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Small-scale topographic variability influences tree species distribution and canopy throughfall partitioning in a temperate deciduous forest

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ABSTRACT

At very large spatial scales, the impacts of topography, elevation, and aspect on throughfall variability are apparent. However, within relatively small catchments (<50 ha), differences in species composition induced by slight changes in elevation coupled with slope orientation, could result in sufficient canopy variability whereby throughfall hydrology would be definitively different across small gradients. This study aims to (1) quantify the differences in throughfall hydrology across small topographic gradients, (2) determine the variability of throughfall across such gradients, and (3) determine the seasonal effects on throughfall hydrology resulting from differences in species composition and growing niches.

Throughfall partitioning was measured during 15 sampling periods at 4 landscape positions including 3 hillslopes with aspects facing north (NF), west (WF), and south (SF) in addition to a flat area (F) situated in the center of a 12 ha deciduous catchment. Throughfall partitioning was significantly lower on the steepest SF plot (TF = 75.0%) than on the moderately sloping NF (TF = 83.9%, $p = 0.001$) and F (TF = 81.7%, $p = 0.037$) plots. SF also had the largest degree of throughfall variability (CV = 20.1), resulting from overlapping canopies, which led to higher rates of canopy interception. NF and WF plots exhibited the largest inter-seasonal differences with decreases in throughfall partitioning of 13.2% ($p = 0.013$) and 12.1% ($p = 0.052$), respectively, and corresponded to the largest differences in plant canopy indices (PAI) between seasons. Although slope and aspect were found to be distinguishing variables in our study, it was the influence of these variables on species composition that led to differences in throughfall quantity. Our study illustrates the systematic distribution of water resources across topographic positions within a relatively small forested catchment and highlights the need for additional consideration of topography-induced controls on microclimate and growing space, which ultimately influence water quality and quantity for effective management strategies.

1. Introduction

Forested ecosystems impact terrestrial water and nutrient budgets through the partitioning of precipitation into interception, throughfall, and stemflow. The partitioning of water into these three pathways is largely controlled by physiological and morphological traits related to forest composition; seasonality and the presence/absence of foliage; precipitation characteristics; and meteorological conditions. Subsequently, these pathways may become enriched in nutrients and other solutes via washoff of dry deposition that accumulated during antecedent dry periods (Kazda, 1990) and/or canopy leaching (Lovett and Lindberg, 1984).

The spatial variability of throughfall hydrology is the result of heterogeneous canopy cover. Variability in canopy density may arise from several inherent physiological traits such as stand density, crown cover percentage, and leaf area index (LAI), which contribute to throughfall variability. In managed pine plantations with evenly spaced canopies, throughfall increased systematically with decreasing stand density (Stogsdill et al., 1989). In tropical plantations, crown traits (e.g., LAI, crown openness, crown depth) and rainfall characteristics interacted to produce interspecific differences in throughfall partitioning among four commercially grown trees species (Park and Cameron, 2008). In a natural

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mixed-deciduous stand, intra- and interspecific differences in canopy density such as the contribution of branch drainage to throughfall generation at higher stand densities were observed to influence variability (André et al., 2011). At even smaller scales within a single canopy, spatial variability is induced by physical characteristics such as distance from stem, although a consensus does not exist whether this variability is systematic (Ford and Deans, 1978; Nanko et al., 2011; Staelens et al., 2006). However, throughfall variability has been shown to be stable across storm events at specific points beneath a leafed canopy (Keim et al., 2005). Consequently, throughfall monitoring requires careful attention to stand characteristics and tree dynamics to accurately quantify the hydrologic flux to the forest floor (Durocher, 1990).

Topography is also a significant factor determining the distribution of water resources across the landscape. Stands located at higher elevations, especially those above the average cloud base, are capable of generating greater total volumetric throughfall via cloud water condensation (Holder, 2004), which may also increase total solute flux (Köhler et al., 2015). The presence of tree canopies creates an abrupt increase in surface roughness, which subsequently introduces frictional drag to the horizontal movement of air masses (Weathers et al., 2001), resulting in increased deposition of airborne gases and sediments on foliar and woody surfaces in forested ecosystems. This property, in addition to the increased potential for atmospheric deposition resulting from the complex geometries of leaf surfaces, provides forest canopies with enhanced scavenging abilities and preferential access to passing air masses (Griffith et al., 2015; Hofhansl et al., 2010; Lovett et al., 1996). At lower elevations, differences in throughfall biogeochemistry between uplands and floodplains are less apparent, especially when studies are designed to monitor forest communities of comparable species composition between both landscape positions (Peterson and Rolfe, 1982). However, catchment aspect has been shown to affect throughfall partitioning, whereby slopes oriented towards oncoming storms receive more precipitation, resulting in overall greater throughfall (McJannet et al., 2007).

At very large spatial scales, the impacts of topography, elevation, and aspect on throughfall variability are obvious. However, within relatively small catchments, differences in these factors can create microclimate conditions that provide competitive advantages for specific species. Differences in species composition across small spatial gradients can be the result of slight changes in elevation and slope orientation that produce understory light and moisture conditions more favorable for regeneration and establishment of certain species (Siegert and Levia, 2011). As a result, these microclimate conditions result in forest canopies composed of predictable species assemblages, which influence throughfall hydrology and nutrient flux in unique ways, even across small topographic gradients. There are always instances of individual outliers resulting from random seed dispersal mechanisms (Nathan and Muller-Landau, 2000), but on the whole, microclimate conditions most greatly influence competition dynamics. Therefore, it is the objective of our study to (1) quantify the differences in throughfall hydrology across small topographic gradients, (2) determine the variability of throughfall across such gradients, and (3) determine the seasonal effects on throughfall hydrology resulting from differences in species composition and growing niches.

2. Site description

Data were collected at Fair Hill Natural Resources Management Area (FH-NRMA) in Fair Hill, Maryland in a 12 ha forested catchment (Fig. 1). Fair Hill NRMA is located in northeastern Maryland (39°42′N, 75°50′W) at an average elevation of 70 m above sea level within the Chesapeake Bay watershed. FH-NRMA is situated in the Piedmont physiographic region and is characterized as a humid subtropical climate with well-defined seasons. Mean 30-year (1981–2010) summertime (JJA) maximum temperature in northeastern Maryland is 30.9 °C (87.6°F) and average summertime minimum temperature is 18.3 °C. Mean 30-year wintertime (DJF) maximum temperature is 0.7 °C and average minimum wintertime temperature is −4.3 °C (MD State Climatologist Office, 2013). Mean 30-year total annual precipitation is approximately 1200 mm, with an average of 523 mm winter seasonal snowfall and the rest falling as rainfall with little annual variation (MD State Climatologist Office, 2013). The wettest season is autumn (320 mm), followed by summer (314 mm), spring (308 mm), and winter (262 mm). Frontal precipitation patterns are typical for fall, winter, and spring; convective precipitation events dominate the summer. Orographic precipitation does not occur at this field site as it is situated relatively close to sea level and changes in elevation throughout the catchment are minor (79.2–97.1 m). Sampling periods that experienced precipitation falling as snow or during periods of below-freezing temperatures were omitted from this study as solid state precipitation requires different collection methods and were not under the purview of this study.

Four study plots were selected within the 12-ha catchment based on landscape position in the watershed and include (1) a north-facing slope (NF), (2) a flat central area (F), (3) a west-facing slope (WF), and (4) a south-facing slope (SF) (Table 1). The site has a tree density of 225 trees ha^{-1} and a basal area of 36.8 m^2 ha^{-1}. Mean diameter at breast height (dbh) is 40.8 cm and mean canopy tree height is 27.8 m. The forest canopy is comprised of *Acer rubrum* L. (red maple), *Betula lenta* L. (sweet birch), *Fagus grandifolia* Ehrh. (American beech), *Liriodendron tulipifera* L. (yellow poplar), and *Quercus* species (white and red oak) as dominant canopy species while the midstory is principally *F. grandifolia* saplings (Fig. 2). Species distribution across the four landscape positions is variable and represents interspecific preferences for microclimate conditions induced by soil moisture and light availability. The dominant canopy trees are approximately 80–100 years old with a total Plant Area Index (PAI) of 5.3 m^2 m^{-2}. Leaf emergence begins in May with the growing season lasting through October when senescence begins. The dormant season is categorized as November through April.

3. Materials and methods

3.1. Throughfall collection

Throughfall gauges were constructed using 3.78 L high density polyethylene (HDPE) collectors fitted with 20.32 cm diameter funnels, which drained into the collecting apparatus and prohibited evaporation between sampling periods. At each of the four landscape positions, a 50 m by 50 m centrally located plot was designated for throughfall monitoring. Ten collectors were randomly placed on the hillslope of each of the four plots (NF, F, WF, and SF). During each collection period, throughfall volume from each gauge was measured, the gauges emptied, and randomly relocated on the respective hillslopes. Roving gauges, in contrast to stationary gauges, were selected for this study as roving gauges are shown to be more accurate in determining throughfall volume (Durocher, 1990; Lloyd and Marques-Filhode, 1988) and reduce the total number of gauges needed to correctly sample for the throughfall mean (Helvey and Patric, 1965; Rodrigo and Àvila, 2001). Throughfall volume was converted to a depth equivalent by dividing by the orifice area of the funnel (324.3 cm^2). Throughfall hydrologic fluxes were measured for one year beginning in September 2011 during