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Use of multiple correspondence analysis (MCA) to identify interactive meteorological conditions affecting relative throughfall

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SUMMARY

Forest canopies alter rainfall reaching the surface by redistributing it as throughfall. Throughfall supplies water and nutrients to a variety of ecohydrological components (soil microbial communities, stream water discharge/chemistry, and stormflow pathways) and is controlled by canopy structural interactions with meteorological conditions across temporal scales. This work introduces and applies multiple correspondence analyses (MCAs) to a range of meteorological thresholds (median intensity, median absolute deviation (MAD) of intensity, median wind-driven droplet inclination angle, and MAD of wind speed) for an example throughfall problem: identification of interacting storm conditions corresponding to temporal concentration in relative throughfall beyond the median observation ($\geqslant$73% of rain). MCA results from the example show that equalling or exceeding rain intensity thresholds (median and MAD) corresponded with temporal concentration of relative throughfall across all storms. Under these intensity conditions, two wind mechanisms produced significant correspondences: (1) high, steady wind-driven droplet inclination angles increased surface wetting; and (2) sporadic winds shook entrained droplets from surfaces. A discussion is provided showing that these example MCA findings agree well with previous work relying on more historically common methods (e.g., multiple regression and analytical models). Meteorological threshold correspondences to temporal concentration of relative throughfall at our site may be a function of heavy *Tillandsia usneoides* coverage. Applications of MCA within other forests may provide useful insights to how temporal throughfall dynamics are affected for drainage pathways dependent on different structures (leaves, twigs, branches, etc.).

1. Introduction

The extent and type of forest cover can exert significant influence over coupled ecological–hydrological (or ecohydrological) processes through the physiological (transpiration) and physical partitioning of meteoric water (Bachmair and Weiler, 2011; Carlyle-Moses and Gash, 2011; Kumagai, 2011; Tanaka, 2011). Physically, when rainfall contacts canopy elements (leaves, branches, epiphytes, etc.) it either: (1) is stored and evaporated (as interception loss), (2) gets diverted along the branch and trunk structures to the soils surrounding the main stem (as stemflow), or (3) penetrates the gaps and drips from the canopy (as throughfall). Of these physical rainfall partitions, throughfall represents the greatest percentage across all measured forest types and climates: generally falling between 60% and 95% (Voigt, 1960; Lloyd and Marques, 1988; Fleischbein et al., 2005). Throughfall has been linked to critical ecohydrological variables: it contributes to stream water discharge and chemistry (James and Roulet, 2006; Inamdar and Mitchell, 2007; Chaves et al., 2008) and watershed stormflow pathways (Singh et al., 2014), and can affect soil microbial community structure (Rosier et al., 2015). In fact, the "pulsed" nature of throughfall plays a major role in these ecological processes—e.g., in the case of soil microbial communities, water pulses may release microbially-mediated nutrient pools via lysing cells or disrupting soil aggregates (Fierer and Schimel, 2002; Rosier et al., in press). Thus, understanding and predicting throughfall amount, and its connection to meteorological conditions, is of critical importance to improved characterization of hydrologic and biogeochemical cycling in wooded watersheds (Levia et al., 2011). It is especially important that methods be applied which can assist in identifying meteorological and stand structural conditions reinforcing pulses of enhanced relative throughfall. Many forests, for example, experience tropical storms and cyclones that are likely to enhance throughfall pulses to soils (see Heartsill-Scalley et al., 2007; Ponette-Gonzalez et al., 2010; Dhillon and Inamdar, 2013). A great body of literature has identified meteorological and stand structural controls over throughfall temporal variability (see reviews

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by Levia and Frost, 2006; Levia et al., 2011), yet research regarding interactive effects of these two conditions and identifying thresholds under changing and extreme storm conditions is needed.

Generally for meteorological influences, throughfall has been shown to increase with rainfall amount and intensity (Helvey and Patric, 1965; Návar and Bryan, 1990; Crockford and Richardson, 2000; Murakami, 2006), while wind conditions can enhance canopy capture and diversion of rain to throughfall in individual canopies (Herwitz and Slye, 1992, 1995). When canopy shaking is induced by winds, it can prevent rainwater coalescence on canopy elements, thereby increasing throughfall drip (Calder, 1996; Hall, 2003; Nanko et al., 2006). Studies have even found threshold values for wind-driven rainfall inclination angle, over which meteoric water flux from the canopy is enhanced (e.g., Herwitz and Slye, 1995). But, under what combination of these meteorological conditions will a forest canopy permit the greatest or least relative throughfall generation? In terms of canopy structural impacts on throughfall generation, leaf shape, configuration, and surface hydrophobicity can alter water storage, increasing or diminishing the canopy water storage threshold after which throughfall can be generated or more efficiently channelled (Horton, 1919; Keim et al., 2006; Holder, 2013; Rosado and Holder, 2013). Bark structures and branching architecture may also affect throughfall generation by changing this water storage threshold (Herwitz, 1985), yet can further amend throughfall by geometric branch orientation impacting the interchange between drip and stemflow drainage (Herwitz, 1987; André et al., 2008). This branch inclination angle relationship also represents a threshold condition (being called a "tipping point" by the Pypker et al. (2011) review), with a ~45° limit being experimentally-derived by Herwitz (1987). Another factor able to increase canopy water storage at the expense of throughfall is epiphyte coverage (Hölscher et al., 2004; Pypker et al., 2006a,b; Köhler et al., 2007; Van Stan et al., 2015). However, the authors are unaware of a threshold in epiphyte-throughfall interactions having been identified (Van Stan and Pypker, 2015). Still, when saturated, stable epiphyte structures may be able to generate hot moments/spots of throughfall generation depending on meteorological conditions (Zimmermann et al., 2007; Van Stan and Pypker, 2015). Stable epiphyte structures in our study forest—*Tillandsia usneoides* L. (Spanish moss)—are extensive (Van Stan et al., 2015). Is there a cocktail of meteorological conditions under which relative throughfall beneath *T. usneoides*-covered forests are enhanced? Do these interacting meteorological thresholds differ for forests without epiphytes, or with other unique characteristics?

Traditional methods used to investigate canopy structural and meteorological influences over throughfall generation include stepwise regression (e.g., Staelens et al., 2008; André et al., 2011) and analytical models (e.g., Rutter et al., 1975; Calder, 1977; Valente et al., 1997). Although each of these methods can provide—and have provided—significant insights, it is surprising how exclusively they are used as this over-reliance can lead to difficulties in generating an overarching conceptual framework for complex multivariate datasets (Whittingham et al., 2006). It is well-documented that stepwise regression has several limitations, including: (1) parameter interference that can lead to bias in parameter estimation (Devore and Peck, 1993; Steyerberg et al., 1999); (2) inconsistency among selection algorithms, parameter selection/deletion order, and number of potential parameters that prevents consistent interpretation and dataset inter-comparison (Derksen and Keselman, 1992); and (3) presence of correlated and "noise" variables that inflates the possibility of false positive results (Wilkinson, 1979; Grafen and Hailis, 2002). Limitations of commonly-used analytical models (e.g., Rutter et al., 1971, 1975; Gash et al., 1995; Valente et al., 1997) include: (1) varied conceptualizations of the throughfall process; (2) violations of assumptions—e.g., Llorens et al. (1997) and Friesen et al. (2015) highlight concerns regarding the assumptions on canopy water storage dynamics; and (3) similarity equifinality, or false linkages between parameters, that can allow other processes (such as interception loss or stemflow) to compensate for errors in throughfall estimates (Pollacco and Angulo-Jaramilo, 2009).

In this paper we describe how a statistical method currently under-utilized in forest ecohydrological research, Multiple Correspondence Analysis (MCA), can be applied to aid in the examination of throughfall temporal dynamics at the intersection of forest structural and meteorological conditions. Specifically, the described MCA method allows determination of thresholds in meteorological conditions correspondent to throughfall conditions of interest (as selected by the scientist). The simultaneous consideration of meteorological conditions as multiple categorical (threshold-based) variables in MCA alleviates and complements some limitations mentioned above regarding stepwise regression and analytical models. For example, the inconsistency issue in stepwise regression brought about, in part, by its series of pairwise comparisons is alleviated by MCA's reliance on the χ^2 statistic to determine significance of association between categorical variables (Hair et al., 1995; Nagpaul, 1999; Hill and Lewicki, 2007). Moreover, MCA, like other data reduction techniques (e.g., principal component analysis), is complementary to analytical models as the reduction and display of contingency tables produces graphics depicting structural relationships among categories within variables (Hair et al., 1995; Nagpaul, 1999; Hill and Lewicki, 2007). This depiction of structural relationships among variable categories can be useful in refining analytical models or selecting the most appropriate conceptualization of the throughfall process.

We provide an example application that assesses what combination of meteorological thresholds (rainfall inclination angle, wind speed variability, rain intensity, and variability in rain intensity) correspond to relative throughfall $\geqslant$73% of rainfall (the median for our study site on St. Catherine's Island, Georgia, USA) in discrete storm events. It is important to note that, since the purpose of this paper is to describe how MCA may prove useful to improving our understanding of temporal throughfall dynamics, the selection of our target throughfall condition ($\geqslant$73% of rainfall) is simply illustrative of throughfall "hot" moments that exceed the midpoint of throughfall conditions. We hope that others will apply MCA in future research to examine throughfall conditions as selected by their unique interests or field site characteristics. In doing so, this will allow more standardized comparison of temporal throughfall dynamics across interacting meteorological conditions.

2. Materials and methods

2.1. Study site description

St. Catherine's Island (SCI) is situated along the Georgia coast (Fig. 1) in the subtropical climate (Köppen *Cfa*) zone, where temperatures rarely dip below freezing during the winter (GA-DNR-WRD, 2013). 30-year mean annual rainfall is approximately 950 mm yr^{-1} (GA Office of the State Climatologist, 2012). In summer, rainfall is dominated by convective thunderstorms, producing mean 30-year rainfall ranging from 65 to 150 mm month^{-1} between May–August. Winter rainfall is sparser (0–100 mm month^{-1} between November–February). Since SCI lies deep within the back curve of the Georgia coastline (Fig. 1) it is at moderate risk for tropical cyclone landfalls. However, SCI does not regularly experience tropical storms or cyclones and no extreme events occurred during the study period. Prevailing wind direction is northwesterly to southwesterly, and mean wind