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Domination of hillslope denudation by tree uprooting in an old-growth forest

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ABSTRACT

Razula forest preserve in the Carpathian Mountains of the Czech Republic is an unmanaged forest that has not been logged or otherwise anthropically disturbed for at least 83 years, preceded by only infrequent selective logging. We examined this 25 ha area to determine the dominant geomorphological processes on the hillslope. Tree uprooting displaces about 2.9 m^3 of soil and regolith per year, representing about 1.5 uprooted trees $ha^{-1}\ yr^{-1}$, based on forest inventory records dating back to 1972, and contemporary measurements of displaced soil and pit-mound topography resulting from uprooting. Pits and mounds occupy >14% of the ground surface. Despite typical slope gradients of 0.05 mm^{-1}, and up to 0.41, little evidence of mass wasting (e.g., slump or flow scars or deposits, colluvial deposits) was noted in the field, except in association with pit-mound pairs. Small avalanche and ravel features are common on the upslope side of uproot pits. Surface runoff features were rare and poorly connected, but do include stemwash erosion associated with stemflow. No rills or channels were found above the valley bottom area, and only small, localized areas of erosion and forest litter debris indicating overland flow. Where these features occurred, they either disappeared a short distance downslope (indicating infiltration), or indicate flow into tree throw pits. Surface erosion is also inhibited by surface armoring of coarse rock fragments associated with uprooting, as well as by the nearly complete vegetation and litter cover. These results show that the combination of direct and indirect impacts of tree uprooting can dominate slope processes in old-growth, unmanaged forests. The greater observed expression of different hillslope processes in adjacent managed forests (where tree uprooting dynamics are blocked by management activities) suggests that human interventions can change the slope process regime in forest ecosystems.

1. Introduction

The key geomorphological role of vegetation on hillslopes is generally one of stabilization. Root systems increase shear strength and overall resistance of regoliths, plants and organic litter shield the surface from raindrop impacts and reduce surface runoff, and living bodies of woody species and coarse woody debris may provide barriers to downslope sediment movement. However, trees may also promote weathering of underlying bedrock and displace mass via root and trunk growth (Lutz and Griswold, 1939; Gabet and Mudd, 2010). Uprooting may be significant as a primary mechanism of downslope mass movement, or may secondarily promote erosion by exposing bare soil. Uprooting also creates distinctive pit-and-mound topography, which has important influences on geomorphic, pedological and ecological processes. Despite the contributions of trees to weathering and mass movements, it is clear that the net, global effects of trees (compared to a hypothetical unvegetated landscape) is to reduce the susceptibility of hillslopes to mass movements and erosion (see reviews by Selby, 1993; O'Loughlin, 2005; Marston, 2010; Schwarz et al., 2010; Pawlik, 2013). In this study we explore the idea that in some cases in unmanaged, old-growth forests, sediment transport on hillslopes may be both severely inhibited in amount and dominated in type by tree uprooting and the resulting topography. We do this via an inventory of field evidence of slope erosion, mass wasting, and soil mixing processes in an old growth forest in the Czech Republic, a site where extensive effects of tree uprooting have already been documented, situated within a region where slope movements are very common.

Exceptions to the general rule of hillslope stabilization by woody vegetation have been noted previously. The generally prevailing downslope direction of uprootings as well as post-disturbance erosion result in net downslope transport associated with tree uprooting and mass displacement (see reviews by Schaetzl et al., 1990; Wilkinson et al., 2009; Šamonil et al., 2010a; Pawlik, 2013). In a few cases, thus far

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noted only in the wet tropics, tree cover may have a net destabilization effect at the hillslope scale. Tree-enhanced infiltration can contribute to slope destabilization due to increases in pore-water pressure, as Thomas (1994) noted for some tropical environments. Vorpahl et al. (2013) found that in some tropical forests massive organic layers accommodate the majority of roots, so that roots are not effective in anchoring underlying soil. Furthermore, accumulation of organic layer and living biomass may have a destabilizing effect on steep slopes due to its great mass (Vorpahl et al., 2013).

An additional complication is that while tree uprooting may promote denudation in the short term due to bioturbation and downslope transport, its effects can stabilize slopes over longer time scales. The latter occurs because pits may serve as sediment traps, and mounds are often stabilized by vegetation. After pit-and-mound microtopography is created it can persist for centuries (even thousands of years in some cases; Šamonil et al., 2013). Mounds are favorable sites for tree reestablishment, and are often protected by trees growing on them. Pits and tree trunks lying parallel to contour lines promote deposition (Šebkova et al., 2012; Pawlik, 2013).

In a short-term perspective biogenic transport processes are apparently stochastic, and discrete in space and time (Roering et al., 1999; Gabet and Mudd, 2010). Tree uprooting is often cited as an example, though in at least some cases tree establishment and uprooting is self-reinforcing and non-random (Šamonil et al., 2014; Shouse and Phillips, 2016). However, over longer time scales the continuous activity of such discrete biologically driven hillslope processes are essentially diffusive (Carson and Kirkby, 1972; Preston, 2004). Diffusive processes are controlled by hillslope morphology (slope length, angle, curvature) and influence post-disturbance sediment flux (e.g. Roering et al., 1999). During the last 50 years several mathematical models of hillslope evolution were developed that took slope angle and curvature as the most important variables controlling sediment transport rates (see Roering, 2008; Gabet and Mudd, 2010). While the models described above indicate that tree uprooting over millennial time scales is primarily associated with diffusion (Roering et al., 1999, 2010; Preston, 2004) numerous exceptions exist. This is true for pit-and-mound topography that can persist for hundreds of years or more when only minor downslope transport may occur. Thus, diffusivity commonly attributed to biogenic activity on hillslopes is halted or slowed.

Whatever effects forest vegetation may have on slope geomorphology, those impacts not only vary geographically, but also over time at a given site. Gallaway et al.'s (2009) studies in the Canadian Rockies, for instance, show that effects of trees on sediment transport vary with the age of forests or stage of vegetation development, and with the timing and frequency of fire. In the mountains of central Europe, forest effects on slope failures, erosion, and regolith development vary with vegetation type, forest disturbances (e.g., blowdown events), and hydrometeorological disturbances (Pawlik et al., 2013, 2016; Šilhán et al., 2014).

From the literature it is clear that trees, both as individuals and as cover, may have a variety of geomorphic impacts. These include critical roles in weathering and soil formation, bioprotection and hillslope stabilization, bioturbation and other biomechanical effects, and indirect geomorphic impacts via effects on hydrology and microtopography (see reviews by Pawlik, 2013; Pawlik et al., 2016). These effects vary geographically and temporally, and it is not always clear which of the multiple geomorphic impacts of trees and forests are dominant. This study is a contribution to better understanding the geomorphic impacts of trees, in this case focusing on hillslope denudation in an unmanaged, old-growth forest. The unmanaged state presumably characterizes forest landform and ecosystem development over most of the Quaternary, and also provides some basis for assessment of management effects.

In this study we evaluate the influence of trees on hillslope geomorphic processes at an unmanaged, old-growth forest, the Razula Reserve in the Outer Western Carpathians region of the Czech Republic, near the border with Slovakia (Fig. 1). The site is underlain by flysch bedrock, and

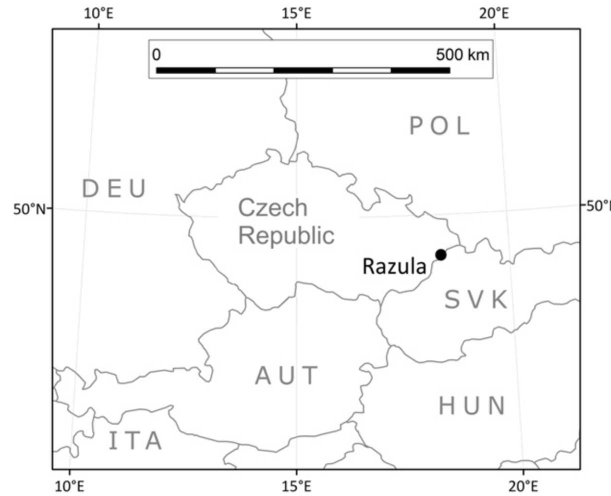

Fig. 1. Study area location map.

forest cover is dominated by European beech (*Fagus sylvatica*). Tree uprooting has previously been studied and inventoried at the site, and in fieldwork we noted limited evidence of surface runoff, sediment erosion or deposition, or mass wasting except in the vicinity of tree uproot pit-mound pairs, though geomorphic studies have found slopes in the region highly susceptible to failures. This motivated us to investigate the role of uprooting in the overall sediment regime of the hillslopes.

The working conceptual model and hypothesis is that forest vegetation, coarse woody debris, and litter cover inhibits surface runoff and erosion (as is the case in many forests), while uproot pit-mound systems dominate short-range topography and limit surface hydrological connectivity. As a result, pit-mounds are highly localized "hot spots" of geomorphic activity surrounded by zones of slow, limited surface processes. Thus at the scale of hillslope, geomorphic processes are hypothesized to be dominated by the direct and indirect influences of individual trees and forest cover.

2. Background

2.1. Geomorphic effects of uprooting

Uprooting of trees (also called treethrow, wind throw, root throw or tree fall; Šamonil et al., 2010a) usually occurs during storms with strong winds, though ice storms can also trigger uprooting, and excessive rainfall resulting in very high soil wetness can increase uprooting propensity. Uprooting typically involves excavation of the soil and regolith around the roots, with this mass termed a rootwad. As the tree decays (or burns) the mass of the rootwad is deposited as a local topographic high adjacent to the depression from which it was removed. The result is a characteristic pit-mound topography. In addition to the bioturbation and creation of pit-mound features, uprooting sometimes results in the "mining" of underlying bedrock where tree roots have penetrated the rock, at least temporarily exposes bare soil to erosion, and results in a net downslope movement of mass where slope gradients are significant. These geomorphic impacts have been reviewed by, e.g., Gallaway et al. (2009), Gabet and Mudd (2010), Šamonil et al. (2010a), and Pawlik (2013).

Geomorphic impacts of tree uprooting on hillslopes include:

1. Disturbance of hillslope surfaces, changing roughness and heterogeneity (decadal and centennial effects are frequently involved)
2. Immediate changes in hillslope hydrology due to canopy gaps (higher portion of rain water reaches the ground), surface gaps (pits) and local topographic change (mounds), resulting in changes in surface wash, erosion and deposition.