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Effects of wind-driven rainfall on stemflow generation between codominant tree species with differing crown characteristics

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ABSTRACT

Meteorological influences on the variability of stemflow generation can affect the hydrology, ecology and soil chemistry of wooded ecosystems, yet the effects of directional wind-driven rainfall on differential stemflow production remain relatively un-researched. This study examines the correspondence of directional wind-driven inclined rainfall with stemflow generation in individual tree crowns utilizing multiple correspondence analysis (MCA) and intrastorm observations at 5 min monitoring intervals. In general, preferential stemflow generation at Fair Hill was observed during episodes of inclined rainfall driven by wind from the east to north-northeast (33.76–101.25°). This was supported by MCAs which produced significant correspondences between stemflow production and periods of inclined wind-driven rainfall for nearly all monitored storm events. Intrastorm plots of stemflow production from dominant and subcanopy trees of each codominant species (*Fagus grandifolia* Ehrh. (American beech) and *Liriodendron tulipifera* L. (yellow poplar)) also verified this correspondence. Interspecific canopy characteristics of *L. tulipifera* and *F. grandifolia* affected crown position, canopy structural characteristics, and, thus, the canopy's response to inclined precipitation. The greater vertical canopy depth observed for *F. grandifolia* trees enabled them to more efficiently capture inclined rainfall for enhanced stemflow production; whereas, the greater horizontal surface area of *L. tulipifera* canopies enhanced their droplet capture efficiency and subsequent stemflow generation for periods of un-inclined rainfall. As inclined wind-driven rainfall occurred within a majority of rain events at this site, preferential stemflow production may be a significant process to consider when examining the spatial distribution of canopy-derived water fluxes to the forest floor of wooded catchments under similar meteorological conditions.

1. Introduction

Evaporation of intercepted rainwater within tree canopies can remove over one-third of precipitation inputs in deciduous ecosystems (Calder, 1990; Link et al., 2004; Klingaman et al., 2007). The remaining two-thirds of incident precipitation over forests is stored on bark and foliar surfaces, released as throughfall, or entrained as stemflow and channeled down the tree stem (Levia and Frost, 2003, 2006). Throughfall and stemflow in broadleaved deciduous forests range between 70–80% and 3–10% of bulk rainfall, respectively (*e.g.*, Helvey and Patric, 1965; Neary and Gizyn, 1994; Levia and Frost, 2003, 2006), and significantly affect the spatial and temporal distribution of hydrologic inputs to the forest floor (Levia and Frost, 2003, 2006). Despite a smaller percentage of incident precipitation attributed to stemflow, many recent studies have shown that stemflow can play significant roles in the hydrologic cycling, ecological functioning and soil chemistry of forested catchments (Klučiarová et al., 2008; Liang et al., 2009; Germer et al., 2010; Nikodem et al., 2010; Liang et al., 2011; Tanaka, 2011). For instance, Liang et al. (2007) observed stemflow gaining preferential access to subsurface hydrological processes on a hillslope and Klučiarová et al. (2008) discovered highly concentrated magnetic susceptibility measurements indicative of pollutant magnification within stemflow infiltration areas. Nikodem et al. (2010) further illustrated the potential for stemflow–subsurface interactions to magnify contaminants in soils using field data in HYDRUS simulations. It therefore stands to reason that investigating processes which affect stemflow inputs will permit a more comprehensive understanding of intrasystem hydrological and nutrient cycling dynamics in forested ecosystems.

Since tree canopies are spatially heterogeneous, crown structure plays a major role in determining the overall amount of rainfall captured by crown surfaces and, therefore, available for entrainment as stemflow generation (Crockford and Richardson, 2000; Levia and Frost, 2003; Levia et al., 2010; Van Stan and Levia, 2010). Structural traits enhance or diminish a canopy's ability to capture

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Table 1
Canopy structural traits for all monitored trees.

Species	*F. grandifolia*		L. tulipifera	
Size class	Large	Small	Large	Small
Height to top of canopy (m)	33.6	10.3	38.9	20.1
Height to bottom of canopy (m)	12.3	3.4	23.8	17.6
Canopy depth (% of total tree height)	63.4	67.0	38.8	12.4
Crown closure (%)	75	81	67	64
LAI ($m^2\ m^{-2}$)	5.1	4.8	3.0	3.3
dbh (cm)	74.9	10.3	73.1	33.7
Bark thickness (mm)	4	2	26	11

rain droplets as stemflow, including: leaf area index (LAI), crown closure, orthogonally projected surface area, crown area, and bark microrelief (Levia and Frost, 2003; Thyer et al., 2004; Fleischbein et al., 2005; Bulcock and Jewitt, 2010; Van Stan and Levia, 2010). Meteorological conditions interact with these morphological characteristics, complicating trends in stemflow production within and among storm events (Levia and Frost, 2003; Carlyle-Moses and Price, 2006; Germer et al., 2010). Some studies have examined stemflow production in relation to rainfall amount, intensity and duration (Crockford and Richardson, 2000; Kuraji et al., 2001; Manfroi et al., 2004; Carlyle-Moses and Price, 2006; Germer et al., 2010; Levia et al., 2010), but no study known to the authors has yet evaluated the effects of directional wind-driven rainfall on stemflow generation for canopies of contrasting morphology. This is a significant data gap as wind-driven rainfall can account for 80–90% of total precipitation in some catchments (Aldridge, 1975; Herwitz and Slye, 1995) and has been shown to significantly affect the spatial distribution of water captured by individual canopies within the stand (Herwitz and Slye, 1995). The resultant magnification of already-concentrated stemflow hydrologic (and related solute) inputs beneath these dominant canopies is, therefore, of great interest as these events may produce biogeochemical “hot moments” or induce “hot spots” of reactivity within soils (McClain et al., 2003).

The investigation of wind-driven rainfall and stemflow generation within storm events and canopies of contrasting morphology also advances our knowledge of how stemflow varies with meteorological and morphological conditions (Levia and Frost, 2003; Carlyle-Moses and Price, 2006; Germer et al., 2010; Levia et al., 2010; Van Stan and Levia, 2010). In particular, intrastorm monitoring by Levia et al. (2010) demonstrated that a direct relationship exists between stemflow generation and rain intensity across species of differing canopy structure and tree size. An examination of the role of stemflow generation in the presence of variable wind conditions may further elucidate interactions between interspecific morphological characteristics and stand dominance in collecting rainfall and affecting the variability of stemflow inputs to forest soils. Building on these earlier studies, this study seeks to understand the role of these complimentary mechanisms by investigating differential stemflow generation within a forest co-dominated by species of contrasting canopy structure and position by (1) quantifying the relationship between frequency of wind-driven rainfall and stemflow production through multiple correspondence analysis (MCA); (2) comparing intrastorm stemflow generation to variable wind speeds, directions, and rainfall inclination angles at 5-min sampling intervals; and (3) evaluating the occurrence of storm conditions conducive to preferential stemflow generation within an experimental broadleaved deciduous plot. To the knowledge of the authors, this investigation is the first to examine how intrastorm stemflow generation is affected by the interactions between directional wind-driven rainfall conditions, canopy architecture and stand dominance; and the first to utilize MCAs to investigate preferential stemflow generation within individual tree crowns.

2. Site description

The experimental stand is located within a 12 ha catchment at the Fair Hill Natural Resource Management Area (NRMA) satellite site of the Christina River Basin Critical Zone Observatory. Fair Hill NRMA is situated between the tip of the Chesapeake Bay and the northeastern corner of the tri-state (Delaware–Maryland–Pennsylvania) border. Due to the site’s proximity to the Chesapeake Bay and the Atlantic coast, its climate is temperate. According to the Maryland State Climate Office and the Delaware Environmental Observation System (DEOS), mean annual precipitation (30 year) is approximately 1200 mm, with little annual variation. Convective rainfall over the summer (June, July, and August) accounts for the largest percentage of mean annual precipitation (MD State Climatologist Office, 2008). Rainfall during the rest of the year is primarily frontal, with winter being the driest season (MD State Climatologist Office, 2008). Storm tracks vary slightly with season as the foliated season is dominated by more localized convective storm systems and the defoliated season by frontal cyclonic systems of more variable origin (Zishka and Smith, 1980; Davis et al., 1993). However, storm tracks across seasons tend to be dominated by movement from the southwest to the northeast, generating these two distinct wind directions during rainfall. Historically, nearly all snowfall occurs during the winter (December, January, and February), averaging 350 mm yr^{-1} (MD State Climatologist Office, 2008). Mean winter temperature is 1.2 °C and mean summer temperature is 23.1 °C (MD State Climatologist Office, 2008). Normal annual frost period ranges from 125 to 250 days (NRCS-WSS, 2010).

The study plot is situated on a moderate hill-slope (8–15%) with 225 trees ha^{-1} and a basal area of 36.8 $m^2\ ha^{-1}$. *Fagus grandifolia* Ehrh. (American beech) and *Liriodendron tulipifera* L. (yellow poplar) co-dominate the experimental plot, representing 46% and 32% of all identified trees (Van Stan and Levia, 2010), respectively. The leafless season began the first week of November and lasted until leaf-out at the end of April. For method evaluation purposes, one dominant- and one sub-canopy tree of each species were chosen for sampling to enhance the probability of capturing lateral canopy rainshadows. Average canopy tree height is 27.8 m with an average diameter at breast height (dbh) of 40.8 cm for all species within the experimental plot. No neighboring tree is taller than the chosen dominant *F. grandifolia* and *L. tulipifera* trees, and these dominant canopies are in the upper elevation quartile for all trees within a 50 m radius of the study site (Lepori-Bui et al., 2011). The selected subcanopy trees are at least 8 m below the average canopy height (Lepori-Bui et al., 2011). The co-dominant tree species significantly differ in canopy structural characteristics and position (Table 1). Both *F. grandifolia* trees exhibit deeper canopies, but lower total canopy heights in comparison to *L. tulipifera* (Table 1). The smaller leaf area indices and canopy closure for both *L. tulipifera* crowns indicate that these trees produce a thinner, less dense canopy than *F. grandifolia* (Table 1). Bark thickness values also indicate that *F. grandifolia* canopies are generally smoother than *L. tulipifera* canopies (Table 1). The smoother, deeper, and