

Short communication

Response to “Comment on fog precipitation and rainfall interception in the natural forests of Madeira Island (Portugal)”

Susana Prada^{a,b,*}, Miguel Menezes de Sequeira^a, Celso Figueira^b, Victor Prior^c, Manuel Oliveira da Silva^d^a Centro de Ciências da Vida da Universidade da Madeira, Campus Universitário da Penteadá, 9000-390 Funchal, Madeira, Portugal^b Centro de Estudos da Macaronésia, Campus Universitário da Penteadá, 9000-390 Funchal, Madeira, Portugal^c Instituto de Meteorologia, I.P., Observatório Meteorológico do Funchal, Rua do Lazareto no. 37, 9060-019 Funchal, Madeira, Portugal^d Departamento de Geologia da Faculdade de Ciências da Universidade de Lisboa, Edifício C6 – 2º Piso Campo Grande, 1749-016 Lisboa, Portugal

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ABSTRACT

In this paper we discuss the comments given by Regalado and Ritter (2010) on our previous work (Prada et al., 2009). Here, we demonstrate that rainfall correction does not significantly change the results; make clear why Site 1's fog precipitation values do not seem to be overestimated due to the low number of gauges; present observational evidence that suggest high water yields in Site 1; and why we consider that fog water may be important for groundwater recharge. We also review different methodological, ecological and climatic factors between Madeira and the Canary Islands' fog precipitation studies that might explain different values between them (Ritter et al., 2008, 2009).

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We appreciate the comments of Regalado and Ritter (2010, hereafter RR) on the article “Fog Precipitation and Rainfall Interception in the Natural Forests of Madeira Island (Portugal)” (Prada et al., 2009, hereafter PF). In their comments RR suggests that the values of fog precipitation obtained by PF at Site 1 (high altitude tree heath forest) are far beyond any previously reported measurements and describe some methodological errors that might explain these results, namely a possible underestimation of the rain value due to high wind velocity at the rim of the gauge and the uncertainty provided by the low number of gauges placed under the forest canopy. Furthermore, RR argues that estimating fog water contribution to groundwater recharge based on this method, without considering other hydrological variables, is doubtful.

1. Underestimation of rain value

As stated by RR, an underestimation of rain under wind exposed conditions is a reality, however, that does not seem to affect significantly the fog precipitation results obtained by PF. In the original paper we did not make that correction, because we considered that under mean wind velocity conditions of 4.1 m s^{-1} (registered by the Portuguese Meteorological Institute between 1961 and 1990 in

the same area), such a correction would not significantly change the results, as we show in Table 1. The standard rainfall gauge that we used in this study belonged to the Portuguese Meteorological Institute, and it was installed according to their guidelines for installation in windy and mountainous zones. In this specific case, it was located in a relatively shielded topographic depression, far enough from the border not to interfere with the rainfall, but providing protection from high wind velocities. Taking into account Førlund et al. (1996), we corrected the rain precipitation values using their simple method, since we did not have the data for hourly wind and rain intensity taken by an automatic meteorological station during the studied period. Even without having this equipment it is possible to extrapolate a correction through the dynamic method by using the 30-year average wind velocity at Site 1 (1961–1990). At the same time the hourly rainfall intensity was determined by an automatic tip-bucket rain gauge in the area during the 2005–2007 hydrologic years (1.7 mm h^{-1} – Laboratório Regional de Engenharia Civil). Table 1 compares the results published by PF with the corrected ones. In the simple method columns, the five correction constants (k) are provided with a 5% increase due to the fact that the gauge was not shielded (Førlund et al., 1996). These constants correspond to different types of exposures of the rain gauge, from an extremely sheltered location (inside a small forest clearing, lowest k) to an extremely unsheltered location in the mountains (highest k). We considered the correction factor for our location to be class 4 ($k = 1.166$), as it is a mountainous area with a forest stand that gives some protection against the wind.

* Corresponding author at: Centro de Ciências da Vida da Universidade da Madeira, Campus Universitário da Penteadá, 9000-390 Funchal, Madeira, Portugal.
E-mail address: susana@uma.pt (S. Prada).

Table 1

Comparison between previous results and the corrected ones according to Førland et al. (1996).

	Prada et al. (2009)	Simple model correction			Dynamic model correction		
Correction factor (k)	–	1.071	1.103	1.134	1.166	1.197	1.131
Sampled days	955	955	955	955	955	955	955
Fog drip days	421	414	411	411	409	407	411
Gross precipitation (mm)	5288	5663.4	5832.7	5996.6	6165.8	6329.7	5980.7
Throughfall (mm)	17197.9	17197.9	17197.9	17197.9	17197.9	17197.9	17197.9
Fog water (mm)	12623.6	12345	12221.6	12102.7	11980.1	11861.5	12114.2
Canopy Interception (%)	–225	–203.7	–194.9	–186.8	–178.9	–171.7	–187.6
Fog water (mm day ⁻¹)	30	29.8	29.7	29.5	29.3	29.1	29.5
Fog water input (%)	73.4	71.8	71	70.4	69.7	68.9	70.4

The results ($k = 1.166$) show that although there is a 5.1% decrease in total fog water and 12 fog drip days less, the average fog water collected in a fog drip day and fog water input remains essentially the same. The most significant change is that the canopy interception value increases. This is easily explained by the increase in corrected gross precipitation. Throughfall remains the same because there is almost no wind near the forest floor. The dynamic correction shows an even lower discrepancy to previous results ($k = 1.131$). Although a correction should be considered when determining rainfall, in this study that correction does not significantly change the results. Results may be related to differences in fog definition. PF defined “fog” based on visibility, when it was less than 1 km (Bloemink, 2008), instead of drop-size. During fog events in Site 1, the visibility is usually reduced to just 2–3 m and probably include large droplet sizes, thus accounting for the high fog precipitation values. RR should also take into account that increasing wind velocity during fog periods increases fog precipitation, because larger volumes of water enriched air flows through the vegetation (Lovett et al., 1982; Schemenauer et al., 1988; Cameron et al., 1997; Chang et al., 2006).

2. Small number of gauges under the forest canopy

In the original paper PF drew attention to the small number of throughfall gauges used in the study. Having obtained such high fog precipitation values at Site 1, and recognizing that there was a large variability associated with canopy dripping because of the stand structure, PF proceeded to check and confirm these results. For this purpose, we used data obtained in March, 1996, from three large collecting gauges (0.28 m² each), corresponding to 17 standard gauges of 0.05 m² or 42 of 0.02 m². Data was collected during intensive fog periods without rain, using the roving gauge method, in an hourly basis (Lloyd and Marques, 1988). These, associated with the small leaf area, diameter of the branches and dense branching of the tree heaths should reduce the scale of variation under the canopy. These are empirical assumptions but, nevertheless, justify the use of a few large gauges for a rough estimate. The average projected area of the tree heaths that were studied was of 70 m² and the combined area of the three collecting gauges used to confirm our results was of 0.84 m². This corresponds to 1.2% of the total area. The average fog precipitation value obtained was 8.20 mm h⁻¹ (196.8 mm day⁻¹), ranging between 7 and 9.5 mm h⁻¹ (168–228 mm day⁻¹) (Prada, 2000). These results clearly demonstrate that in a full day of intense fog, frequent on Madeira's northern slope, the total amount of fog precipitation can reach totals as high as 200 mm day⁻¹. Besides, observational evidence shows that even on an ordinary foggy day, the water dripping is clearly visible, anyone there becomes rapidly soaked, needing to use water-proof clothing or even an umbrella to stand beneath the canopy. Certain dripping points can be seen pouring water into the soil like a small tap. Surface run-off is visible close to the trunk, showing that stemflow (as stated by PF for Sites 1 and 2) is an important factor, and also demonstrating empirical evidence of a large water yield. Besides this, the tree heath stems are



Fig. 1. Pendant epiphytic bryophytes on an *E. arborea* branch.

almost completely covered by epiphytes, especially mosses and, to a much lesser extent, lichens (Fig. 1). This coverage can be so thick, that some stems can double their diameter, also contributing to the capture of fog droplets (González, 2000). It is also known that due to physiological constraints in very wet forest, epiphytic bryophytes are much more frequent than lichens (Sillet and Antoine, 2004). Another observational proof of the high water content that drops under these trees is the marked division line (Fig. 2) between ground soil vegetation under the tree canopy and outside the forest. It is easy to see a very marked frontier between the mountain prairie land dominated by *Agrostis castellana* and *Pteridium aquilinum* and the soil community under the forest canopy that is dominated by bryophytes. This is due to differences in evapotranspiration, desiccation, radiation and water availability conditions between canopy's shaded and open areas.

3. Contribution of fog water to groundwater recharge

RR argue that fog precipitation does not constitute a significant water input for groundwater recharge because previous results from canarian laurisilva forests suggest that fog precipitation is a localized phenomenon and that assessing whether fog water contributes to groundwater recharge based on above ground measurements is not straightforward.

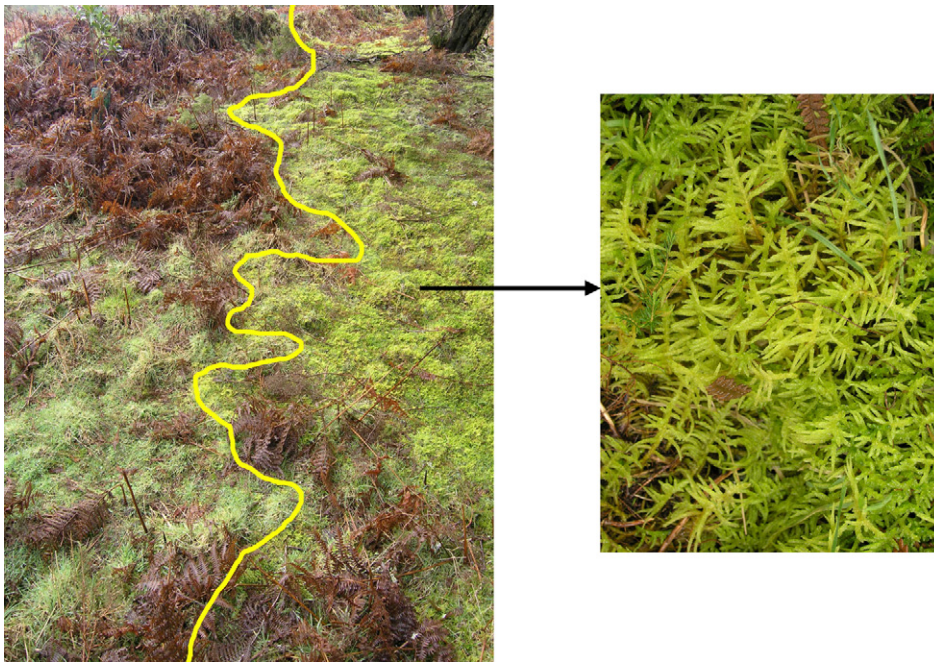


Fig. 2. Division line (in yellow) between prairie grass in the open (left) and bryophyte community under the canopy (right). In the right, a detailed image of these spongy mosses. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

Madeira has a 125.1 km² area of indigenous altitude forests inside the windward fog belt, between 800 and 1600 a.s.l. (Prada et al., 2008). This area is characterized by very steep slopes which are mainly exposed to the prevailing north-easterly trade winds. These factors (steep slopes, great exposure to the humid trade winds and presence of forest vegetation) when combined, facilitate fog precipitation, so it is not a localized phenomenon, but a generalized one throughout the fog belt area of Madeira's northern slope. We acknowledge that the values obtained at Site 1 are extreme, not representative of the entire high altitude tree heath forests. It is not the sheer volume of fog water entering a specific point that is important to groundwater recharge in Madeira, but the large area of favourable conditions for the occurrence of the phenomenon that happens on the island.

In the original publication, we suggested that fog precipitation could be a significant water source of groundwater recharge based on previous knowledge. These sources include studies about recharge and discharge areas, flow mechanisms, the different groundwater body characteristics of Madeira Island (Prada et al., 2005) as well as Paul da Serra's hydrological balance (Madeira's largest groundwater recharge area, Prada, 2000).

Still unpublished data of stable isotopic composition of Madeira Island's groundwater, shows evidence that some of the fog water infiltrates and recharges the island's groundwater system, as observed in other places by Ingraham and Matthews (1988, 1990, 1995).

4. Comparing Madeira's Site 1 and other locations

RR compares the results obtained in Madeira with the ones obtained in tropical broad-leaf rainforests and, in particular, with the subtropical canarian tree heath forests at La Gomera's Garajonay National Park, previously studied by RR (Ritter et al., 2008, 2009). Morphological and ecological differences between those and madeiran high altitude tree heath forests should be pointed out to make it easier for the readers to compare the results. Different climatic factors between Site 1 and their studied site namely, different altitudes, rainfall, fog, etc., should also be taken into account.

In Madeira Island the geography and topography, vegetation cover on the northern slope (above 80%) and the almost constant cloud cover (more than 230 days per year) makes fog precipitation a generalized phenomenon and not a localized one as stated by RR.

Fog droplet-size spectrum could be one of the key-missing pieces in the comparison between Madeira and La Gomera data. At Site 1's altitude, "fog" is undoubtedly of orographic origin, formed by the cloud-base touching the ground. As the air mass is pushed upwards by the island barrier, it is adiabatically cooled, forming clouds. If a previously existing cloud is pushed into the island barrier and forced upwards, it experience an increase in both size and liquid water content (Barry, 2008). The fog originates in orographically generated or cumulus clouds. As such it is not a light, calm radiation fog like the one that often forms at morning in coastal and valley areas and that dissipates through the day, but a thick, very moist and turbulent fog that can be better described as a "cloud interception" and have a duration of several days long. Empirically, the "in situ" observation of fog events in Madeira seems to be characterized by relatively large size droplets. The fog droplets are sometimes visible, as a very thin spray floating around in the air. If the fog droplet diameters indeed are as high as we suspect, then they are more able to be retained in the vegetation, thus increasing fog precipitation values (Shuttleworth, 1977). Besides, the narrow interception surfaces of the small need-like leaves of tree heaths seem to avoid the wind flow diversion, therefore small droplets would not be carried away and more fog precipitation would occur (Went, 1955).

Finally, another important reason for the difference in values between Madeira and the Canary Islands may be the different methodology. RR used artificial fog collectors and then combined this data with a physically based impaction model (Ritter et al., 2008) and PF used the "throughfall excess technique". Because the relationship between these interceptors and the forest vegetation is difficult to correlate (González, 2000), it is possible that the values may not correspond to what really occurs in the vegetation. That is why it is important to

only compare studies that use the same methodology as we did.

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