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Percolation through leaf litter: What happens during rainfall events of varying intensity?

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SUMMARY

Simulated rainfall experiments with a layer of eucalypt leaf litter showed that the flux of percolate emerging from the layer was influenced by the intensity profile of the incident rainfall. Experiments involved several different fixed rainfall intensities, and also seven different temporal patterns of changing intensity (event profiles). The event profiles all had a mean intensity of 10 mm/h and the same 30 min duration, but included intensity bursts or peaks of up to 100 mm/h early or late within the event, as well as events with multiple intensity peaks.

The litter percolate flux associated with early rainfall intensity peaks was typically attenuated by nearly 50% in comparison with the intensity of the incident rainfall. In contrast, percolate flux from late rainfall peaks was often magnified, in some cases by up to 360%. Even under rainfall of constant intensity, the percolate flux exhibits fluctuations of about ±25% of the mean flux. In most cases, peaks in percolate flux lagged peaks in the incident rainfall by 4–5 min.

The potential importance of diminished or enlarged litter percolate fluxes is their effect on water partitioning and the potential for lateral flow within and beneath litter layers, especially if the peaks in percolate flux exceed local soil infiltrability.

1. Introduction

Plant litter falls toward the ground where, perhaps dispersed slightly by wind and more so by water (Burnham et al., 1992), it accumulates to form a porous barrier between the mineral soil and the lower atmosphere. Litter accumulation is a characteristic of diverse ecosystems, from arid shrublands to tropical rainforests. In places, litter rests loosely on the mineral soil. In contrast, in some forests, the litter forms just the uppermost zone of the thicker forest floor, which also includes organic material in various stages of decay. In the remainder of this paper, ‘leaf litter’ is used to refer solely to the layer of undecomposed plant material. As noted below, leaf litter often contains subsidiary components of bark, twigs, and other plant materials.

The litter layer modifies bidirectional fluxes of liquid water and water vapor (Matthews, 2005), and influences soil moisture and evaporation from the soil. In turn, litter moisture content can affect fire behavior and so drive temporal changes in litter loading (Hoffmann et al., 2012). Litter layers also interact with rainfall, throughfall, and overland flow in ways that can be erosionally significant, modifying splash and scour processes (Meginnis, 1935; Bochet et al., 1998; Sato et al., 2004; Sayer, 2006).

The interactions among rainfall, throughfall, standing vegetation and plant litter lying on the soil surface are of concern to forest hydrologists and others interested in the partitioning and disposition of rainfall. Many studies made through the last century explored rainfall interception and the water-holding capacity of plant materials (Horton, 1919; Lowdermilk, 1930; Jack, 1935; Clark, 1940; Moul and Buell, 1955; Bernard, 1963; Park et al., 2010; Li et al., 2013). During rainfall or throughfall, splash on foliage and woody plant parts, as well as on litter, may produce impact droplets whose large surface area to volume ratios result in rapid evaporation, contributing to interception losses (Dunkerley, 2009). The interaction of rain and throughfall with standing vegetation affects the timing and flux of released throughfall falling from the canopy, as well the drop size and erosive energy of the flux of throughfall drops incident at the ground surface. Many of these modifications have the potential to affect the rate of splash dislodgment of soil, or the size of the particles that could be moved, and other processes on exposed surfaces (Miyata et al., 2009). However, water drops arriving at a litter layer (rather than bare soil) undergo further interactions, including additional splash, absorption, and adhesion depending upon the character of the litter. The time-varying flux of rainfall and/or throughfall arriving at a

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litter layer differs from that of the open-field rainfall, owing to water retention and gradual liquid flow and drip processes in the canopy overhead. The throughfall flux may be larger (beneath preferential drip points) or lower (at site sheltered by branches or thick foliage), and in general exhibits different temporal variations, such as delayed start and continuation after the cessation of rainfall, to the open-field rainfall. It seems probable that when water passes through litter layers, the spatio-temporal characteristics are again modified, such that the flux of percolate emerging from the base of the litter layer and finally onto the uppermost mineral soil differs in timing and magnitude from the rainfall/throughfall (hereafter, simply 'rainfall') flux arriving at the top of the litter layer. The spatio-temporal variability of the percolate flux during rainfall have not been widely studied. Thus, whilst there are published studies of the ways in which rainfall intensity, drop size, and other characteristics are altered by plant canopies to yield a distinctive throughfall drop population (Nanko et al., 2006), we lack a corresponding understanding of how the intensity of the rainfall incident on a litter layer is altered by passage through the litter to yield the percolate flux. This forms the subject of the present paper.

The specific research questions addressed here are as follows:

1. How does the flux of percolate emerging from a litter layer change in response to varying fixed intensities of rainfall?
2. Does increasingly intense rainfall result in larger amounts of water being stored in the litter layer at the end of rainfall? If so, how does the quantity held in the litter vary under different fixed rainfall intensities?
3. How does the flux of percolate emerging from a litter layer fluctuate during rainfall having a variable intensity profile? Does the litter layer damp or merely convey rainfall intensity fluctuations?
4. Do rainfall events having different intensity profiles result in differing amounts of water being stored in the litter layer at the end of rainfall? If so, how is the amount of water held related to the intensity profile of the rainfall event?

2. The nature of litter

Depending on climate, fire history, and other factors, the litter layer can develop to significant thicknesses, exemplified by the ~40 mm reported from 20 year unburned *Eucalyptus marginata* forest in Western Australia (Croton and Norton, 2001) or the ~60 mm reported under *Pinus pinaster* in France (Ogée and Brunet, 2002). For five types of forest in seven southern states of the USA, Ottmar and Andreu (2007) reported an average litter depth of ~37 mm (1.44 in.). Larger litter thicknesses have also been reported, including a mean of 86 mm under *Cryptomeria japonica* in Japan (Sato et al., 2004). In some kinds of forest, significant amounts of litter also accumulate within the canopy, on the surfaces of branches (Couto-Santos and Luizao, 2010), but this form of litter is not considered here. Leaf litter is continually broken down and decomposed (Gosz et al., 1973), and can also be actively transported downslope (Steart et al., 2006; Abe et al., 2009; Funada et al., 2009). Thus, the period since litterfall, and the frequency of movement and restructuring of the leaves and other organic components, can be reasoned to also affect the porosity and hydraulics of litter layers. Classifications of litter according to composition and form of the component litter items have been devised, though these were intended primary for the description and analysis of forest floor habitat as it relates to litter-dwelling fauna (e.g. Heatwole, 1961). These recognize that there are significant variations in the porosity of different kinds of litter, and in the size of the interstitial spaces within the litter. A classification suitable for the study of litter hydraulics does not appear to have been formulated. Litter properties have however been measured for many different litter types. Ogée and Brunet (2002) studied a 5–6 cm thick litter layer comprised of pine needles and grass. For this litter, the porosity was 95% and the bulk density 42.5 kg/m^3. Matthews (2005) investigated litter from *Eucalyptus globulus*, and reported bulk density of ~37 kg/m^3, and about 6% of the litter volume occupied by leaves (porosity 94%). Matthews (2005) additionally reported reduced porosity in decomposed *E. globulus* litter, of about 73%. From the Lake Tahoe basin, Banwell and Varner (2014) reported litter bulk densities in the range 14.4–43.8 kg/m^3. Litter loadings vary widely, from <1 t/ha in drylands (Sharafatmandrad et al., 2010) to >10 t/ha in humid forests (Couto-Santos and Luizao, 2010).

3. The hydrologic influences of litter layers – brief review

Research has highlighted a number of roles of litter, especially forest floor litter, in modifying infiltration, the generation of overland flow, and erosion (Lowdermilk, 1930; Walsh and Voigt, 1977; Miyata et al., 2009). Some studies have focused on the water-holding capacity of litter, and the potential for storage within the litter to reduce the proportion of throughfall ultimately reaching the mineral soil. For instance, Lowdermilk (1930) immersed baskets of litter in water and subsequently observed their weight gain once gravity drainage was complete. He reported that litter samples could retain water amounting to 200–300% of their dry weight. Immersion of litter samples for 24–48 h has been used by later workers also (e.g. Gillon et al., 1994). Putuhena and Cordery (1996) reported litter storage capacity of 1.69 mm (eucalyptus litter) and 2.78 mm (pine litter), as estimates of the interception capacity of the forest floor. Others have reported comparable values (e.g. 2.76–3.2 mm, Zhang et al., 2009). Despite these significant interception losses, there is a widespread view that at the same time, litter enhances infiltration and thereby increases the soil moisture content (Sayer, 2006; Asiedu et al., 2013). Litter may also act as a mulch, reducing vapor transfer to the atmosphere.

3.1. Interception on litter

The interception of rainfall on litter forms one component of the overall effect of litter on infiltration and the generation of overland flow. Litter interception losses have been investigated primarily in the context of forest vegetation. Following field measurements, Helvey (1964) estimated that at Coweeta, about 3% of the gross annual rainfall was intercepted, and cited comparable results from prior studies at other locations where litter interception ranging from 2% to 34% of gross rainfall had been estimated. A similar range was reported by Helvey and Patrick (1965). From Texas, Thurow et al. (1987) reported that litter interception under oak mottes was 20.7% of the annual rainfall. Sato et al. (2002) reported a range of 1.3–9.9% of monthly gross rainfall, while Bulcock and Jewitt (2012) found 6.6–12.1% of gross rainfall. For a mulch of wheat straw, Cook et al. (2006) reported 10.7% of gross rainfall intercepted, though for smaller rainfall events on straw mulch, Price et al. (1998) reported interception of 44%. Tsiko et al. (2012) reported loss of 19% in Msasa leaf litter in Zimbabwe. Another high result, 10–19% interception of gross rainfall, was reported by Sun et al. (2013) for forest floor interception. For prairie litter, Brye et al. (2000) reported interception loss of ~70% of gross rainfall, and this appears to be at the upper end of the reported range of data for litter or crop residue interception losses. Interception loss of up to 50% of incident throughfall was reported for moss cover by Moul and Buell (1955).

It appears that, in terms of the annualized interception loss arising on litter, residues, and soil microphytes, the range is wide, from 1–2% to 50–70% of gross rainfall. There are inconsistencies in