plots within stands were sampled randomly. An additional 60 individual mounds were sampled outside of plots for potential comparison to the randomly sampled mounds.

The combined basal area of trees within each plot was assessed with a Bitterlich's Spiegel Relaskop. A hand-held clinometer was used to measure hillslope gradient at the plot scale. Aspect was taken using a Brunton compass corrected for local declination. Topographic categories of each plot were assigned as follows: *ridges* are local divides that receive no upland runoff; *slopes* are areas that both receive and transmit runoff; and *valleys* are low-gradient areas that concentrate runoff. Elevation values for sites were approximated to ±50 m using topographic maps. Forest types were assigned based on the Life Zone map in Ewel and Whitmore (1973). A map by the U.S. Global Change Research Program (2000) was used to derive precipitation during the 1998 hurricane event (using midpoint values for rainfall categories) and to determine whether the hurricane eye crossed a given plot.

Standing trees >10 cm dbh and uprooted trees of any size within each plot were noted as standing live, standing dead, snapped or uprooted, and classified as a needleleaf (typically *Pinus caribaea* or *Casuarina equisetifolia*), palm (*Prestoea montana*) or broadleaf tree (hundreds of species thrive in Puerto Rico). Tree diameter at breast height (1.3 m), bole length, slope of the fallen bole, ground slope, and treefall direction were measured on each fallen tree. Trunk area (i.e., trunk basal area) as derived from diameter at breast height [BA = $\Pi\ (1/2\ d)^2$), was used to represent tree size because values could be summed when more than one bole formed a single mound/pit complex. Mounds and pits were

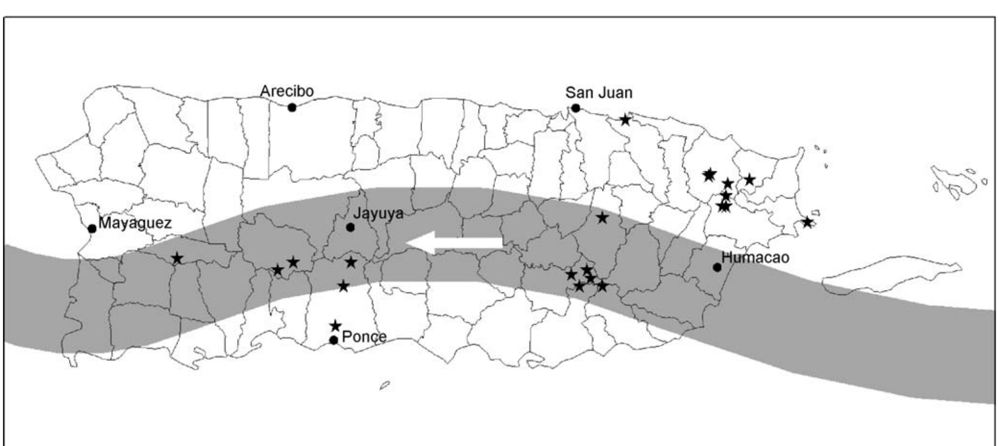

Fig. 1. Path of 1998 Hurricane Georges across Puerto Rico; Xs indicate approximate locations of the 21 sites from which 42 plots were sampled in this study.