An impaction model for estimating fog water collection in a subtropical laurel cloud forest of the Garajonay National Park

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ABSTRACT

Subtropical laurel ecosystems of the Macaronesian Archipelagos are assumed to be dependent on fog precipitation. An hybrid approach combining a physically-based impaction model, micrometeorological variables, and data from artificial fog catchers was used to evaluate the contribution of fog water captured by needle-like leaves of *Erica arborea* L. trees in a selected watershed of the Garajonay National Park (La Gomera, Canary Islands) for a two-year period. Changes in fog water collected by the artificial fog catchers were observed between the four measuring sites located at different altitude within the watershed, being only significant in the watershed ridges exposed to the predominant trade winds at higher altitudes. The average amount of water collected by artificial fog catchers was about 500 L m^{-2} $year^{-1}$, representing 95% and 41% of the observed yearly rainfall during the first and second year, respectively. While conventional precipitation exhibited seasonality with rainy and a dry season, fog water contribution was distributed around the year, being most frequent during night until early morning and on late afternoon. Fog water captured by the vegetation predicted by the impaction model indicated a significant amount collected by a single *E. arborea* tree, on the order of 1810–2090 L $year^{-1}$. However, taking into account the spatial distribution of *E. arborea* within the watershed, fog captured by the vegetation represents, at its best, an important (>100% rainfall) water supply only on localized windward ridges with high *E. arborea* density.

1. INTRODUCTION

Microclimatological conditions in the relic laurel ecosystems of the Macaronesian Archipelagos are unique due to the influence of a trade wind (temperature) inversion, which prevents moist air from rising up on the north side of the islands. This leads to an almost permanent layer of clouds between 900 m and 1500 m known locally as ‘mar de nubes’ (sea of clouds). This north-side cloud belt provides low evaporation and favorable fog formation conditions, which may help to sustain these evergreen cloud forests in windward areas at middle elevations, in an otherwise rather arid environment, such as that of the Canaries situated at 28º North in front of the Sahara dessert. However, it has not yet been quantified to what extent fog water can actually contribute to the laurel forests.

In this paper we follow a hybrid approach between traditional fog quantification methods (Bruijnzeel, 2001) and modeling techniques, in order to estimate fog captured by needle leave species (*Erica arborea* L. trees), such that artificial fog catchers’ data are used to derive fog characteristics, which are then combined with a physically-based impaction model (Shuttleworth, 1977; Goodman, 1982) and terrain topography in order to quantify fog collection efficiency by a subtropical elfin cloud forest. We focus on fog precipitation in the most extensive and best conserved laurel ecosystem in the Canary Islands: the subtropical cloud forests of the Garajonay National Park in La Gomera Island, added to UNESCO's World Heritage List in 1986.

2. MATERIALS AND METHODS

The area of study was a small watershed (43.7 ha) within the Garajonay National Park located between 1090 and 1300 m.a.s.l. Four locations were selected in the watershed based on elevation, orientation and vegetation type, denoted as P1145, P1185, P1230 and P1270 according to their altitude in m.a.s.l. (Figure 1).

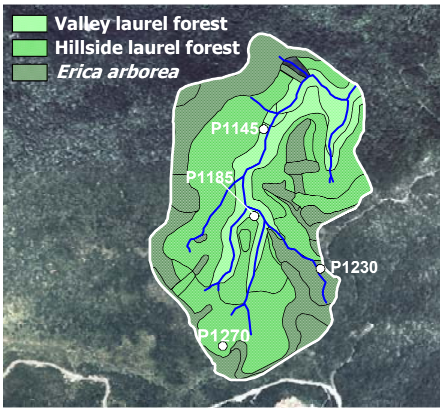

Figure 1. Location of the measuring sites and distribution of *E. arborea* within the watershed.

At each plot a scaffolding tower was installed and instrumented for collecting fog water (QFCs) and for monitoring micrometeorological variables above the canopy. The artificial fog catchers (QFCs) consisted of 0.5x0.5 m screens with a single layer of polypropylene, Raschel-type mesh with 65% shade coefficient. Wet canopy potential evaporation rate was estimated by the Penman-Monteith approach from micrometeorological measurements at 15-minutes intervals (Allen et al., 1998).

The theoretical amount of fog water droplets captured by impaction on a cylindrical leaf element (needle leave of *E. arborea* trees) or obstacle (mesh thread elements of the QFC) under wind-driven fog conditions was estimated from (Goodman, 1982; Walmsley et al., 1996):

$$q = w\,A\,\eta_{imp}\,u \qquad (1)$$

where q is the rate of collected fog water (L h^{-1} after multiplication by the 3.6 $sh^{-1}Lg^{-1}$ conversion factor); w is the liquid water content (g m^{-3}); A is the cross-sectional area (m^2) of the obstacle; η_{imp} is the impaction efficiency (-) (Friedlander, 2000); and u is the wind speed (m s^{-1}). Collection efficiencies were calculated for fog droplet diameters of 5, 10, 15, 25, 40 and 50 µm, a mean diameter of the mesh elements in the fog catcher of 1.4 mm, and an average *E. arborea* leaf diameter of 0.25 ±0.02 mm. During fog-only conditions (i.e. no precipitation) fog collector data were used to estimate w following (1). Since the QFCs were oriented to North-East, we calculated an effective wind velocity, perpendicular to the mesh surface, from the wind speed and direction data. The impaction model described in (1) was then applied to estimate the fog water captured by an individual *E. arborea* tree from data on the above computed w. Finally, in an attempt to provide an approximate estimation of the fog water contribution within the watershed, we have applied the following scaling procedure. Firstly, we have simplified the problem of estimating fog water captured by a single *E. arborea* tree by considering its dependence on elevation. Thereby, we have fitted a function to compute fog water captured by a single tree at every site plotted on a digital elevation map of the watershed. Combining this map with the distribution of *E. arborea* within the watershed, we have obtained the areas that potentially received an additional water input from wind-driven fogs.

3. RESULTS

Data obtained from the artificial catchers from February 2003 until February 2005 indicate that fog water was collected at the four locations mainly at low intensities (<0.25 Lh^{-1} per horizontal area). Seasonal variation in rainfall can be observed from October to May (rainy season) and from June to September (dry season). Fog collection by catchers was observed in the four locations throughout the observation period, however the amounts observed in P1270 were significantly higher than those obtained at lower elevations. Compared to P1230, P1270 yielded 6 times more fog water. This value increases to 13 and 19 if the latter is compared to the plots located at lower altitudes (P1145 and P1185). Focusing on P1270, differences were found between the amounts collected from February 2003 to January 2004 and those obtained from February 2004 to January 2005. In addition, fog water collection in the second measuring period was almost distributed throughout the year. However, in the first period the amounts captured in the first semester (Feb03-Jul03) are higher than in the second one (Aug03-Jan04). Both periods (Feb03-Jan04 and Feb04-Jan05) yielded about 500 L m^{-2} $year^{-1}$. Expressing the yearly amount of fog water captured by the artificial fog catcher relative to yearly rainfall, it follows that in the first period this was similar to conventional precipitation (95%). This is not the case in the second period (41%), where rainfall was more than double the collected fog water. Average fog water yield in both periods ranged between 0.2–5.0 L m^{-2} day^{-1} and 0.1–2.1 L m^{-2} day^{-1}, respectively. We have applied the impaction model described in Section 2 at P1270 only, because the amounts of fog water collected at plots P1145, P1185 and P1230 were not relevant. Liquid water contents computed using different fog droplet sizes yield mostly values <0.1 g m^{-3} (70 ±7%) and less frequent values (13 ±2%) of 0.1–0.2 gm^{-3}. Similarly, computation of the average frequency distribution of fog water collected by an *E. arborea* tree, shows that rates of 0.05-0.5 L h^{-1} $tree^{-1}$ predominate (56 ±3%) during the measurement period, and with relatively small error bars. These results suggest that model (1) is robust, being little affected by the uncertainty in fog droplet diameter (D_g). According to the parameterization of the fog droplet size distribution proposed by Klemm et al. (2005) for eight w classes, it follows that for w = 0.025–0.1 g m^{-3} and w = 0.1–0.2 g m^{-3} the maximum droplet diameter frequencies are placed at D_g=10 and 15 µm, respectively. Thus, in our case D_g=10 and 15 µm were the relevant diameters for the most frequently (83%) computed w values (<0.2 g m^{-3}). Furthermore, the hourly distribution of fog water collection during the day computed for both measuring periods shows that fog collection occurs mostly during night until early morning and on late noon (Figure 2).

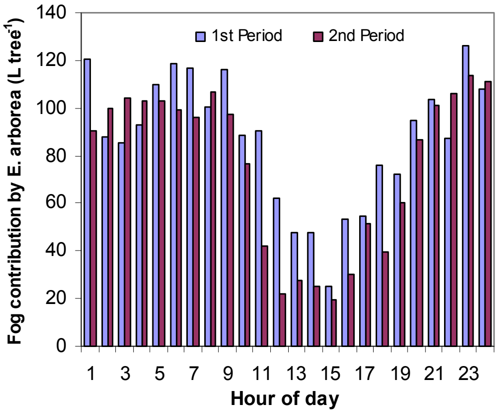

Figure 2. Hourly distribution of fog water captured by an *E. arborea* tree during the day computed for both measuring periods.

The yearly totals of fog water captured by a single *E. arborea* tree are given in Table 1 as the average of the results obtained using D_g=10 and 15 µm. Error of fog water estimates at 15-minute intervals was ±1.0 L $h^{-1}tree^{-1}$. Wet canopy potential evaporation was subtracted from collected fog water at 15-minutes intervals, assuming that water which does not evaporate drips into the soil. Thus, a single *E. arborea* tree may contribute with a considerable amount of fog water (>1500 liters) to the annual water inputs into the soil. Taking tree density (trees m^{-2} of soil surface) into account, the mean yearly contribution to soil moisture of the fog water captured by *E. arborea* trees was 266 mm.

Table 1. Yearly totals of fog water captured by *E. arborea* at P1270

Period	Fog water captured ($l\ tree^{-1}$)	Fog water contribution to the soil ($l\ tree^{-1}$)	Fog water contribution to the soil (mm)
Feb03–Jan04	2086	1875	281
Feb04–Jan05	1812	1674	251

By applying the impaction model as described above to the four measurement sites, it follows that there exists an empirical relationship (R^2=0.993) between elevation and the collected fog water contribution of a single *E. arborea* tree (Figure 3).

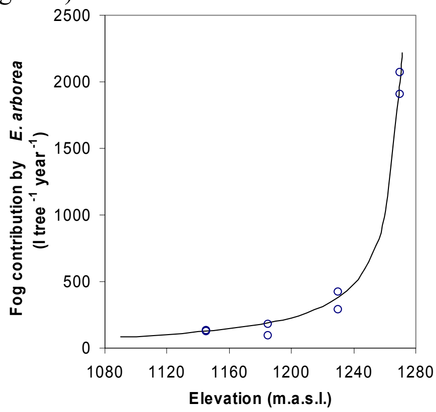

Figure 3. Fog water captured by an *E. arborea* tree according to elevation for both measuring periods.

Thus, the fitted function allows us transforming the digital elevation map into a map of fog contribution by *E. arborea* trees (L m^{-2} $year^{-1}$). Combining this map with the spatial distribution of *E. arborea* across the watershed (Figure 4) provides the amount of fog water that is captured yearly by this needle-leaved vegetation, and that is envisaged as an additional input of water into the soil. This procedure was applied to compare the fog water contribution during both the rainy and the dry season. Fog water contribution was expressed as percentage of the average monthly rainfall, being 81 mm for the rainy and 3 mm for the dry season. From October to May (rainy season) fog water contribution was small compared to rainfall (Fig. 5a). Only at localized places this was over 100 % rainfall. From June to September (dry season), fog precipitation is the main water supply, thus the relative importance of fog water is increased, although it remained constrained to the exposed watershed ridges (c.f. Figs. 5a and 5b). Notice that high values in Fig. 5b are a consequence of the almost absence of rainfall during this period.

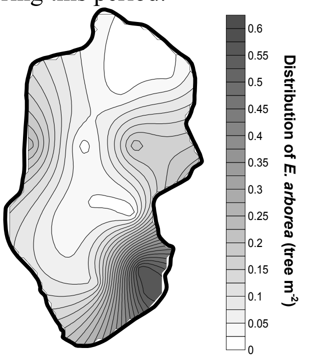

Figure 4. Interpolation across the spatial domain of the data provided by Golubic (2001) about *E. arborea* tree density in ten different plots distributed within the watershed.

a) b)

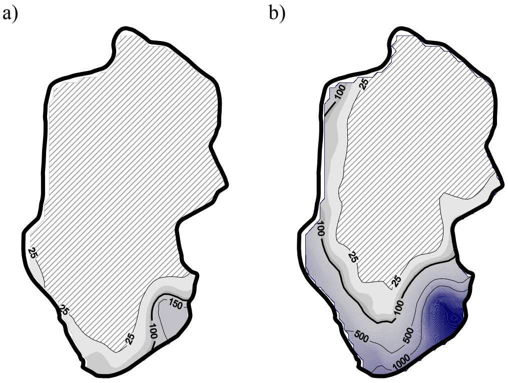

Figure 5. Relative fog water contribution expressed as percentage of the average monthly rainfall during a) rainy season and b) dry season.

4. CONCLUSIONS

The importance of the water supplied by wind-driven fogs in the Garajonay National Park is limited to particular sites. The amount of fog water that can potentially be collected by artificial fog catchers or by the vegetation is highly dependent on site elevation, being only significant in localized areas of the laurel forest ecosystem where wind-driven fogs blow against the vegetation. From the measurements of micrometeorological variables in four locations within an elfin laurel forest watershed and the application of a physically-based impaction model, and rather generous assumptions about the canopy fog capture process, it follows that trees located at higher elevations capture note-worthy amounts of fog water (≥50 mm year^{-1}), so that fog contribution to water inputs in this laurel forest is constrained to the ridges in the southern part of the watershed (about 5 ha), particularly the peak located in the Southeast area. The mean yearly amount of fog water provided by needle-leaved trees such as *E. arborea* was estimated to be about 260 mm. This water input is distributed throughout the year, while conventional precipitation exhibits seasonality.

Acknowledgements

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