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# Spatial patterns of throughfall isotopic composition at the event and seasonal timescales

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SUMMARY

Spatial variability of throughfall isotopic composition in forests is indicative of complex processes occurring in the canopy and remains insufficiently understood to properly characterize precipitation inputs to the catchment water balance. Here we investigate variability of throughfall isotopic composition with the objectives: (1) to quantify the spatial variability in event-scale samples, (2) to determine if there are persistent controls over the variability and how these affect variability of seasonally accumulated throughfall, and (3) to analyze the distribution of measured throughfall isotopic composition associated with varying sampling regimes. We measured throughfall over two, three-month periods in western Oregon, USA under a Douglas-fir canopy. The mean spatial range of $\delta^{18}O$ for each event was 1.6‰ and 1.2‰ through Fall 2009 (11 events) and Spring 2010 (7 events), respectively. However, the spatial pattern of isotopic composition was not temporally stable causing season-total throughfall to be less variable than event throughfall (1.0‰; range of cumulative $\delta^{18}O$ for Fall 2009). Isotopic composition was not spatially autocorrelated and not explained by location relative to tree stems. Sampling error analysis for both field measurements and Monte-Carlo simulated datasets representing different sampling schemes revealed the standard deviation of differences from the true mean as high as 0.45‰ ($\delta^{18}O$) and 1.29‰ (d-excess). The magnitude of this isotopic variation suggests that small sample sizes are a source of substantial experimental error.



## 1. Introduction

Stable isotopes of water are useful for tracing the movement of water through catchments (Kendall and McDonnell, 1998). The isotopic composition of precipitation and other end members are used as input signals for estimating streamwater sources (Klaus and McDonnell, 2013), transit time (Tetzlaff et al., 2011), plant water sources (Goldsmith et al., 2012), and multiple other applications.

However, precipitation rarely infiltrates or runs off without some preceding fractionating process (Gat and Tzur, 1968). Rainfall from the open sky (gross precipitation; $P_g$) is intercepted by vegetation canopies resulting in some evaporation (interception loss). The remainder reaches the soil as throughfall (TF), composed of both water that bypasses or is temporarily intercepted by the canopy, or as stemflow that runs down the bark surfaces. Consequently, interception changes numerous characteristics of precipitation (Levia et al., 2011), including its isotopic composition. Throughfall is generally heavier isotopically than $P_g$, but variable within and among events (Ikawa et al., 2011; Kato et al., 2013; Saxena, 1986). Kubota and Tsuboyama (2003) showed that ignoring the isotopic difference between TF and $P_g$ is a source of error in storm hydrograph separation. Accordingly, TF isotopic composition is a more appropriate input concentration for models that employ stable isotopes of precipitation for water tracing.

Event-mean isotopic differences between TF and $P_g$ have been the focus of previous studies (e.g., Ikawa et al., 2011; Saxena, 1986), but few studies to date have examined the spatial variability of throughfall isotopic composition within and among events. Recent work has shown that, within short measurement periods, the range in isotopic composition at individual TF sampling locations can exceed the difference between open precipitation and TF (Allen et al., 2014; Brodersen et al., 2000; Kato et al., 2013).

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This intra-event spatial variability is substantial and may parallel the well-known spatial variability observed for TF amount (Raat et al., 2002).

At the plot scale, TF amount is often autocorrelated spatially (Gerrits et al., 2010; Keim et al., 2005; Loescher et al., 2002) and temporally (Gerrits et al., 2010; Keim et al., 2005; Raat et al., 2002; Staelens et al., 2006). This has been largely attributed to canopy architecture (Gerrits et al., 2010; Staelens et al., 2006; Whelan and Anderson, 1996). Studies of the spatial structure of TF amount have led to improved sampling as well as realization of how TF variability affects subsurface hydrology (Coenders-Gerrits et al., 2013; Hopp and McDonnell, 2011; Raat et al., 2002). Because spatial patterns in TF amount are temporally persistent, repeated sampling in fixed or too few locations can result in large anomalies in estimates of the mean. Thus randomly relocating TF collectors between events (roving collectors) has been advocated as a way to reduce measurement uncertainty (Holwerda et al., 2006; Ritter and Regalado, 2014).

Multiple interacting processes affect TF. Consequently the relationship between amount and isotopic composition is complex (Brodersen et al., 2000; Saxena, 1986). One important process controlling isotopic composition appears to be time-varying transmission of precipitation (that varies in isotopic composition through the event) through the canopy (i.e., the 'selection' process; Brodersen et al., 2000; DeWalle and Swistock, 1994; Ikawa et al., 2011; Kato et al., 2013). Evaporative fractionation (Kato et al., 2013) and isotopic exchange (Kendall, 1993; Saxena, 1986) can occur and result in complex relations with spatial variability in TF amount. Understanding this spatiotemporal variability of TF isotopic composition is critical for using TF as an input value or end member in isotope tracer studies. Understanding such behavior also offers potential mechanistic insights into intra-canopy processes during rainfall (Allen et al., 2014).

While the spatiotemporal variability of TF amount has been addressed and has led to comprehensive analyses of sampling errors in TF amount (Ritter and Regalado, 2010; Zimmermann et al., 2010), strategies to sample throughfall for isotopic composition are poorly developed. Such study requires consideration of a suite of controlling processes that likely differ from those controlling TF amount.

Here we characterize the spatiotemporal structure of coupled amount and isotopic composition variability of throughfall. Specifically, we measured throughfall amount and isotopic composition over two three-month periods to address three objectives: (1) to quantify the spatial variability of isotopic composition at the event scale, (2) to determine if there are persistent controls over the variability and how these affect variability of seasonally accumulated throughfall, and (3) to analyze the distribution of measured TF isotopic composition associated with varying number of collectors and using fixed versus roving collectors.

## 2. Methods

### 2.1. Site description

This study was conducted in Watershed 1 (WS1) of the H.J. Andrews Experimental Forest in the western Cascade Range of Oregon, which has been extensively described in previous studies (e.g., Lutz and Halpern, 2006; Rothacher, 1965). The steeply-sloped, 96 ha basin was clear-cut harvested in the late 1960s and is now covered with a dense canopy dominated by Douglas-fir (*Pseudotsuga menziesii*). The climate is typical of the Pacific Northwest; mean annual precipitation exceeds 2000 mm with 80% falling between October and April. All TF collection was at plots at 500 m elevation. Humidity and rainfall intensity were measured at the H.J. Andrews benchmark meteorological station about 500 m from the study plots.

Two separate experiments were conducted. Experiment 1 (Exp1) took place on a relatively flat area of predominantly Douglas-fir forest coinciding with a 75 m long section of a study transect established in 1962 (Halpern and Dyrness, 2010) and the site of multiple ecological and hydrological experiments (e.g., Bond et al., 2002; Halpern and Franklin, 1990). Experiment 2 (Exp2) used a pair of 12 × 5 m plots as a north-aspect-plot (NAP) and a south-aspect-plot (SAP), 100 m apart on steep opposite slopes of WS1. Canopy cover for SAP and NAP was 92% and 95% respectively, estimated using Fusion software (United States Forest Service Remote Sensing Applications Center, Salt Lake City, UT) from a LiDAR flight in August, 2008. Canopy cover for Exp1 was not quantified but was similar to Exp2. Three $P_g$ collectors were located within 180 m of all sampling plots in a 0.04 ha clearing surrounded by trees 15–20 m tall.

### 2.2. Sample collection

Experiment 1, described by Allen et al. (2014), was conducted between October and December 2009. Sampling was by 13 TF collectors with 9.5 cm diameter openings placed along the transect under Douglas-fir trees, randomly with respect to boles, crowns, and other collectors. Storms were sampled per event and collected after precipitation and the majority of drip ceased. Logistical constraints caused some sampling periods to consist of multiple consecutive storm events, yielding 11 collection periods (1.1–1.11). Intra-event dry periods never exceeded 2 days.

Experiment 2 was conducted between April and July 2011 and used higher spatial density of collectors than Exp1 to better characterize spatial patterns. Thirty-six collection points were established at random positions in each plot. Eighteen TF collectors were used at each 12 × 5 m plot and were randomly relocated among the 36 fixed locations for each sampling period. Inter-collector distances ranged from 0.2 m to 12 m with a mean distance of 4.3 m. Both $P_g$ and TF were collected with 2 l polyethylene bottles attached to 15.5 cm diameter funnels about once per week, depending on precipitation. Within the sampling periods, there was never more than one calendar day without rain. There was a total of seven Exp2 collection periods (2.1–2.7; Table 1).

For sampling during both experiments, the volume of water accumulated in each collector was measured and a zero headspace subsample was taken with a 20 ml glass vial for isotope analysis.

### 2.3. Analyses

We calculated interception loss as the difference between mean $P_g$ and TF for each event, and a volume weighted mean over all events for seasonal interception loss. Although stemflow occurs, we assumed it was not substantial in Douglas-fir forest (Link et al., 2004; Rothacher, 1963).

All isotope data are expressed in terms of $\delta$, calculated as:

$$\delta = \left(\frac{R_{\text{sample}}}{R_{\text{V-SMOW}}} - 1\right) \times 1000‰ \quad (1)$$

where V-SMOW is the Vienna Standard Mean Ocean Water (Coplen et al., 2002) and $R$ is $^{18}O/^{16}O$ or $^{2}H/^{1}H$. Water samples from Exp1 were analyzed for $\delta^2H$ and $\delta^{18}O$ on an off-axis integrated cavity output laser spectrometer (Los Gatos Research LWIA, Mountain View, CA) by the Institute for Water and Watersheds Collaboratory (Corvallis, Oregon). Accuracy was 0.18 ± 0.07‰ and −1.02 ± 0.92‰ (mean ± standard error) for $\delta^{18}O$ and $\delta^2H$ respectively, calculated as deviation of a third standard from a two-point calibration line