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Synthetic roving: A numerical technique to estimate fog water dripping below the canopy

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ABSTRACT

Oppositely to the fixed arrangement of gauges, the ‘roving’ technique consists in the regular random relocation of gauges among different positions below the canopy. By doing so, the area over which water dripping below the canopy is integrated increases. Also extreme throughfall values are averaged out. Thus variability of measurements and bias due to sampling of a particular canopy fraction are reduced. These issues may be particularly relevant when dealing with fog water dripping because of the low amounts of water that have to be measured. Consequently the roving technique may be considered a more accurate and precise method to measure horizontal precipitation. However such superiority claims of the roving versus the fixed technique are restricted to particular field experiments, which cannot take into account all possible spatial combinations of gauges. By synthetic roving we refer to a numerical algorithm whereby a representative number of computer-generated random iterations, reproduce possible combinations of moving gauges via Monte Carlo simulations. This permitted us to investigate suitable statistics of both the fixed and synthetic roving arrangements, such as the mean dispersion or the bounds of the coefficient of variability. The method is illustrated via a case study from throughfall measurements (during fog-only conditions, i.e., no precipitation) carried out with a set of 22 fixed gauges, placed below a subtropical cloud forest in the Garajonay National Park (La Gomera, Spain) during a seven-month period.

1. INTRODUCTION

Among others, artificial fog catchers and throughfall gauges are two of the basic instruments widely used for measuring fog water precipitation. While the former may be indicative of the fog water potentially available for interception by the vegetation, the latter approach takes into account the actual fog water intercepted and evaporated from the wetted canopy, and it thus provides information about the amount of fog water (mm) reaching the soil surface. However, using throughfall gauges for quantifying the fog water dripping from the vegetation poses several problems, because of the small volumes of fog water to be detected, of the order of 0.65-2.15 mm day^{-1} (Bruijnzeel et al., 2005), and the large spatial variability imposed by the canopy upon the drip pattern. Intercepted drops are preferentially channeled through specific dripping points within the stand, and consequently throughfall distributions are not spatially uniform but highly skewed (Lloyd and Marques-Filho, 1988; Zimmermann et al., 2009). Accordingly, large numbers of gauges would be needed to obtain reliable estimates of the mean fog water dripping from a particular stand. The ‘roving’ technique (Wilm, 1943), consisting in the random relocation of N gauges among M different positions ($M > N$) below the canopy, has been proposed as a strategy to increase the area over which throughfall is integrated given a certain number of gauges available. Extreme throughfall values would thus be averaged out and bias, due to sampling of a particular canopy fraction, reduced. Various studies have compared the fixed versus the roving technique (e.g. Holwerda et al., 2006; Ziegler et al., 2009), reporting higher accuracy and precision rendered by the roving arrangement. Such field studies are however based on a particular set up of N gauges, M roving locations, and a relocation frequency, f, during an observation period of length T. Investigation of the large number of all possible roving set-ups ($T/f \times {}_{M}C_{N}$) via field experiments results prohibitive, and therefore the conclusions of such studies may be incomplete or bias. As an alternative to this, we propose what we refer as *synthetic roving*, whereby a representative number of $T/f\times_M C_N$ combinations are computer generated via Monte Carlo simulations (Kimmins, 1973; Rodrigo and Ávila, 2001). The method of synthetic roving is illustrated via a case study from measurements carried out during fog-only conditions (i.e., no precipitation) with 22 fixed gauges, placed below an evergreen tree heath-laurel cloud forest in the Garajonay National Park (La Gomera, Spain) during an eight-month period.

2. MATERIALS AND METHODS

2.1. Site description

The area of study is situated at 1300 m.a.s.l. on the upper border of a small watershed (43.7 ha) within the Garajonay National Park (La Gomera, Canary Islands). The watershed is under the influence of fog throughout the year due to the existence of a well-developed 1200-1500 m temperature inversion, which prevents moist air from rising up. The vegetation is mainly composed of wax myrtle-tree heath ('fayal-brezal'), typical of the most degraded areas of the Park usually located at crests and upper-slopes. It is characterized by 7-12 m height, thin and shrubby *Erica arborea* L. trees with a high abundance of epiphytic mosses and lichens. The needle leaves of *E. arborea*, with diameters (∅ = 0.25 mm) on the order of magnitude of the fog droplets (5-50 μm) are efficient structures for the collection of fog droplets by impaction (Ritter et al., 2008). *Laurus azorica* (Seub.) Franco and *Myrica faya* Ait. broad-leave individuals are also present in the area of study.

2.2. Fog water measurements

A line transect was selected within this upper windward plot for installation of 22 autonomous tipping-bucket pluviometers (Davis Instruments Corp., California; 0.2 mm resolution; ∅ = 0.165 m), provided with a Hobo event logger (Onset Computer Corp., Bourne) placed at the following relative distances: 0, 10, 15, 18, 19, 20, 25, 28, 29, 30, 50, 55, 58, 59, 60, 70, 80, 90, 100, 110, 130, and 140 m. Data were collected from 5th October 2006 until 20th April 2007. Nearby, a micro-meteorological station provided 15 min frequency concomitant data on climatic variables and pluviometry above the stand. Event-based throughfall data were first totalized to daily values. Dripping fog water was then obtained from the original throughfall data set by selecting those days with no daily rainfall above the stand, or when this was less than 1 mm, a value lower than the maximum canopy storage capacity of the forest, $S_{\max}$=1.2 mm (Ritter et al., 2009a). In addition to this, a more restrictive condition was also imposed, and this was to remove those daily throughfall values preceded by a day with rainfall >2 mm. This 24h "security" interval was chosen to reduce the possible contribution of events registered by throughfall gauges due to delayed dripping of rainfall water stored by the vegetation. Therefore the fog estimates provided in this study may be considered as a conservative lower bound of the fog water intercepted by vegetation. Other criteria, such as subtracting throughfall from rainfall, may be prone to errors (Bruijnzeel et al., 2005; Muzylo et al., 2009; Regalado and Ritter, 2010), and therefore was not considered here. As an additional check, we verified that, during days when fog was registered, maximum relative humidity was >90%, global radiation was reduced and plant transpiration (measured with sap-flow gauges) suppressed, after Ritter et al. (2009b).

2.3. Numerical experiments

The synthetic roving experiments were carried out by randomly selecting N=2…21 daily fog values from the original data set of 22 throughfall measurements. Fog data were then summed up for the whole measurement period and the mean and coefficient of variation (CV) of the N cumulative values computed. In order to achieve a sufficiently representative data set of random combinations of gauge locations the above procedure was repeated 1000 times. The same simulation scheme was applied to the cumulative throughfall totals, such that 1000 iterations of random fixed arrangements for N=2…21 gauges were generated (Czarnowski and Olszewski, 1970; Rodrigo and Ávila, 2001) for comparison of both mean and CV values with those obtained from the synthetic roving throughfall distributions. Finally, the 95% confidence interval of the average CV and the population mean of the 1000 iterations for each N were computed, for both fixed and roving arrangements. It is worth pointing out that, the 1000 iterations provide a distribution of a sufficiently large population of mean values, and thereby the central limit theorem ensures normality of the data.

3. RESULTS

3.1. Fog water contribution

Table 1 summarizes the main statistics for the period studied. Mean and median fog water dripping below the canopy were 34.4 and 31.9 mm, respectively. Total registered median throughfall was 299 mm. Thus, disregarding the small contribution of stemflow (Ritter et al., 2009), fog represents 11% of the water that reaches the ground.

Table 1. Main statistics of cumulative fog events during the period 5-Oct-06 to 20-Apr-07.

Nº (days)	85
Mean (mm)	34.4
CV (%)	54.4
Skewness	1.6
Median (mm)	31.9
MAD (mm)	9.8
Octile skewness	0.03

3.2. Fixed gauges

Fig. 1 shows the confidence intervals for both the CV and mean cumulative throughfall for different number *N*=2,…, 21 of fixed and roving gauges. With respect to the fixed arrangement of gauges it is shown that as the number of gauges decreases, the CV confidence intervals increase rapidly, such that for *N*=2 the CV is close to 90% (Fig. 1a). The confidence interval of the mean total throughfall spreads out symmetrically as *N* is reduced, such that for a small number of gauges (e.g., *N*=2) the dispersion around the mean is 50 mm (Fig. 1b). The mean total throughfall may be estimated within an error of 25% for *N*=22 only (asterisk in Fig. 1a). For *N*<22 we may encounter by chance a fixed gauge set-up that estimates the mean within a 25% error (i.e., a set-up rendering a CV within the confidence intervals depicted in Fig. 1a), but this is not *a priori* ensured. With more restrictive conditions, e.g., error=10%, virtually none of the fixed arrangements investigated would ensure estimating the mean throughfall with confidence.

3.3. Synthetic roving

The repositioning or "roving" may be an alternative to the fixed set-up of gauges. By virtually relocating the gauges it is shown that both the CV and the mean cumulative throughfall confidence intervals are shortened with respect to the fix gauge arrangement. Notice also that the CV confidence interval upper bound remains below the measured CV=54.4% for any combination of roving gauges, as opposed to the fixed set-up (Fig. 1a). The mean may be estimated with 25% error with *N* >14 roving gauges. This results from the interception between the CV confidence interval upper bound and the 25% error dash line in Fig. 1a. Thus, taking also into account the results given in Fig. 1b, an optimum roving strategy with minimal mean dispersion would be *N*=15 gauges relocated among 22 positions, rendering a throughfall dispersion interval of [32.3, 36.4] mm, compared to the [29.2, 39.6] mm larger interval obtained with *N*=15 fixed gauges (Fig. 1b). The CV would in this case range within [27.9-44.2] % (Fig. 1a).

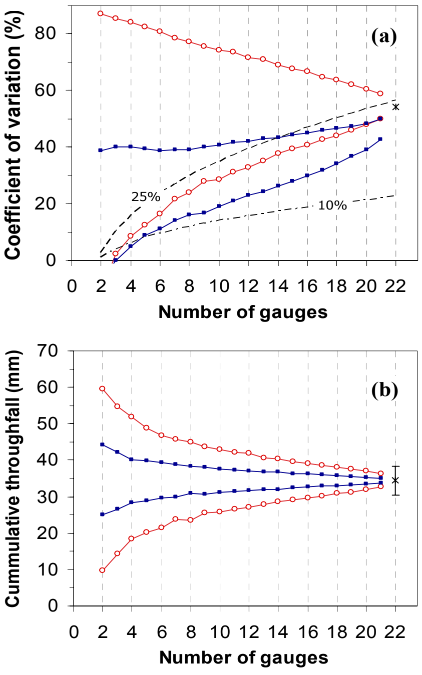

Fig. 1. Confidence intervals of the CV (a) and mean cumulative throughfall (b) for roving (solid symbols) and fix (empty symbols) *N* gauge arrangements. Dash lines represent the CV required for estimating the mean, within a preset 10 or 25% error. Up-down bar in the mean measured cumulative throughfall (*N*=22) represents the standard error.

4. CONCLUSIONS

The numerical experiment carried out here for quantifying particular statistics associated with both the fixed and the roving arrangement of a set of gauges below the canopy, provided information about the suitability of the roving technique. This numerical method was applied to throughfall measurements obtained under fog-conditions (i.e. no rainfall) in an evergreen heath tree-laurel forest in the Garajonay National Park, which represented 11% of the total throughfall water that reached the ground (299 mm) during a seven-month observation period. Using a number *N* of gauges in a fixed arrangement, the confidence intervals of both the CV and mean fog water throughfall spread out rapidly, such that for *N*=2 the CV was close to 90% and the dispersion around the mean was 50 mm. By contrast, the roving technique, for any combination of *N* roving gauges, was proved to be more advantageous in terms of minimization of the confidence intervals of both the CV and mean total fog water throughfall at the end of the measurement period. An optimum roving strategy with minimal mean dispersion was obtained for *N*=15 gauges relocated among 22 positions. This rendered a fog water throughfall dispersion interval estimate of [32.3, 36.4] mm. The results obtained here complement others previously obtained in the same site with fog collectors, and point to a limited contribution of water with fog origin to the laurisilva forests.

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