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Pit-mound microrelief in forest soils: Review of implications for water retention and hydrologic modelling

Martin Valtera [a,*], Randall J. Schaetzl [b]

[a] Department of Forest Ecology, Silva Tarouca Research Institute for Landscape and Ornamental Gardening, Lidická 25/27, 602 00 Brno, Czech Republic
[b] Department of Geography, Environment, and Spatial Sciences, 673 Auditorium Rd, Michigan State University, East Lansing, MI 48823, USA

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ABSTRACT

Forest ecosystems are known for their capacity to retain and redistribute water. Nevertheless, even in some forested watersheds, prolonged or intense rainfall events often exceed the retention threshold of the system, generating accelerated runoff. Surface microrelief is an important attribute of forest ecosystems that often act to mediate potential runoff. In most natural forests, the soil surface is typically unevenly broken with pit and mound microrelief, formed by both historical and recent tree uprooting events. In managed forests, however, tree uprooting is traditionally seen as undesirable. The systematic repression of this process may lead to gradual loss of microrelief. To date, little attention has been paid to the impacts of the pit-mound microrelief, or its absence, on forest hydrology. Restoration of naturally undulating microrelief in managed forests can help to accentuate water retention and mitigate runoff, while reducing drought stress and reinforcing forest productivity and resilience.

This paper summarizes the literature and presents insights on the effects of tree uprooting on the microrelief of forest soils and forest hydrology, focusing on its consequences to water retention, tree water supply, and forest health. Furthermore, we explore the mechanisms and possible consequences of the long-term repression of these processes in intensively managed forests, with implications for forest management and further research.

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* Corresponding author.
E-mail address: martin.valtera@vukoz.cz (M. Valtera).

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1. Introduction

Various forecasts of climate change foresee the continuing rise in the incidence of hydrological extremes such as floods and prolonged droughts, which may cause an increased hazard to terrestrial ecosystems, global water resources, production, and human society (Allen et al., 2010; Ciscar et al., 2014; Dai, 2011). The main factors to be concerned with are (i) decreased effectivity of water retention on the land, particularly in urban and agricultural soils, therefore (ii) increased heating, especially over the land surfaces with limited evaporation (Bates et al., 2008; Dai, 2011; Jung et al., 2010), which in turn may result in (iii) more intense precipitation events in cooler (usually upland and forest) areas (Pielke, 2001). These aspects will result in increased demands on forest ecosystems for water retention and mediation.

Soils and vegetation play a crucial role in terrestrial water cycling, as they intercept, retain, store and recycle water. In forest ecosystems, vegetation intercepts precipitation, lessening runoff and accentuating infiltration and groundwater recharge. Indeed, forests are recognized as the most effective runoff retarders and water recyclers from among all terrestrial ecosystems (Archer et al., 2013; Makarieva et al., 2013). However, even in forested catchments, a prolonged or intense rainfall (or rapid period of snowmelt) often exceeds the retention threshold of the system, generating accelerated runoff (Tromp-van Meerveld and McDonnell, 2006).

Surface microrelief, a common feature in most forests, is an important component of slope hydrology (Frei and Fleckenstein, 2014; Kishné et al., 2014; Thompson et al., 2010; van der Ploeg et al., 2012). The soil surface in forests is characterized by microtopographic irregularities formed by various natural processes and/or by human activities. In natural forests, the soil surface is typically unevenly broken with paired pits and mounds, formed by both historical and recent tree uprooting events. The impacts of this type of microrelief, with its indirect impacts on soil formation and forest ecology, have been studied since the first half of the last century (Beatty and Stone, 1986; Denny and Goodlett, 1956; Lutz, 1940; Lyford and MacLean, 1966; Stephens, 1956). Several comprehensive reviews have been dedicated to the mechanisms of soil disturbance and the various ecological and pedological impacts of tree uprooting (Schaetzl et al., 1990; Schaetzl et al., 1989a,b; Šamonil et al., 2010a). However, no study to date has quantified, or reviewed the effects of these types of pits and mounds on forest hydrology. This paper addresses that deficit by summarizing the pertinent literature and bringing together new insights on the effects of tree uprooting on the microrelief of forest soils and hydrology. We choose to focus on the consequences of surface microrelief to water retention, tree water supply, and forest health. Furthermore, we explore the mechanisms and possible consequences of the long-term repression of these processes in intensively managed forests. We hope that this study will initiate further research on the importance of soil-surface microrelief formed by tree uprooting on forest hydrology. Such work might include future direct hydrological measurements and experimental verifications of some of the processes outlined in this paper, and wider inventories of the treethrow pits and mounds in forests, thereby enabling quantifications of their contribution to the hydrology of these types of watersheds.

2. Hydrological function of forests

Forest ecosystems are an essential component in the terrestrial water cycle. Their high capacity to retain and redistribute water is usually attributed to: (i) the high specific area of the aboveground biomass (Myneni et al., 2002); (ii) the presence of a litter mat (Stuart and Edwards, 2006), and macropores, which retain moisture and reduce the potential negative effects of soil freezing on infiltration (Isard and Schaetzl, 1995; Lin et al., 2008; Stuart and Edwards, 2006); (iii) the deep penetration of forest soils by roots and the formation of highly permeable root channels (Jost et al., 2012); and (iv) water uptake by trees (Nadezhdina et al., 2010). Much of the precipitation impacting forest ecosystems is captured at the vegetation-atmosphere interface (interception), and only slowly delivered to the soil surface. Here, it is eventually allowed to infiltrate into the soil, where it is further utilized by plants or stored in the deeper groundwater reservoirs (Lin et al., 2008). Moreover, comparatively high evapotranspiration rates in most forest ecosystems increase atmospheric humidity locally, and substantially reduce or moderate air and soil temperatures (Pokorný, 2001). Thus, the effect of water retention in forests is crucial not only for their own water supply, but also for the water budget of the larger ecosystem (Makarieva et al., 2013). Therefore, the joint management of forests and water resources has become one of the leading environmental and economic issues of both global and local policy makers (Bates et al., 2008; European Commission, 2013), and in hydrological research (Rewald et al., 2011; Vose et al., 2011).

Forest structure and composition, as well as soil properties, are important synthetic factors of soil moisture and runoff dynamics in forest ecosystems, and significantly influence their ability to protect the lower parts of watershed against floods during extreme hydrological events (Hümann et al., 2011; Jost et al., 2012). Nonetheless, most studies on soil water dynamics in forests have focused on the effects of the aboveground structures of the forest stand (Schume et al., 2004; Vertessy et al., 2001), or the belowground structures in soil and tree-root systems (Lin et al., 2008; Nadezhdina et al., 2010). Other key physiographic attributes that control soil water dynamics are topographic features (Bachmair and Weiler, 2012; Lin et al., 2008; Yeakley et al., 1998), including soil surface microrelief (Frei and Fleckenstein, 2014; Martin et al., 2008; Thompson et al., 2010; van der Ploeg et al., 2012), which is the focus of this discussion.

3. Microrelief in forest soils

3.1. Types and factors of soil surface microrelief

Surface microrelief (here considered at the scale of decimeters to meters) in forests is formed by natural processes and/or by human activities. The most common anthropogenic causes of forest-soil microrelief formation are the wakes after mechanical soil preparation, traces of axles, scratches after skidding, or excavations along forest roads. Although some exceptions exist (see Hupy and Schaetzl, 2008), all of the most common anthropogenic elements of soil microrelief in forests have a linear character, hence serving as potential water-discharge accelerating structures (unless they run parallel to the contour; Schüler, 2006). Other forms (either natural or artificial) of microrelief in forest soils include trenches, rills, or other forms of microrelief, all of which act as water-discharge agents, and are outside the scope of this paper.

Moreover, soil surface microrelief in forests can form in many other natural ways, mostly generating point features that do not promote concentrated runoff. Beyond some site-specific, less obvious, or easily-erodible microrelief features formed by soil fauna (Gabet et al., 2003; Richards et al., 2011; Wilkinson et al., 2009), and substrate- or climate-specific microrelief formed by various physical forces, such as wind accumulation, argilliturbation (e.g., gilgai microrelief; Kishné et al., 2014), or cryoturbation (e.g., frost heaving and patterned ground), surface microrelief in forests is