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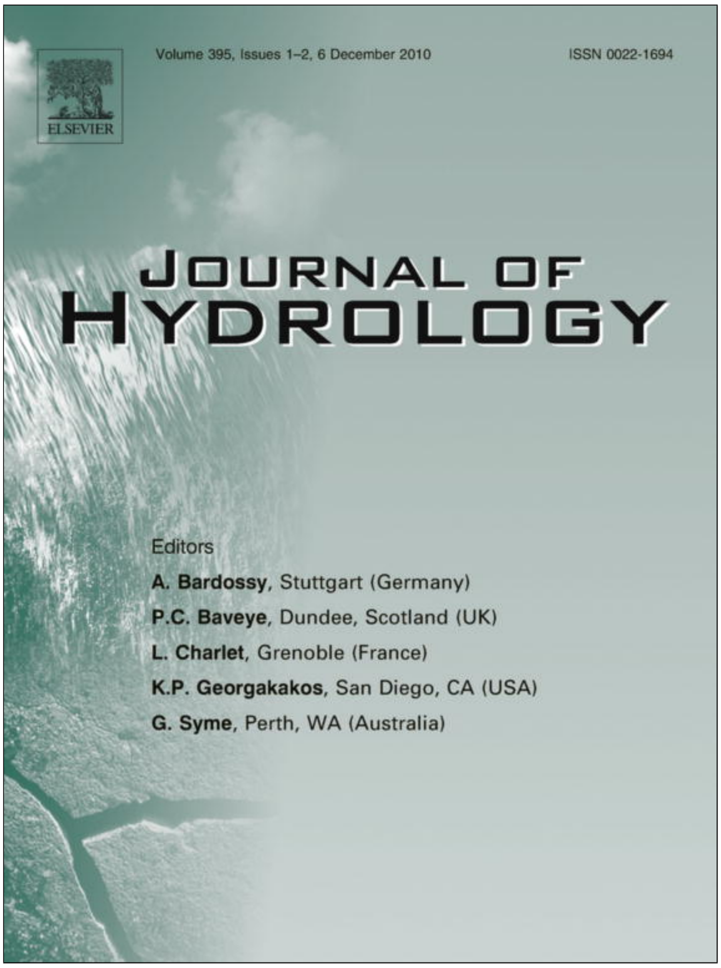

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Discussion

Comment on "Spatial throughfall heterogeneity in a montane rain forest in Ecuador: Extent, temporal stability and drivers" by Wullaert et al. [J. Hydrol. 377 (2009) 71–79]

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1. Introduction

Redistribution of rainfall in forest canopies results in a considerable small-scale variability of throughfall (e.g. Loustau et al., 1992; Staelens et al., 2006). For decades, researchers have tried to understand the drivers of this variability (e.g. Helvey and Patrick, 1965; Kimmins, 1973; Beier et al., 1993; Staelens et al., 2006; Zimmermann et al., 2009), and many attempts have been made to predict throughfall patterns in the spatial and temporal domain (e.g. Ford and Deans, 1978; Whelan and Anderson, 1996; Keim et al., 2005; Staelens et al., 2006; Zimmermann et al., 2009). Wullaert et al. (2009) investigated the spatial and temporal variability of throughfall in undisturbed and managed Ecuadorian montane forests and concluded that throughfall measurements show temporal persistence during a four-year monitoring period; a stability which they considered long-term and which they linked to the differentiation of ecological niches and plant diversity. Furthermore, Wullaert et al. (2009) concluded that meteorological conditions have a negligible influence on throughfall spatial variation. In this comment we will discuss these findings in light of their data-analytical approach.

2. Temporal persistence of throughfall measurements and its implications

Wullaert et al. (2009) used time stability plots to investigate the temporal persistence of throughfall spatial variability. A closer examination of these plots (Fig. 4, Wullaert et al., 2009) reveals that – using the authors' criterion for persistence (see below) – less than 25% of the sampling locations received throughfall volumes which clearly deviate from median throughfall (undisturbed forest: collectors 25, 36, 15, 52, 47, 6, 13, 14, 18, 23, 42, 5, 40; managed forest: collectors 50, 2, 32, 58, 49, 8, 46, 54, 26, 38, 29). Do these plots contain sufficient information to infer any influence of throughfall distribution on ecological processes? We argue that this is not the case, for although time stability plots may support preliminary suppositions regarding the spatiotemporal distribution of throughfall, they are not suited to confirm links between throughfall patterns and ecological processes. This contention is based on the following three arguments.

To begin with, time stability plots are highly sensitive to the applied criterion of persistence; for this reason alone, they have to be interpreted with utter circumspection. More precisely, the decision whether to use the standard deviation (mean ± 1 SD) (e.g. Vachaud et al., 1985; Raat et al., 2002; Staelens et al., 2006), or the interquartile range (IQR) (Wullaert et al., 2009) as criterion of persistence strongly influences the outcome because these criteria comprise different proportions of data (assuming normally distributed data, they include 68.2% and 50% of the data, respectively). To demonstrate this difference in practice we calculated time stability plots based on these two criteria of persistence. Briefly, our comparison (Fig. 1) clearly indicates that the obtained results differ markedly. The version which applied the IQR as criterion of persistence (following Wullaert et al. (2009)) shows a considerably larger amount of persistent sampling locations (Fig. 1a) than does its counterpart that was based on the standard deviation (Fig. 1b). The example indicates that the use of an alternative criterion could completely change the results of Wullaert et al. (2009). Another problem inherent to time stability plots arises in the analysis of long-term datasets. This is because time stability plots 'deteriorate' when the observation period exceeds the range of temporal correlation (Zimmermann et al., 2009); at this point, an increasing number of sampling positions show a temporal mean (or median) of normalized throughfall close to zero. In other words, these plots do not preserve information about temporal persistence of spatial patterns once the correlation decays. To overcome the aforementioned problems and to provide a solid basis for the rather far-reaching conclusions of Wullaert et al. (2009), we suggest using temporal variograms (Zimmermann et al., 2009). Contrary to time stability plots, temporal variograms differentiate in temporal lags, usually improve with an increasing monitoring period, and reveal the temporal correlation length (Zimmermann et al., 2009). These characteristics make them particularly suited for the analysis of long-term datasets. If the available sample size does not meet the requirements for variogram analysis, a calculation of correlations between throughfall measuring periods (e.g. Raat et al., 2002; Staelens et al., 2006; Zimmermann et al., 2008) can be used to underpin the results of time stability plots.

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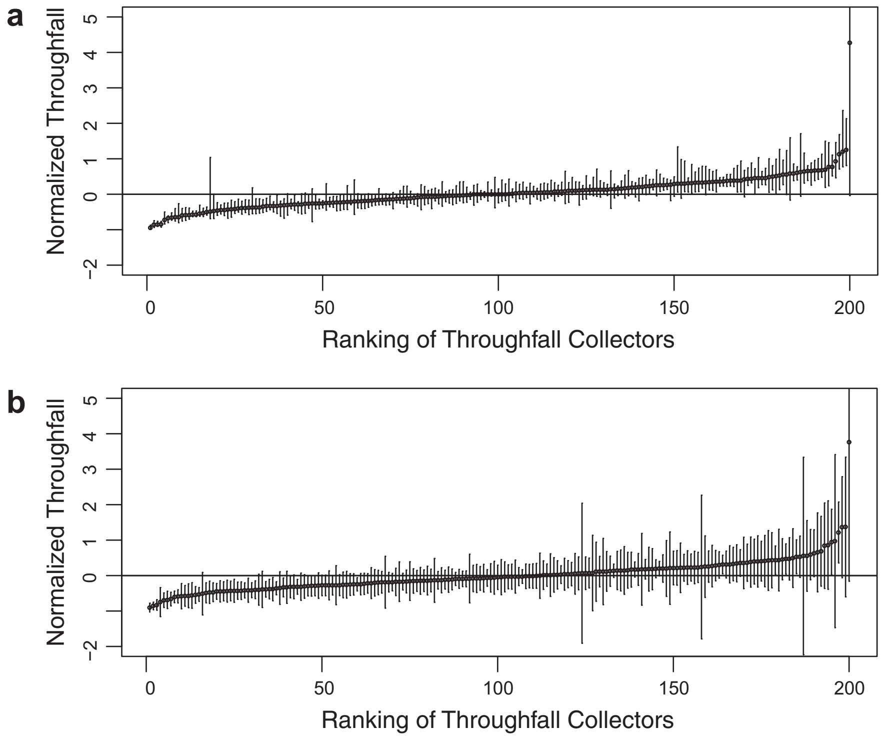

Fig. 1. Time stability plots for a throughfall dataset of 44 events and 200 sampling positions based on the interquartile range (a) and ±1 standard deviation (b) as criteria of persistence, respectively. The data contains no missing values, for an in-depth description of these data we refer to the work of Zimmermann et al. (2009, 2010). The upper graph (a) is calculated according to Wullaert et al. (2009): Dots indicate the median of normalized throughfall at each sampling position, bars show the interquartile range. The lower graph (b) displays a time stability plot for the same data; its calculation follows Vachaud et al. (1985): Dots mark the mean of normalized throughfall at each sampling position, and bars illustrate ±1 standard deviation. Sampling positions are considered persistently dry or wet if their bars do not intersect with the horizontal line that shows the median of all throughfall measurements. Note the distinct proportion of persistent sampling locations in both graphs: The upper graph indicates a proportion of 49% of persistent locations, whereas the lower graph displays only a proportion of 24%.

Secondly, in a further attempt to infer high temporal stability, Wullaert et al. (2009) compared their results with a two-year throughfall study by Staelens et al. (2006) and concluded that differences of relative throughfall in the Ecuadorian forests are relatively pronounced. Apart from the questionable support for Wullaert et al.'s (2009) inferences discussed above, this conclusion is not surprising anyway: Whereas Staelens et al. (2006) investigated throughfall patterns beneath a single beech tree, Wullaert et al. (2009) focused on whole forest stands which inherently comprise a larger variability due to canopy gaps, the existence of different tree species etc. Hence, this obvious scale effect casts a doubt on any such comparison.

Finally, we wish to point out that even temporally stable throughfall patterns do not necessarily influence soil moisture patterns and, subsequently, site conditions conducive to plant growth because the water content of the forest floor also depends on a variety of other factors such as the thickness of the organic layer, preferential flow paths to the mineral soil, and micro-topography (e.g. Raat et al., 2002; Shachnovich et al., 2008). In this context, Goller et al. (2005) investigated hydrological flow paths at the Ecuadorian study site and detected the lateral redistribution of throughfall in the thick organic layers of the forest floor during intense rainfall (i.e. >6.5 mm/h). Given that higher intensity rainfalls at the site contribute to the bulk of the annual total (Fig. 2, Zimmermann and Elsenbeer, 2009), this observation does not exactly support the notion of a tight coupling of throughfall and soil moisture patterns, which is a prerequisite to link throughfall patterns with plant (i.e. seedling) responses. Hence, the overall conclusion of Wullaert et al. (2009) that observed throughfall variation and its inferred long-term persistence contributes to the creation of ecological niches appears rather speculative.

3. Influence of meteorological parameters on spatial variability of throughfall

3.1. Interactions between meteorological parameters and canopy structure: why attempts to eliminate the influence of the canopy structure fail

In contrast to previous studies (Helvey and Patrick, 1965; Kimmins, 1973; Loustau et al., 1992; Vrugt et al., 2003; Carlyle-Moses et al., 2004; Holwerda et al., 2006; Staelens et al., 2006; Zimmermann et al., 2008), which simply used throughfall spatial variability as the dependent variable to investigate the influence of meteorological conditions, Wullaert et al. (2009) attempted to eliminate, prior to further analysis, that part of the spatial variability which they deemed attributable to canopy structure. To separate canopy effects from meteorological characteristics, the authors multiplied each weekly throughfall value for a given collector with a factor (the second term of their Eq. (3)) that depends on the median of all throughfall values measured with the respective collector over the whole study period. Then they calculated the interquartile ranges of the rescaled data for every monitoring week, and subsequently analyzed the relation between the resulting IQR's and a number of meteorological variables. Unfortunately, Wullaert et al. (2009) did not provide the rationale for this approach, but most likely it arose from the belief that a correlation between, e.g., total rainfall and throughfall spatial variability does not necessarily indicate a causal relationship but may instead reflect the influence of some other, confounding variable. Wullaert et al. (2009) seem to believe that the canopy structure acts as such a confounder. In our opinion, this approach is subject to a number of fallacies, which we examine taking into account the influence of rainfall on throughfall variability.

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To begin with, it is largely the interaction between rainfall and canopy structure that determines throughfall variability. Small events, for instance, tend to show a large positive skew (e.g. Bellot and Escarre, 1998; Zimmermann et al., 2009) and hence, a large variability (e.g. Loustau et al., 1992; Zimmermann et al., 2009), because throughfall mainly consists of the free throughfall component which originates from rain falling through gaps (Rutter et al., 1971; Gash, 1979; Loustau et al., 1992). Larger events, in contrast, saturate the canopy, and drip becomes increasingly important (Rutter et al., 1971; Gash, 1979; Loustau et al., 1992; Zimmermann et al., 2009). Interestingly, drip points occur at spatially random positions (Loustau et al., 1992; Zimmermann et al., 2010) and even sheltered spots receive some water (Zimmermann et al., 2009). As a result, throughfall variability usually decreases with increasing rainfall. Numerous other examples, such as the activation of drip points during heavy rainfall due to overflow of epiphytes (e.g. Veneklaas and Van Ek, 1990; Zimmermann et al., 2007), or the influence of rainfall intensity and angle on water storage capacities of leaves and bark (e.g. Aston, 1979; Crockford and Richardson, 1990; Calder, 1996), reveal links between rainfall characteristics and canopy structure. Hence, any attempt to eliminate the influence of the canopy structure negates these interactive processes.

The impossibility of partitioning throughfall variability becomes also obvious on closer inspection of Eq. (3). Wullaert et al. (2009) claimed that after removing the inter-site differences of throughfall, the remaining scatter within each collector location is attributable to meteorological conditions or temporal changes in the canopy. The latter are considered negligible because of the inferred stability over time (Wullaert et al., 2009). Thus, if Eq. (3) was indeed able to separate the variation in throughfall data which originates from canopy structure from that induced by meteorological conditions, and if temporal changes in the canopy were essentially absent, the remaining intra-location variation at all collectors would have to be very similar. In order to evaluate the performance of Eq. (3) we applied it to that part of a large throughfall dataset which is within the temporal correlation range (Zimmermann et al., 2009). Plotting the remaining intra-location variation reveals that there are obvious non-stationarities within the rescaled time series (Fig. 2), which clearly indicates the influence of canopy structure on the rescaled data, too. To summarize, it seems largely impossible to disentangle the various sources of throughfall variability; hence, the failure of Wullaert et al.'s (2009) attempt appears rather unsurprising.

3.2. Meteorological parameters and throughfall variability: Effects of temporal scale

Finally, we wish to discuss a scaling issue. Though the effects of meteorological parameters (e.g. precipitation type, rainfall intensity, wind speed and direction) on throughfall variability are not yet fully understood, the influence of total rainfall is well documented. Many studies detected a negative correlation between rainfall and the spatial variation of throughfall (e.g. Helvey and Patrick, 1965; Kimmins, 1973; Loustau et al., 1992; Vrugt et al., 2003; Carlyle-Moses et al., 2004; Holwerda et al., 2006; Staelens et al., 2006; Zimmermann et al., 2009). Wullaert et al. (2009), in contrast, did not detect such a relationship. This finding may simply derive from inappropriate sampling in time. Given that the studied Ecuadorian forests are subject to a high rainfall frequency (2971 rain events were registered during a four-year monitoring period; Wullaert et al., 2009), weekly throughfall measurements are likely to comprise several events, and, hence, to underestimate the number of single small events (<2 mm). These events, however, are exactly the ones that show a high spatial variability of throughfall. The sampling-induced bias towards multiple-event and larger throughfall volumes is apt to reduce variability (cf. Fig. 1, Vrugt et al., 2003), which is why the detection of a strong asymptotic

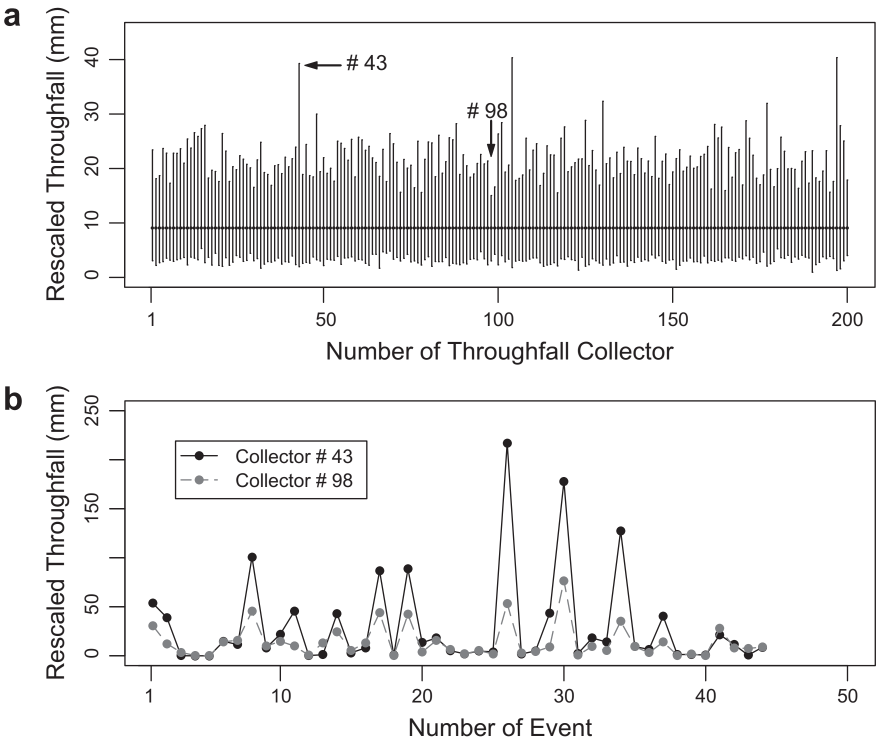

Fig. 2. The upper graph (a) shows the intra-location variation of throughfall for 44 events and 200 sampling positions after rescaling all measurements according to Eq. (3) of Wullaert et al. (2009). The data contains no missing values, for an in-depth description of these data we refer to the work of Zimmermann et al. (2009, 2010). The dots represent the temporal median at each sampling position, and the bars indicate the interquartile range. The arrows mark two exemplary sampling positions (collector #43 and #98). The temporal trend of rescaled throughfall at these locations is shown below (b). Note the distinct variation of rescaled throughfall data at the sampling sites.

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relationship between throughfall variation and event size appears elusive, if not impossible, at this temporal resolution. Prime examples of such relationships were found in a variety of forest ecosystems, comprising temperate (Helvey and Patrick, 1965; Vrugt et al., 2003; Staelens et al., 2006) and tropical forests (Holwerda et al., 2006; Zimmermann et al., 2009). Since other meteorological parameters, for example, wind speed, often change at much smaller temporal scales (Crockford and Richardson, 2000), weekly sampling intervals do not match the scale of the process in question.

4. Conclusions

One main conclusion of Wullaert et al. (2009) was that throughfall in the investigated Ecuadorian montane forests shows a long-term persistence, which the authors link to the differentiation of ecological niches and to regional biodiversity. Furthermore, Wullaert et al. (2009) concluded that a variety of meteorological parameters do not influence throughfall spatial variation.

As to the first issue, we argue that the applied methodology, i.e. time stability plots, does not suffice to infer a link between persistence of throughfall and ecological processes. First, time stability plots are highly sensitive to the applied criterion of persistence which hampers their interpretation. Second, these plots are not particularly suited to analyze long-term datasets as they ‘deteriorate’ when the observation period exceeds the range of temporal correlation. Third, persistent throughfall measurements alone do not provide evidence for the influence of throughfall patterns on biotic processes as the redistribution of throughfall at the forest floor may disconnect throughfall and soil moisture patterns. To overcome the difficulties associated with time stability plots we recommend using temporal variograms. Variogram analysis is particularly suited for long-term and large datasets, and provides, unlike time stability plots, information on temporal correlation lengths. This information will be of importance for the assessment of links between throughfall patterns and biotic processes.

With respect to the influence of meteorological parameters, we argue that the authors’ attempt to eliminate the influence of canopy structure prior analysis fails due to the inability to separate different drivers of throughfall spatial variability. Moreover, we doubt whether the sampling frequency of the study is appropriate to evaluate the influence of meteorological conditions on throughfall spatial variability. To investigate the influence of meteorological parameters we suggest using throughfall spatial variability as the dependent variable and to consider an appropriate sampling frequency.

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