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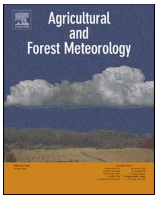

ResearchPaper

Linked spatial variability of throughfall amount and intensity during rainfall in a coniferous forest

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ABSTRACT

Routing of rainfall through forest canopies causes spatial variability in throughfall amounts and intensities, but the covariance of these effects has not been investigated. We investigated the relationship between point throughfall amount and intensity reduction in an old-growth seasonal temperate rainforest in southwestern Washington, USA, using tipping bucket rain gauges both under and above the coniferous forest canopy. Mean hydraulic residence time of rainfall in the canopy was 25 min, with event means ranging between 4 and 52 min. Locations of high throughfall accumulation received throughfall at intensities similar to rainfall, and locations of low accumulation experienced more variable intensities. Drip points funneling water to zones of high accumulation are not typical of this coniferous seasonal temperate rainforest. There was a positive relationship between intensity reduction by the canopy and evaporation during rain events that indicates that refilling of storage made available by evaporation is important for buffering throughfall intensities.

1. Introduction

Routing of rainfall through forest canopies causes spatial variability in throughfall amounts, intensities, and chemical composition, which in turn affect soil water and biogeochemical patterns and processes (Durocher, 1990; Raat et al., 2002; Rosier et al., 2015). The temporary detention of water in canopies that smooths intensity of throughfall delivered to the forest floor (Keim and Skaugset, 2004) also entails flow along canopy surfaces (Herwitz, 1987) to cause spatial redistribution. However, details of linkages between these two phenomena remain unclear, preventing development of a general conceptual model for how water is routed through forest canopies.

Many investigations of spatial variability in throughfall have found locations where event-total throughfall exceeds event-total rainfall, even for events with substantial wet-canopy evaporation (e.g., Keim et al., 2005; Germer et al., 2006). Thus, lateral redistribution must play an important role in creating local concentration of throughfall as drip points as it also does for stemflow (Levia et al., 2011). However, it remains unclear whether total throughfall at drip points is dominated by water funneled through the canopy along canopy surfaces, or whether that funneled water may instead be a minor supplement to water moving more directly through the canopy. An important difference between these alternative scenarios is the residence time of water in the canopy, which has implications for affiliated processes such as throughfall chemistry (e.g., Olson et al., 1985) and spread of foliar pathogens (Garbelotto et al., 2003). Also, the relationship between throughfall amount and intensity may influence hydrologic processes in forest soils such as soil moisture redistribution, groundwater recharge, and runoff generation (Manderscheid and Matzner, 1995; Guswa and Spence, 2012; Klos et al., 2014).

Although the importance of residence time in canopy hydrology and biogeochemistry has been recognized (e.g. Olson et al., 1985; Allen et al., 2014), most researchers have quantified it indirectly; for example by comparing rainfall and throughfall hyetographs (e.g., Reid and Lewis, 2009). Keim and Skaugset (2004) used a linear system convolution to model time series of throughfall from time series of rainfall and capture damping and lagging of rainfall intensity by the canopy in a general way. This method has been rarely used in canopy hydrology, but is familiar in watershed hydrology as the unit hydrograph approach to flow modeling (Dooge, 1959).

The general objective of this research is to shed light on the underlying processes responsible for generating spatiotemporal variation in throughfall. The specific objective is to understand the generation of spatial patterns of throughfall and the dependence of throughfall processes on the specific characteristics of rainfall events. To accomplish these objectives, we investigated the relationship between point throughfall amount and intensity smoothing in an old-growth seasonal temperate rainforest in southwestern Washington, USA, using tipping

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bucket rain gauges to measure the gross and net rainfall in the open and under the canopy, respectively.

2. Methods

2.1. Experimental site and data collection

Rainfall and hydrometeorological observations were made at The Wind River Canopy Crane Research Facility (WRCCRF), located on a gently sloping site in the southern Cascade Range of Washington, USA. The site is located at 45°40′N latitude, 121°57′W longitude at an elevation of 371 m amsl. The location is characterized by cool, wet winters and warm, dry summers. The average annual precipitation is 2223 mm, with a relatively short snow season typically lasting from Nov through Mar, and seasonally dry summers with only about 5% of the precipitation occurring in Jun–Aug. Mean annual air temperature is 8.7 °C with mean monthly maxima and minima of 17.7 °C in Jul and 0.1 °C in Jan, respectively (Shaw et al., 2004). Mean climatic data are based on observations for the period from 1978 to 1998 recorded 5 km north of the WRCCRF contained in the National Climate Data Center (NCDC) database as reported by Shaw et al. (2004).

Vegetation at the site is composed of a roughly 500 year-old Douglas-fir (*Pseudotsuga menzesii*), western hemlock (*Tsuga heterophylla*), and western redcedar (*Thuja plicata*) canopy, with an understory of Pacific yew (*Taxus brevifolia*), Pacific silver fir (*Abies amabilis*), and vine maple (*Acer circinatum*). The average height of the Douglas-firs at the site is 52.0 m, with the tallest individual reaching 64.6 m. The forest at the site fits the structure-based definition of old-growth, which is characterized by large, old trees, a vertically continuous canopy, high spatial heterogeneity, a well-developed understory, and diversity of canopy epiphytes (lichens and bryophytes). The biophysical characteristics and ecological setting of the site were described in detail by Shaw et al. (2004).

Hydrometeorological data were collected on an 85 m tower crane installed within the WRCCRF old-growth forest site, and at an open field location approximately 1.5 km south of the tower. Precipitation was measured above the canopy with an Alter-shielded weighing gauge (Belfort Instrument Co., Model 6071) installed on the counter-jib of the crane and at the open site using both weighing (Belfort Instrument Co., Model 5-780) and tipping bucket rain gauges (Texas Electronics, Inc., Model TE-525). The variety of gauges were used to provide instrumental redundancy to ensure a continuous high-quality precipitation record. The record from the open site tipping bucket was primarily used for this study since it had the best temporal resolution, but was supplemented by data from the weighing gauges for brief periods where the gauge was not functioning correctly. Incoming shortwave and longwave radiation were measured with a four-component net radiometer (Kipp and Zonen, Model CNR-1) mounted at the highest point of the tower at 85 m. Air temperature and relative humidity were measured with a combined sensor (Vaisala, Inc., Model HMP35C) in a mechanically aspirated Gill radiation shield mounted at 68.4 m on the crane tower. Wind velocity was measured with a three-dimensional sonic anemometer (Gill Instruments Inc., Solent Gill HS) also mounted at 68.4 m. These meteorological data were recorded as averages over 0.5 h intervals.

An array of 24 tipping bucket rain gauges (Texas Electronics Inc., TE-525I) equipped with individual event loggers (Onset Computer Corp., HOBO Event) were installed approximately 1 m above the ground within the 2.3 ha circular plot centered on the crane tower. Gauges had a collection area of 325 cm^2 and were calibrated to record 0.254 mm per tip. Events recorded by the automated array ranged from 13 Apr through 5 Nov 2000, encompassing most of the snow-free period. Times were synchronized for each data logger, including the gauges above the canopy and at the open site, and the time of each tip was recorded on the event loggers. Gauges were periodically cleaned, re-leveled, and randomly relocated every 4–8 weeks following a stratified random design to increase the total number of sampling points. Each automated gauge record for each event was manually assessed to identify instances of clogging or failure, and if problems with specific sensors were identified, the record was eliminated from the dataset prior to further analysis. Specific data on the canopy characteristics at each sampling point were not recorded; therefore the event was treated as the basic experimental unit, with each throughfall record as a sample of the canopy effects during each event. Further details and analyses of the high-resolution throughfall and hydrometeorological dataset were provided by Link et al. (2004).

The specific canopy storage capacity (S) above each gauge was derived from gross and net throughfall data for three selected events (each of which had different random gauge arrangements). Gauge-specific values for S were estimated by determining the inflection point in the gross to net precipitation values by using a least-squares regression to fit curves to the period preceding and immediately following canopy saturation (See Fig. 1 in Link et al., 2004 for specific details). A total of 65 sampling points spaced approximately 3–25 m apart was used for analyses involving gauge-specific canopy storage, due to the combined requirements of unique gauge arrangements, accurately functioning gauges, and storms of sufficient magnitude to produce well-defined inflection points on plots of gross vs. net rainfall. Many more gauges would be required to thoroughly characterize spatial throughfall structure (Voss et al., 2016), but we treated sample locations as independent and did not draw inferences about spatial patterns.

2.2. Data analysis

We modeled intensity smoothing following Keim and Skaugset, (2004), who used the discrete-time form of the convolution integral to model throughfall rate, *TF*(t), as rainfall rate, *R*(t), convolved with a transfer function, $g(t)$:

$$TF(t) = \sum_{\tau=1}^{n} R(\tau)g(t-\tau) \ , \tag{1}$$

where $t = (0, 1, 2, \ldots)$ is the index of sample periods, $\tau = (0, 1, 2, \ldots)$ is the index of time shift in sample periods backward from t, and $g(t-\tau)$ is a transfer function defining the response of *TF* for all time shifts τ after rainfall input, R. Conceptually, Eq. (1) describes how the signal R is filtered by g to produce an output signal *TF*. The transfer function, g, is a distribution describing probability of residence time within the system.

In practice, g is not known a priori, and must be inferred from $TF(t)$ and $R(t)$. We selected the exponential distribution as a simple, one-parameter form of transfer function to model intensity transformations by canopies:

$$g = ae^{-at} \ , \tag{2}$$

where a is a parameter. This transfer function describes a linear reservoir,

$$\mathrm{TF(t) = aC(t)}, \tag{3}$$

where C is canopy storage. Some form of exponential drainage from canopy storage is a common assumption; data from laboratory tests have shown that this simplest form does not describe canopy drainage as well as related forms with additional parameters (Calder, 1977), but it performs nearly as well as higher-parameter models in variable field conditions (Keim and Skaugset, 2004). The exponential model specifies a mean residence time of $1/a$, modal residence time of zero, and longer residence times as exponentially less probable.

There are two important assumptions of the linear system model: (1) the transfer function is time invariant: i.e., the probability distribution of residence time of water in the canopy is the same no matter when it enters the canopy; and (2) conservation of mass. To best ensure the expectation of constant residence time distribution, we restricted analysis to only the portion of rain events after canopy storage capacity