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Temporal persistence of spatial patterns in throughfall

R.F. Keim[a,*], A.E. Skaugset[b], M. Weiler[c]

[a]School of Renewable Natural Resources, Louisiana State University, LSU AgCenter, Baton Rouge, LA 70803, USA
[b]Department of Forest Engineering, Oregon State University, Corvallis, OR 97331, USA
[c]Departments of Forest Resources Management and Geography, University of British Columbia, Vancouver, BC V6T 1Z4, Canada

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Abstract

Spatial and temporal variability of throughfall beneath forests are potentially important controls on soil processes, watershed hydrology, and biogeochemistry. We used a set of 94 rain gauges to measure variability of throughfall beneath three forest stands in the Pacific Northwest, USA. The length scale over which throughfall amounts were correlated (spatial correlation lengths) was between one-half- and one crown diameter in mid-age and old stands of conifers. In a deciduous stand, the spatial correlation length was about one crown diameter when in leaf condition and throughfall was not correlated spatially in leaf-off condition. Spatial patterns of storm-total throughfall were temporally stable in two ways: semivariograms, which provide a measure of the continuity of a spatial phenomenon, were similar among storms, and throughfall amounts of an individual gauge could be predicted relative to the plot average. Time stability plots of throughfall amounts, normalized with respect to mean and variance, were useful for comparing temporal persistence of spatial throughfall variability among stands. Together, semivariograms and time stability plots appear to be suitable descriptors of throughfall variability for modeling water flux at the soil surface.

Keywords: Throughfall; Canopy interception; Spatial variability; Geostatistics

1. Introduction

An important effect of forest canopies on precipitation is spatial redistribution that occurs by throughfall and stemflow. Spatial variation in infiltration influences spatial variation in a range of physical, chemical, and biological processes, including soil moisture (Eschner, 1967; Bouten et al., 1992; Si, 2002; Zhou, et al., 2002; Schume et al., 2003; Raat et al., 2002), pedogenesis (Buol et al., 1989; Baba and Okazak, 1999), nutrient cycling (Chang and Matzner, 2000), root growth (Ford and Deans, 1978), composition of the forest floor (Mottonen et al., 1999), soil solution chemistry (Manderscheid and Matzner, 2000), groundwater chemistry (Bottcher et al., 1997), and streamwater chemistry (Beier, 1998). The spatial and temporal variability of throughfall therefore is potentially an important control on watershed

* Corresponding author. Tel.: +1 225 578 4169; fax: +1 225 578 4227.
E-mail addresses: rkeim@lsu.edu (R.F. Keim), arne.skaugset@oregonstate.edu (A.E. Skaugset), markus.weiler@ubc.ca (M. Weiler).

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hydrology and biogeochemistry (Zirlewagen and von Wilpert, 2001).

Previous work has identified lateral flow on stems and branches, differential accumulation on exposed canopies, and differential evaporative loss of intercepted precipitation from trees of varying leaf area as processes affecting spatial redistribution of precipitation by canopies (Herwitz and Slye, 1992; Beier et al., 1993). Early work focused on the deterministic effects of these processes at the scale of individual trees (e.g., Horton, 1919; Wood, 1937; Stout and McMahon, 1961). However, attempts to predict spatially varying throughfall amounts from immediate canopy cover in forests have mostly seen limited success (Tobón Marin et al., 2000; Loescher et al., 2002), or require calibration to both canopy characteristics and measured throughfall (Whelan and Anderson, 1996). An example of this problem is the inconsistent relationship between throughfall and position relative to tree stems and crowns. For example, Voigt (1960), Ford and Deans (1978), and Herwitz (1987) observed higher throughfall amounts near stems than at crown edges, yet Aussenac (1970), Swank (1972), Johnson (1990), and Beier et al. (1993), all found throughfall consistently lower near stems. Kittredge et al. (1941) found throughfall highest near stems during large storms, but highest near crown edges in small storms. The lack of consistent relationships among stands, even when species are identical, defeats the predictive power of distance-to-stem predictors of throughfall patterns.

Investigations of spatial patterns of throughfall using spatial statistics (e.g., Loustau et al., 1992; Bellot and Escarre, 1998; Loescher et al., 2002; Gómez et al., 2002) are less common than deterministic regressions using vegetation characteristics, and have yielded equivocal results. Some of these investigators have reported data accumulated over several storms, preventing detection of pattern variation from storm to storm. Few researchers have investigated whether spatial variability of throughfall is repeated only statistically, or arise from spatial variations in throughfall occurring at the same points among storms.

Canopy structure and architecture have been generally accepted as the most important control on throughfall redistribution (e.g., Herwitz and Slye, 1992; Whelan and Anderson, 1996). Existing, process-based models of this redistribution suitable for providing boundary conditions for fine-scale models of infiltration, groundwater recharge, soil moisture patterns, or watershed hydrology require many parameters that are difficult to measure (e.g., Whelan and Anderson, 1996; Davie and Durocher 1997 a, b). Hence, a conceptualization of temporal and spatial variability of throughfall that does not rely on vegetation mapping or intracanopy micrometeorological measurements would allow incorporating canopy redistribution of throughfall into soil models more easily.

A full model of how spatial patterns of throughfall vary may include both deterministic and stochastic characterizations of spatial variability, but clearly must include temporal variability of spatial patterns. The specific objectives of this research were to describe the spatial variation of throughfall under three different forest stands and to determine how spatial variations in throughfall persist among storms, with the goal of developing a model of spatial distribution of throughfall useful for modeling water fluxes at the forest floor at fine spatial scales. In this paper, we take the strategy of developing statistical tools for quantifying patterns and time stability of throughfall without regard to canopy measurements.

2. Methods

2.1. Study sites

We selected three forest stands in the Pacific Northwest, USA, for this study. The study sites are important forest types of the region and represent a gradient of canopy complexity from a homogeneous, tended stand to a complex, unmanaged stand with large trees and gaps. We established a single plot in each stand that was $\geq$10 times the area of the crowns of dominant trees (about three crowns wide). Plots were placed within transects randomly located previously within each stand for related research.

One study site, a young conifer stand, is an even age stand of conifers originating after a clearcut 60 years before the study. The dominant tree species is Douglas-fir (*Pseudotsuga menziesii*), with a few grand fir (*Abies grandis*), and bigleaf maple (*Acer macrophyllum*). The canopy is closed and spatially homogenous. Maximum tree size in the plot was 0.4 m breast height stem diameter and 43 m tall, and basal area in the plot was 111 $m^2\,ha^{-1}$. The crowns of the dominant trees were approximately 5 m diameter, so the plot in this stand was 15×15 m.

The second site is a stand of deciduous trees about 60 years old that is located in a riparian area. The dominant species are red alder (*Alnus rubra*), bigleaf maple, Oregon ash (*Fraxinus latifolia*), and vine maple (*Acer circinatum*). The canopy is less homogenous than the young conifer stand, and is intermediate in complexity of the stands in this study. Maximum tree size in the plot was 1 m breast height stem diameter and 30 m tall, and basal area in the plot was 75 $m^2\,ha^{-1}$. The crowns of the dominant trees were approximately 6 m diameter, so the plot in this stand was 13.5×22.5 m. The plot was not square because the riparian area was not wide enough to accommodate a plot three crowns square.

The final site is an old, uneven-age conifer stand, where the oldest trees are about 600 years old. The dominant species are Douglas-fir, western redcedar (*Thuja plicata*), and western hemlock (*Tsuga heterophylla*), with some bigleaf maple and vine maple. The canopy is spatially complex, both horizontally and vertically. Maximum tree size in the plot was 3 m breast height stem diameter and 60 m tall, and basal area in the plot was 198 $m^2\,ha^{-1}$. The crowns of the dominant trees were approximately 10 m diameter, so the plot in this stand was 30×30 m.

Previous work has illustrated the importance of gaps in spatial variability of throughfall (Zirlewagen and von Wilpert, 2001; Loescher et al., 2002), so we excluded this source of variability and focused on intra-crown processes by placing all three plots in areas where density of trees was higher than the stand average. Stand-density index, SDI (Reineke, 1933), of the plot in the young conifer stand was 2130 (SI units), compared to a stand-total SDI of 1130 and a theoretical maximum SDI for Douglas-fir of 1470 (Reineke, 1933). The SDI of the plot in the deciduous stand was 1460, compared to theoretical maximum SDI for red alder of 1125 (Hibbs and Carlton, 1989). The SDI of the plot in the old conifer stand was 2700, compared to a stand-total SDI of 1770.

2.2. Instrumentation and data

To measure throughfall, we placed 94 wedge-shaped storage rain gauges with a 9.2 cm^2 orifice within each plot (Fig. 1). Each gauge was mounted on a wooden stake, 25–50 cm above the forest floor, and permitted a rainfall reading accurate to ±1 mm. We excluded low shrubs, grass, ferns, and herbs from the study by removing them for at least 0.5 m around each gauge. The gauge positions were coordinates selected by random number generation, and we used a total-station theodolite to place each gauge within 0.1 m of its assigned coordinates. If a gauge fell inside a tree stem, we moved it at a pre-generated random azimuth and distance.

We measured storm-total throughfall at each gauge for three to seven storms at each plot (Table 1) from 18 January 2002 to 8 July 2002. After measuring several storms in one stand, we removed the gauges and placed them in the next stand. The dominant form of precipitation was rain in all storms except two, which we excluded from the analyses. The measured storms included both winter (leaf-off) and spring (leaf-on) condition in the deciduous stand. We assumed rainfall was spatially homogeneous over these small plots.

2.3. Analyses

We used variograms as one measure of spatial patterns in storm-total throughfall. Variogram analysis is a tool to measure the continuity of spatial phenomena. It expresses continuity as the average squared difference between quantities measured at different locations. The semivariance γ for measurements taken distance h apart is then given as:

$$\gamma(h) = \frac{\sum_{n(h)}(x-y)^2}{2n(h)}, \tag{1}$$

where x and y are measurements of storm-total throughfall and $n(h)$ is the number of measurement pairs in the data set that are distance h apart (Olea, 1999). The distance h is known as the lag. In applications where measurements are not evenly spaced, such as this study, γ is calculated for h classified over some range of distance. Variograms strictly have three dimensions (lag, semivariance, and

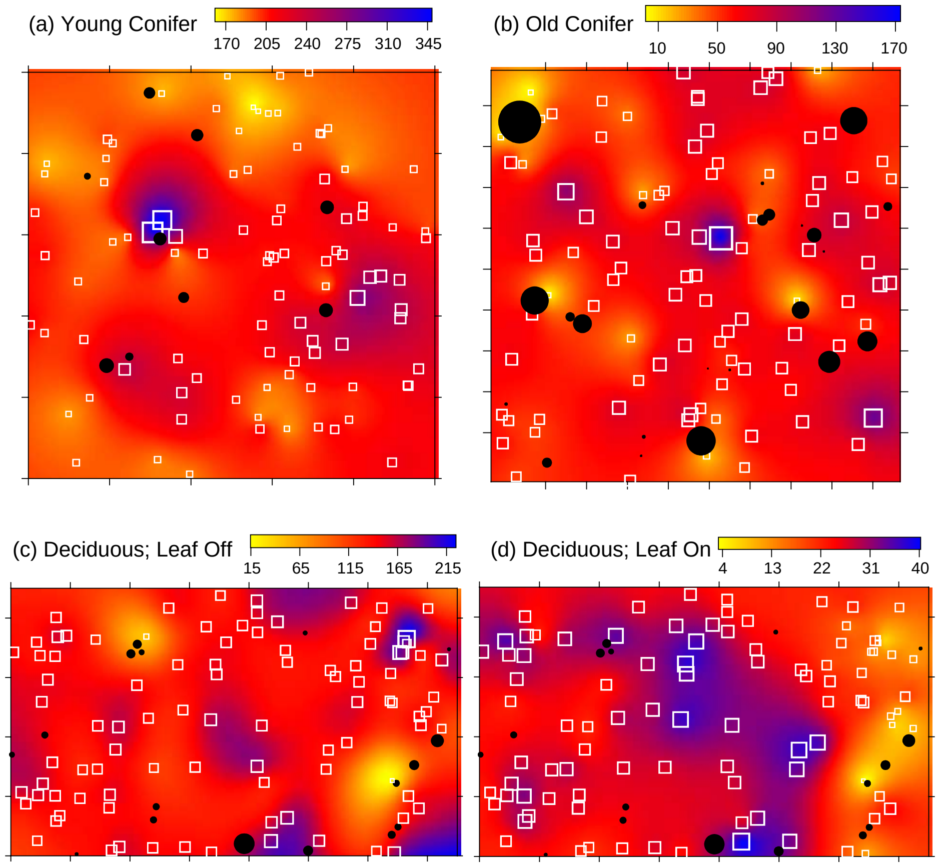

Fig. 1. Total throughfall (mm) recorded in three forest stands in the Pacific Northwest, USA. Map scale is indicated by 3-m tick marks on the margin of each subplot. Solid black circles indicate trees, scaled to breast-height diameter. Open white squares indicate throughfall collectors, scaled to storm-total throughfall. Color indicates throughfall between collectors for visualization purposes. Each interpolation is the result of Kriging parameterized from variograms.

direction), but, for ease of interpretation, are often plotted in two dimensions by averaging over all directions. Variograms plotted this way are referred to as omnidirectional. Variograms can be characterized by the sill, the maximum semivariance defined by the overall variance of the data, and the range, the distance at which the variogram reaches the sill. The range describes the length scale over which throughfall amounts are correlated, and is also known as the spatial correlation length.

We used omnidirectional variograms with a maximum distance of 75% of plot size, and semivariance $\gamma(h)$ calculated for observations classified within annuli that were one fifteenth of the maximum distance wide. To allow comparison of variograms among storms, we standardized variograms as: $\gamma_s(h)=\gamma(h)/\sigma^2_{Lh}$, where σ^2_{Lh} is the lag variance defined as the geometric mean of the variances of observation pairs distance h apart. We plotted the standardized variograms for each storm together with the standardized variogram of the total throughfall to assess the time stability of throughfall patterns at each stand.

Variograms only describe the length scale over which throughfall amounts are correlated, but do not identify whether high or low throughfall areas persist among storms. To quantify this, we modified a measure that has formed the basis of previous time-stability descriptions of soil moisture and throughfall. Raat et al. (2002), following Vachaud et al. (1985),

Table 1
Storms used to study temporal persistence of spatial variability of throughfall in three forest stands in the Pacific Northwest, USA

Stand	Storm #	Opening rainfall (mm)	Throughfall		
			Mean (mm)	Coefficient of variation	Coefficient of skew
Young conifer	1	19	9	0.19	0.09
	2	72	47	0.19	0.06
	3	36	20	0.26	0.17
	4	83	56	0.17	0.03
	5[a]	32 snow[b]	32	0.22	0.02
	6	88	54	0.14	0.03
	7	46	23	0.17	0.02
Deciduous (leaf-off)	8	48	38	0.29	0.11
	9	n.a.[c]	53	0.20	0.03
	10	31	24	0.26	0.10
	11[a]	20 snow	11	0.21	−0.13
	12	42	29	0.22	−0.01
Deciduous (leaf on)	13	7	5	0.30	−0.19
	14	16	9	0.38	0.02
	15	n.a.	5	0.38	−0.05
	16	n.a.	6	0.32	−0.03
Old conifer	17	21	15	0.59	0.12
	18	47	43	0.39	0.01
	19	7	3	0.65	0.00

[a] Data excluded from analyses because storm included significant snowfall.
[b] Data from the tipping-bucket rain gauges in the opening are unreliable in snowy conditions.
[c] Data missing owing to malfunctioning rain gauge in nearby opening.

employed a normalized measure of throughfall,

$$\hat{T}_i = (T_i - \bar{T})\bar{T}, \tag{2}$$

where T_i and $\hat{T}_i$ are throughfall and normalized throughfall, respectively, at sample point i and $\bar{T}$ is the mean storm-total throughfall for all sample points in that storm. This method does not taken into account variance of the sample points, with the result that extreme values of T_i have a potentially large effect on $\bar{T}$ and thus on $\hat{T}$. Therefore, we quantified throughfall using standardized throughfall, $\tilde{T}$, for each sample point as

$$\tilde{T}_i = \frac{T_i - \bar{T}}{s_T}, \tag{3}$$

where s_T is the standard deviation of storm-total throughfall for all sample points in that storm. The value of $\tilde{T}$ for each observation is thus corrected to zero mean and unit variance. Skewed distributions distort the meaning of $\tilde{T}$ for $T_i < \bar{T}$ compared to $T_i > \bar{T}$, but the measured coefficient of skewness for many stands and storms was near zero (Table 1). Although (3) should not strictly be termed normalization, we refer to $\tilde{T}$ as normalized throughfall in the remainder of the paper for ease of communication. Time stability plots of normalized throughfall are obtained by plotting $\tilde{T}$ for each storm at each throughfall collector, sorted by the mean $\tilde{T}$ for all storms.

To investigate possible deterministic effects of tree locations on throughfall amounts and to allow comparison with previous work, we measured the distance from each collector to the stem of the nearest overstory tree, and plotted the relationship between this variable and both storm-total and study-total throughfall.

3. Results

There was a distinct pattern of throughfall in each stand (Fig. 1), which tended to reproduce itself among storms (Fig. 2). Variogram analysis and time-stability plots of normalized throughfall were useful methods

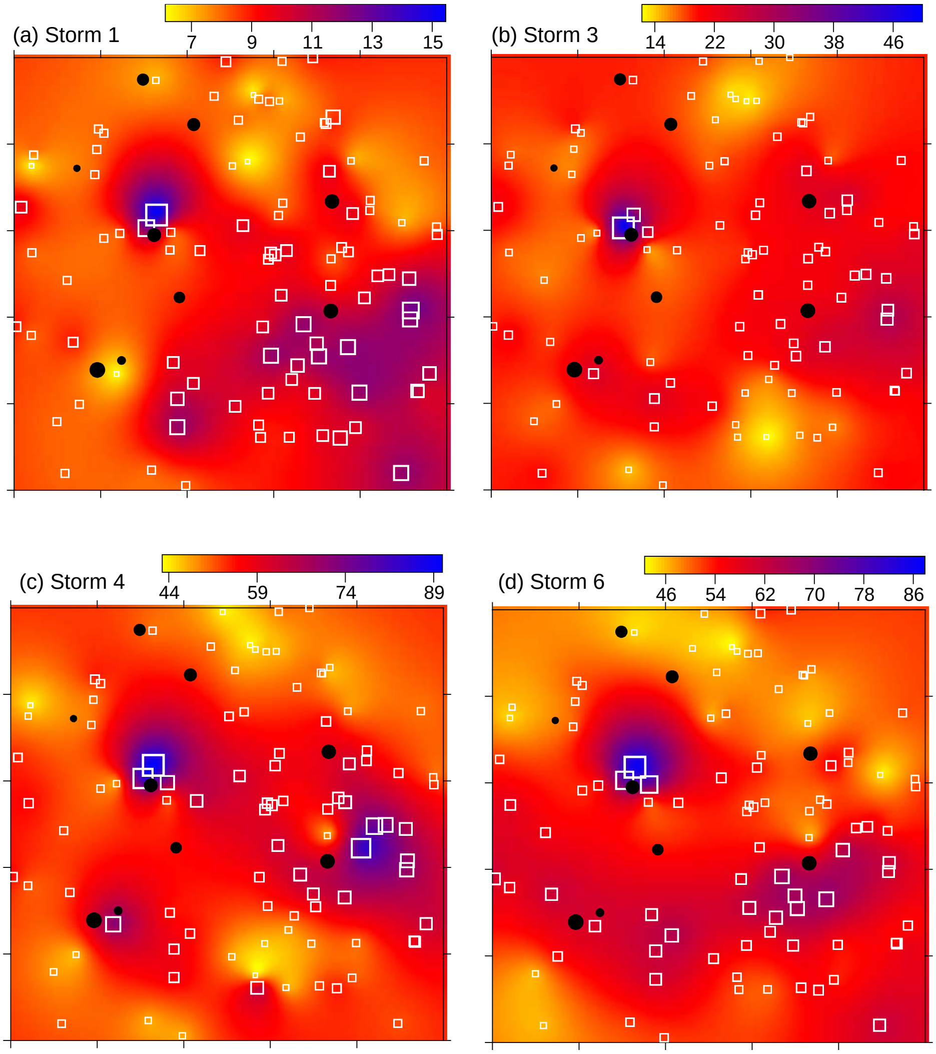

Fig. 2. Throughfall (mm) recorded in four storms in a stand of young conifers in the Pacific Northwest, USA; storm numbers are keyed to Table 1. Map scale, symbols, and colors are as Fig. 1.

for quantifying these patterns and their variability in time.

3.1. Nature and persistence of geostatistical patterns

The spatial patterns of throughfall, as quantified by spatial continuity measured with variograms, varied among stands and between seasons (for the deciduous stand), but the variograms were similar within each stand among storms (Fig. 3). The variograms were most similar and most similar and spatial correlation the spatial correlation of throughfall was greatest in the deciduous stand under leaf-on condition, and least pronounced in the deciduous stand, leaf-off condition. The spatial correlations of throughfall in the two conifer stands were evident but not as strong as for the deciduous stand in leaf-on condition. The length scale over which throughfall amounts were correlated (the range) was about 5 m for both conifer stands and 10 m for the deciduous stand in leaf-on condition

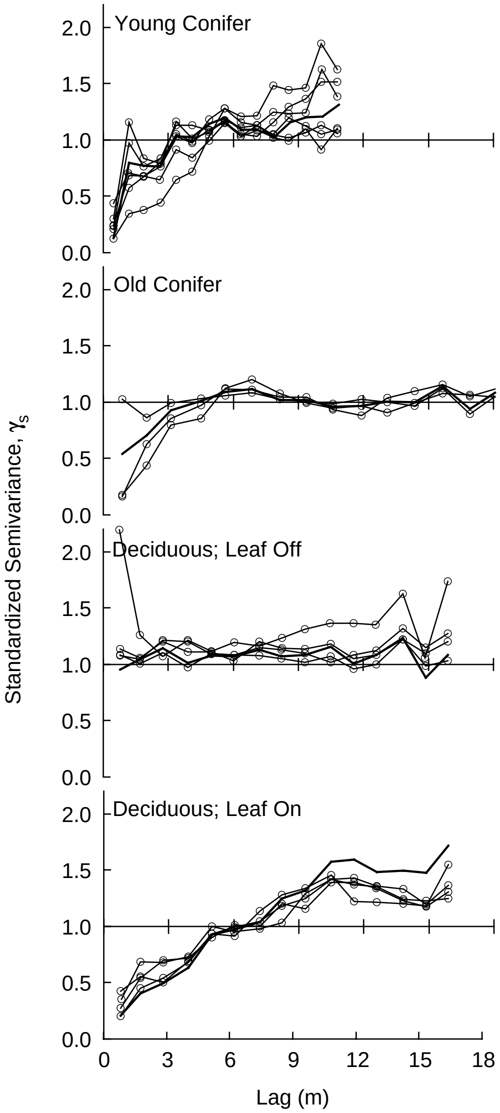

Fig. 3. Standardized semivariograms of storm-total throughfall for three forest stands in the Pacific Northwest, USA. Bold lines are variograms of throughfall summed across all storms for each stand.

(Fig. 3). There was no detectable spatial correlation length of throughfall in the deciduous stand during leaf-off condition.

Variograms of throughfall amounts show qualitatively repeated patterns among storms for each stand, and variograms of total throughfall for all measured storms in each stand were similar to variograms of individual storms (Fig. 3). There were some storms that did not conform to the general behavior of each stand, but overall it was possible to characterize each stand by a single variogram and thus by a measure of throughfall variability and a typical length scale over which throughfall amounts were correlated.

3.2. Temporal Persistence of Throughfall at Individual Collectors

Normalized throughfall amounts at individual collectors were not randomly distributed over time. Depending on the stand, 31–46% of collectors had study-average normalized throughfall significantly different than zero (*t*-test; $\alpha = 0.05$). Also, normalized throughfall $\tilde{T}$ was always either greater or less than mean storm-total throughfall $\bar{T}$ at 24% to 71% of sample points (depending on stand), which are much greater proportions than would be expected by chance (χ^2 test; $p \ll 0.01$).

Ranked plots of the normalized throughfall amounts ($\tilde{T}$) (Fig. 4), in which a bold line indicates the study-wide average of normalized throughfall and points indicate normalized throughfall of an individual storm at an individual collector, were useful tools to quantify time stability of the spatial variation in throughfall. These time stability plots indicated temporal persistence of normalized throughfall at each stand. In general, the time stability plots show two kinds of persistence. First, steeply sloping tails of the study-wide average of the normalized throughfall (bold line) indicates sites that were persistently very wet or very dry; we term this ‘extreme persistence’. Second, the general slope of the line in the middle quantiles indicates the propensity of individual collectors to be persistently wetter or drier than the mean, but not extremes; we term this ‘general persistence’. There were varying degrees of both kinds of persistence at the stands.

The young conifer stand showed moderate general persistence, no gauges that were very dry, and a heavy tail indicating persistence of extremely wet gauges. These persistently wet gauges were near tree stems (Figs. 1, 2, and 5), where we speculate that flow along upper branches concentrated throughfall (*sensu* Ford and Deans, 1978). However, not all trees had associated persistently wet gauges, and it was not apparent why individual trees varied in this respect.

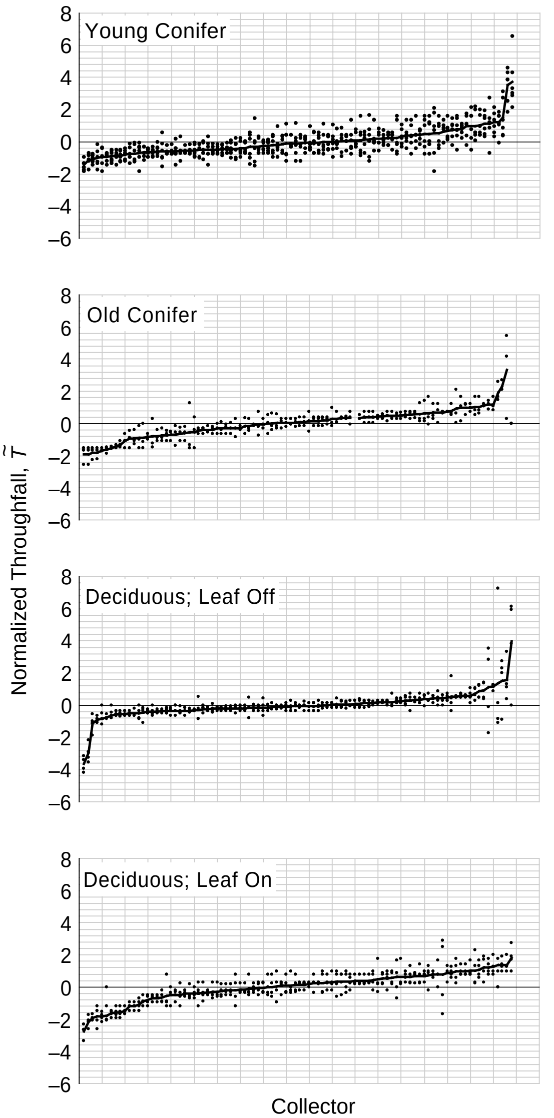

Fig. 4. Time stability plots of normalized throughfall, $\tilde{T}$, for three forest stands in the Pacific Northwest, USA. Each dot represents one observation of storm-total throughfall at a single collector, normalized to zero mean and unit variance for that storm. Dots for each collector are plotted at the same position on the horizontal axis, and collectors are positioned along the horizontal axis sorted by mean $\tilde{T}$ pooled for all storms at that stand (indicated by dark lines).

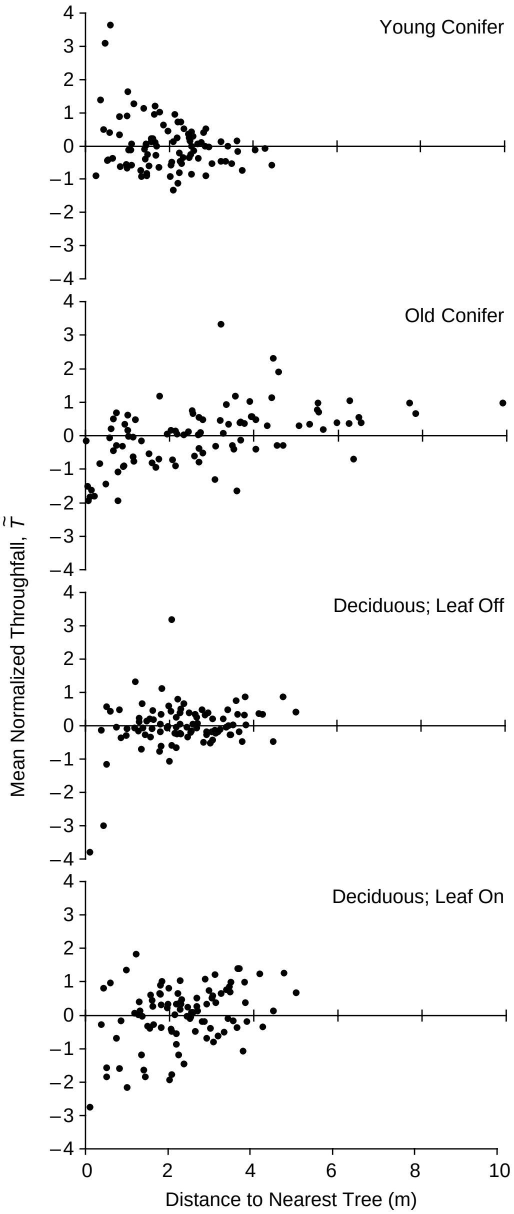

Fig. 5. Mean normalized throughfall, $\tilde{T}$, pooled across all storms related to distance to nearest tree stem in three forest stands in the Pacific Northwest, USA.

In contrast to the young conifer stand, the time stability plot of the old conifer stand was characterized by greater general persistence, persistence of extremely dry gauges, and fewer very wet collectors. The dry gauges were mostly adjacent to tree stems (Figs. 1 and 5), two of which never received any throughfall. The wet gauges were not obviously related to position relative to tree boles (Fig. 5).

There was less general persistence in the deciduous stand during leaf-off condition than in either conifer stand, but more in leaf-on condition (Fig. 4). The leaf-off condition time stability plot was characterized by extreme persistence of both wet and dry gauges, but more gauges were extremely dry than extremely wet in the leaf-on condition. There were two collectors very near and underneath leaning trees, where throughfall was persistently low during leaf-off condition (Figs. 1 and 5). One of these collectors remained dry during leaf-on condition, but the other received variable throughfall, most likely as dripping stemflow, during that time. There were seven collectors under a midstory vine maple heavily colonized by mosses where total throughfall was 119% of the stand average for all storms in the leaf-off condition (upper right corner of Fig. 1c and d). As a group, these collectors exhibited the largest temporal variation in $\tilde{T}$ of any in the entire study. We speculate that flow along stems and branches on the tree and in the moss concentrated throughfall under the tree, but not always at exactly the same location. Drip points seemed to move among storms within an area about 1 m across. This area of throughfall concentration disappeared during leaf-on condition, and the collectors under the mossy tree were consistently drier than the mean.

Relationships between average normalized throughfall and distance to nearest tree varied among the stands (Fig. 5). Relationships were weak at all stands, but the observations indicate a zone of slightly higher throughfall within 0–2 m of trees in the young conifer stand, slightly lower throughfall within 0–2 m of trees in the old conifer stand, and, except for sites under leaning trees, no relationship between throughfall amounts and tree locations in the deciduous stand.

4. Discussion

Spatial patterns of throughfall in our three stands were quantifiable and repeated from storm to storm, but not predictable a priori from tree locations. The temporal persistence of areas with lower and higher throughfall from storm to storm implies consistent deterministic controls on the persistence of spatial throughfall variability, but the location of areas with lower and higher throughfall could not be predicted based on tree locations.

Previous applications of geostatistical methods to describe throughfall in forests have yielded mixed results. Loustau et al. (1992) found no evidence of any spatial correlation at distances of approximately 2–35 m in storms in a pine forest in France. Bellot and Escarre (1998) found no evidence of any spatial structure in six storms in a Mediterranean dry forest. Loescher et al. (2002) found a spatial correlation length of 43 m integrated across storms in a wet tropical forest in Costa Rica, but had limited data at short distances and included canopy gaps in the analysis. Gómez et al. (2002) reported a spatial correlation length of approximately 1–3 m integrated across storms under isolated olive trees in Spain, but in an analysis that violated assumptions of spatial isotropy. Our data indicated the length scale over which throughfall amounts were correlated varied by stand and season from no correlation to spatial correlation lengths of approximately 3–10 m.

These published differences in the spatial correlation of throughfall among stands can be expected, because differences in canopy species, canopy structure, density, spatial homogeneity, and meteorological phenomena are known to alter patterns. Differences in experimental design, such as size of plots, number, size and spatial density of collectors, time scale of integration (time between observations of collected throughfall), make it difficult to directly compare our results to previously published work. Nevertheless, it seems reasonable to expect a relationship between stand characteristic and the length scale over which throughfall is correlated. In this study, for example, the relatively unstructured canopy of leafless deciduous trees produced an uncorrelated throughfall pattern. In contrast, the more-structured canopies of conifers or deciduous trees in leaf produced length scales of about one crown diameter over which throughfall amounts were correlated.

This study purposely omitted data from gaps in the forest canopy, which strongly influenced the results and inferences. Zirlewagen and von Wilpert (2001) demonstrated that spatial variability of throughfall at the spatial scale of canopy gaps is an important control on water quantity and chemistry at the watershed scale. Inferences at the smaller scale of our study should be considered within a broader context that accounts for variability at larger scales that incorporate more types of heterogeneity.

Our preliminary finding of a relationship between the size of tree crowns and the correlation length of the throughfall pattern should be studied further in the light of different driving forces (e.g., precipitation amounts, intensity, or stand configuration) that this study did not address. However, the relationship between the spatial scales of canopies and throughfall seems more promising for understanding the spatial patterns of throughfall than predictions based on distances to tree stems, and is simpler than previously published efforts to estimate throughfall by deterministic modeling based on spatially explicit canopy data (e.g., Whelan and Anderson, 1996; Davie and Durocher, 1997a).

The results of this research suggest that calibrated statistical models of throughfall are viable as characteristic descriptors of throughfall in a stand. Variograms and stability plots of throughfall appear to be stable measures of throughfall variability, and require no canopy measurements to obtain. Coexistence of variogram shapes and normalized throughfall amounts that were persistent in time at individual samplers indicates that the spatial patterns were deterministically reproduced among storms rather than simply being repeated statistically (e.g., Fig. 2). Although temporally repeated spatial distributions of throughfall has been reported by others (e.g., Beier et al., 1993; Whelan and Anderson, 1996; Raat et al., 2002), this time stability has not previously been explicitly linked with the geostatistical properties found by other work (e.g., Loustau et al., 1992; Bellot and Escarre, 1998; Loescher et al., 2002; Gómez et al., 2002).

The combination of time-stability plots and variograms allows spatial interpolation of throughfall between measurements, reduction in the number of required measurements in an individual stand after calibration, and mathematical simulation of the throughfall process. The results of this study indicate that stand type and season affect these measures; data from more stands and storms would improve the versatility of this approach by identifying other relevant variables.

Many papers have indicated less-variable throughfall during larger storms (e.g., Tobón Marin et al., 2000; Bouten et al., 1992). We found this in our data as well, but lacked enough storms to fully evaluate this relationship (Table 1). Notably, there was no relationship between geostatistical structure and storm-total throughfall in our data. We speculate that spatial patterns may persist among storms but be muted in larger events, but more data are needed to quantify this effect.

Several researchers have used Spearman's rank correlation test to compare normalized throughfall amounts or soil moisture at individual sites between time periods (e.g., Vachaud et al., 1985; Raat et al., 2002; Si, 2002). We found this technique to be less powerful than the stability plot approach for detecting temporal persistence in middle-quantile sample points, because large variations in rank among time periods may arise from only minor differences in throughfall. The Spearman test is also unable to address the possibility of persisting locations of extremly wet or dry sites because it only tests for 'general persistence'-that is, it tests whether the mean line in the stability plot is statistically different than a flat line.

Research has shown that spatial variation of throughfall and the resulting infiltration variation contribute to spatial variation in soil moisture patterns in forest soils (e.g., Eschner, 1967; Bouten et al., 1992; Si, 2002; Zhou, et al., 2002; Schume et al., 2003; Raat et al., 2002). However, owing to spatial variability of soil thickness and physical properties, it is often not possible to relate patterns in throughfall directly to patterns in water content (Raat et al., 2002). Nonetheless, temporal and spatial persistence of throughfall has important implications for soil hydrology. Consistent and marked spatial differences of water infiltrating into the forest soil will not only produce consistently wetter and drier areas, but also influence the rate of percolation through the unsaturated zone. Thus, repeated patterns of infiltration may be considered a kind of preferential flow at the scale of several meters, perhaps akin to preferential flow in macropores at smaller spatial scales. Consequences may include lateral subsurface flow or rapid recharge to groundwater as infiltration bypasses portions of the soil profile (Weiler and Naef, 2003). Nutrients and other solutes may thus also be transported faster than in homogeneous matrix flow. Persistence of throughfall variability may also be related to the decadal-scale temporal stability of preferential flow paths as observed in a structured forest soil by Hagedorn and Bundt (2002).

This complex subsurface suite of hydrological processes might be best modeled stochastically using spatiotemporally variable boundary conditions, compared to the common approach of modeling infiltration as spatially homogeneous. The results of this study would be directly applicable to such modeling. After obtaining parameters necessary to define variograms and time stability plots from field data, inter-event variability in spatially explicit throughfall can be simulated stochastically. For example, a model grid of throughfall might be seeded with mean normalized throughfall at each grid node assigned from a probability distribution defined by the stability plot, then arranged spatially using the measured variogram as a constraint. Subsequent events might be simulated by allowing normalized throughfall at each grid node to vary according to the observed distribution about the mean obtained from time stability plots. This or some other scheme would allow virtual experiements (*sensu* Weiler and McDonnell, 2004) to help understand the role of spatiotemporally variable throughfall in vadoze zone hydrology.

5. Conclusions

Spatial patterns of throughfall at the three study stands varied in quantifiable ways over time and space. Semivariograms indicated that patterns of normalized throughfall persisted among storms, and persistent normalized throughfall at individual collectors indicated the geostatistical patterns persisted because of deterministic processes that consistently redistributed precipitation to create patterns of throughfall.

Patterns of throughfall can be described by variograms and time stability plots of normalized throughfall. These techniques in combination allow quantification of the variability of throughfall in space and time. These measures are flexible enough to describe variability that is strong or weak, and temporally persistent or random. Each of the forest stands we investigated had characteristic semivariograms and persistence plots that can serve as the basis of models of throughfall for application to, for example, models of infiltration, soil processes, and watershed hydrology. Further work may reveal characteristic changes in these parameters with stand disturbance and development.

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