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Throughfall heterogeneity in tropical forested landscapes as a focal mechanism for deep percolation

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SUMMARY

Forest structure can both reduce and intensify precipitation inputs to the ground surface at fine spatial scales. Areas of localized input at the soil surface may have large effects on deep drainage because of the strongly nonlinear relationship between soil water content (SWC) and unsaturated hydraulic conductivity. We therefore explored the following questions: Does forest structure that creates high spatial heterogeneity in canopy throughfall also create associated deep percolation pathways capable of quickly moving water beyond the rooting zone? Or alternatively, do soil properties resulting from biological activity (e.g. root networks) reduce SWC heterogeneity created by the focused inputs from the canopy and eliminate the potential for these deep percolation pathways? We explored these questions by measuring spatial variation in both throughfall and SWC within 8 forested plots of the Sarapiquí region, Costa Rica where soil texture is relatively homogeneous within deep, clay-rich soils. A novel method that combined soil augering and frequency domain reflectometry was used to assess SWC profiles below the most extreme wet and dry throughfall locations within each plot. Findings revealed relatively homogeneous soil moisture within the surface root zone (0–90 cm depth) with SWC values of roughly 45%. Below the root zone, SWC heterogeneity increased, with the wettest throughfall sites having significantly ($\alpha = 0.05$) higher SWC than their paired driest throughfall end-members (by 2–15%). Below approximately 130 cm depth, SWC homogeneity was observed again. Physically-based modeling in HYDRUS-3D supports these findings and suggests processes that may explain these changes in SWC patterns observed with increasing depth, such as redistribution through macropores, focused deep-percolation, and lateral downslope flow, respectively. This is the first field-based study that explores the linkage between throughfall heterogeneity and focused deep-percolation, and therefore advances the integrated understanding of how the structure, diversity, and spatial heterogeneity of forests influence their hydrologic outputs.

1. Introduction

Landscape conversion is occurring at unprecedented rates worldwide, with many forest systems being replaced by alternate land uses such as pasture or fields. As a consequence, landscape processes that are driven by the amount and type of vegetation cover, such as canopy interception and surface infiltration, can also change dramatically. Previous work has found that forest patches increase infiltration relative to adjacent non-forested areas (Ludwig et al., 2005; Niemeyer et al., 2014). This may be due to several factors, including compaction and loss of macropore networks in non-forest soils (Trimble and Mendel, 1995). At a finer scale, another process linked to infiltration dynamics is throughfall, whereby plant canopies redistribute, reduce, and in some cases, locally increase precipitation at the ground (Levia and Frost, 2006). The focusing of throughfall has been found to be temporally consistent at time scales relevant to hillslope and watershed processes (Raat et al., 2002; Keim et al., 2005; Zimmermann et al., 2009). Theoretically, increased precipitation at specific locations under a vegetation canopy should create focused pathways for

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deep percolation due to the strongly nonlinear relationship between soil water content (SWC) and hydraulic conductivity (e.g. Van Genuchten, 1980). Modeling investigations have begun to incorporate this nonlinear relationship into throughfall and deep percolation processes at plot and hillslope scales relevant to streamflow generation, with previous results suggesting a large increase in downward deep percolation rate due to focused throughfall, ranging from 129% (Guswa and Spence, 2011) to 300% (Keim et al., 2008) relative to homogenously distributed throughfall. Despite the strong theoretical basis and simulated examples, direct field measurements of combined throughfall and SWC patterns are lacking, and are therefore needed to assess the reality of this process's existence in forested landscapes.

In this study, we assess the role of heterogeneous throughfall in creating focused deep percolation pathways capable of facilitating the movement of water rapidly beyond the root zone using a combination of observational and simulated data. We explore two main questions: (1) Does forest structure that creates high spatial heterogeneity in canopy throughfall also create rapid deep percolation pathways? Or, alternatively, (2) do soil properties resulting from biological activity in the shallow soil, such as root development, homogenize these soil water inputs created by the focused canopy throughfall and eliminate the potential for focused deep percolation pathways below the surficial root zone? Beyond these questions, this study seeks to aid an interdisciplinary objective of understanding how biodiversity, and in particular structural diversity of forest canopies, impacts the movement and transfer of water through tropical forest systems. A companion study (Chain-Guadarrama et al., in preparation) addresses related questions regarding canopy structural and functional properties and their relationship to throughfall patterns across both old-growth and secondary tropical forests. In combination, these studies seek to understand the impacts of alternative forms of forest cover on the provisioning of water as an ecosystem service.

2. Materials and methods

2.1. Site description and throughfall collection

The study was located within the Sarapiquí region of Costa Rica, a lowland plain within a humid tropical climate on the windward side of the central Mesoamerican volcanic range. Soils in the region are uniform, deep (>5 m), clay-rich Ultisols, which are characterized by spatially uniform soil textures. Fluvial processes have created a hummocky topography with small high-relief hillsides up to 30° in slope. Additional detailed descriptions of the landscapes characteristics can be found in McDade et al. (1994) and Finegan and Camacho (1999).

Fieldwork was conducted over an 8-week period during the rainy season from July to September of 2011. Mean rainfall rates within the region during the study period were ~10 mm/day (Chain-Guadarrama et al., in preparation), produced by high-intensity convective storms that developed nearly every afternoon. Additional rainfall and throughfall metrics can be found in Section 3.2.

Fourteen 1-hectare forested plots (Fig. 1) were selected to measure throughfall spatial heterogeneity. Plots corresponded both to old- and secondary-growth forests encompassing a range of taxonomic and functional composition (Finegan et al., 1999; Chazdon et al., 2010). The secondary-growth forest ranged in age from roughly 20 to 50 years since abandonment. These 14 forest plots are characterized by high stem density and high species richness, with an average of 563 individuals ⩾10 cm dbh per hectare, corresponding to an average basal area of 29 m^2 per hectare, with 98 tree and palm species represented. Heterogeneous stand structure and varying height classes of vegetation exist in these wet tropical forests, particularly within the oldest forests where both taller stature and a greater rate of mortality and windfall of adult trees creates larger heterogeneity within the canopy (Guariguata and Ostertag 2001; Montgomery and Chazdon 2001). Secondary-growth forests in this region rapidly reach structural characteristics (basal area and stem density) of old-growth forests, with higher density of adult canopy palms (Guariguata et al. 1997). Leaf area index (LAI) values of secondary- and old-growth forest in this region have been estimated between 5.20 and 5.62 $m^2\ m^{-2}$ (Tang et al. 2012), with canopy trees, lianas and palms accounting for 89% of total LAI (Clark et al. 2008).

Within each plot, 25 throughfall collectors were systematically placed 20 m apart in a gridded pattern to cover the entire spatial extent of the plot (Fig. 1); an additional reference collector was placed outside the plot in the nearest unobstructed clearing. Collectors were constructed as cylindrical low-density polyethylene (A = 182 cm^2) containers similar to the traditional funnel-type collectors common for distributed throughfall sampling (Zimmermann and Zimmermann, 2014). Collectors were installed ~1 m above the ground surface so as to accurately measure throughfall variations created by the largest-order canopy size class and thus minimizing highly localized variations due to small (sub-meter) herbaceous understory vegetation. Throughfall was measured manually on a weekly basis during the experiment.

The methods and results for the throughfall work are further expanded in Chain-Guadarrama et al. (in preparation). This throughfall sampling scheme, combined with the complexity of the forest stands sampled, allowed for accurate measurement of total plot-level weekly throughfall within 5–15% relative error (Zimmermann and Zimmermann, 2014); had a relative error of under 5% been desired, approximately 100–200 collectors per one-hectare plot would have been needed.

2.2. Measurement of volumetric water content in soils

We measured SWC profiles within 8 of the 14 forest plots (not all 14 were measured due to equipment failure). Half of the 8 measured plots occurred within secondary-growth forests, while half occurred within old-growth forests. Within each plot, SWC profiles were measured adjacent to the throughfall collectors with wettest and driest throughfall measurements, as determined after at least one week of throughfall data collection. Vertical profiles of soil moisture were measured *in situ* by manual augering to access sequentially subjacent soil layers. Augered holes were 8 cm in diameter. At each location, the soil was tested for SWC, texture (Thien, 1979), and presence or absence of roots at 20 cm increments, starting at the surface and continuing down to either 60 cm below the deepest observed roots, or to the maximum depth capable with the auger (~280 cm). The SWC at each undisturbed soil depth layer was measured *in situ* with a portable frequency domain reflectometry (FDR) probe (*Stevens Hydra Probe*) over an integrated volume surrounding the 5 cm long sensing tines (Seyfried et al., 2005) prior to disturbing the layer in order to access the subjacent layers. Measurements occurred between rainfall events, usually in the mornings because the augered holes filled with rainfall during events. Each plot was only sampled once, with both the wettest and driest throughfall sites sampled on the same day for each plot to account for antecedent rainfall conditions specific to each plot. This novel method for *in situ* SWC measurement was implored because installing long-term SWC probes would have disturbed the sites, potentially creating artificial deep percolation pathways.

2.3. Physically-based modeling

To test the conceptual validity of the findings, HYDRUS-2D/3D was used in 2D mode to simulate water transport in the vadose