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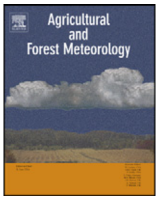

Fog precipitation and rainfall interception in the natural forests of Madeira Island (Portugal)

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A B S T R A C T

Situated in the Atlantic Ocean, Madeira is a within-plate volcanic island, approximately 600 km northwest of the Western African coast. Cloud cover formed mainly of orographic origin persists on Madeira for more than 200 days per year between 800 m and 1600 m altitude. Since vegetation occupies 2/3 of the island's surface, fog precipitation, which occurs when fog droplets are filtered by the forest canopy and coalesce on the vegetation surfaces to form larger droplets that drip to the forest floor, is an important hydrological input. Rainfall interception and fog precipitation data were collected between 1996 and 2005 in the natural forests of Madeira. Six throughfall gauges were placed under the canopy of three different types of forest: high altitude tree heath forest (1580 m), secondary tree heath forest (1385 m) and humid laurisilva forest (1050 m). Fog precipitation is higher under high altitude heath forest (average canopy interception was −225% of gross precipitation) and dependent both on altitude and vegetation type, due to different tree architecture and leaf shape. Although results are conservative estimates of fog precipitation, they point towards the importance of fog-water as a source of groundwater recharge in the water balance of the main forest ecosystems of Madeira.

1. Introduction

Fog precipitation is due to the simultaneous presence of a thick and persistent cloud cover, wind, and dense vegetation cover. It occurs when fog droplets are filtered by the forest canopy and coalesce on the vegetation surfaces to form larger droplets that drip to the forest floor (Kittredge, 1948; Prada and Silva, 2001).

Fog precipitation is also known as occult precipitation, horizontal precipitation, fog drip, cloud drip, cloud milking, occult condensation and precipitation by direct interception of cloud water (Kittredge, 1948; Twomey, 1957). Precipitation by direct interception of cloud water best describes the process of fog precipitation, as it suggests that in the absence of interception, there is no significant deposition. Fog droplets stay suspended in the atmosphere because their drop velocity is smaller than the velocity of the ascending currents inside the cloud. Only a very small percentage of droplets, dragged by the wind, can precipitate directly on the soil in quantities that do not exceed 0.2 mm/day (Cunha, 1964).

According to Twomey (1957) vegetation can directly influence the rainfall of a given area, i.e. water reaching the ground, because in an elevated region (frequently covered with low clouds), cloud water intercepted by trees and other vegetation may constitute an appreciable fraction of the total runoff.

During a rainfall event, vegetation intercepts precipitation and stores water in the canopy, a large proportion of it being evaporated thereafter (Kittredge, 1948). As a result of the process of interception, a rain gauge placed in the open normally receives more water during a rainfall event than throughfall gauges placed under a forest canopy.

The purpose of this study was to quantify fog precipitation and interception in the main forest types in Madeira, corresponding to the cloud cover altitudinal range, and to evaluate the importance of fog water to the water resources of the island.

2. Methods and materials

2.1. Site description

Situated between 32°38′ and 32°52′N and 16°39′ and 17°16′W, Madeira is a within-plate volcanic island, approximately 600 km northwest of the Western African coast. It is a hot-spot originating from a mantle plume dating back to Miocene times, about 5.6 My (Ribeiro et al., 2005).

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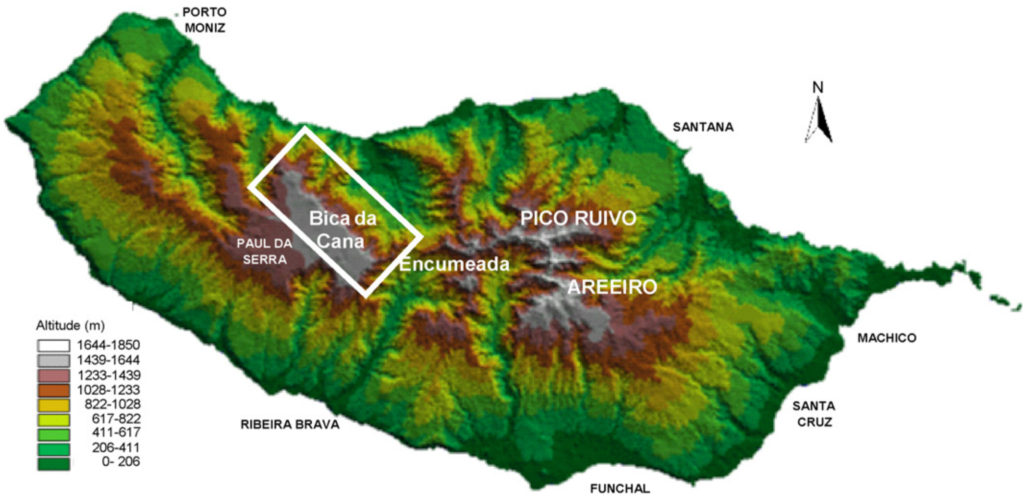

Fig. 1. Location of study area in the Paul da Serra massif, Madeira Island.

With a 737 km^2 surface area, a length of 58 km, a 23 km wide and a maximum altitude of 1861 m (Pico Ruivo), the island forms an E–W oriented barrier, with deep valleys.

Madeira's climate is heavily influenced by the Azorean Subtropical Anticyclone's intensity and location, but also by relief, altitude and orientation. The trade winds are predominantly blowing from the northeast for most of the year.

Since the island barrier (E–W) has an almost perpendicular orientation with the prevailing wind direction (NE), temperature and rainfall vary remarkably on each of the slopes. The northern slope is more humid than the southern at the same height, and the amount of rainfall increases with altitude on both slopes (Prada, 2000).

The highest precipitation is 2966.5 mm at *Bica da Cana* (1580 m altitude), and precipitation decreases above this height. The lowest precipitation occurs on the southern slope's lowlands in locations like Funchal and Ponta do Sol, where the annual precipitation is 513 mm and 583 mm, respectively (Prada, 2000; Fig. 1).

Cloud cover over the island is higher than over the sea. This effect is due to the formation of orographic clouds and fog when the humid maritime winds ascend along the island slope. Air cools and condensates the water vapour into small particles that stay suspended, originating in fog and clouds, whether the condensation occurs near or far from the ground, respectively.

In Madeira, fog is almost exclusively of orographic origin, forming in the North and dissipating to the South of the island. In Bica da Cana, as much as 235 days of fog per year were registered, whilst in Pico do Areeiro the value is 229 days of fog per year (INMG, 1979). Cloud cover persists between 600–800 m and 1600 m and its liquid water content varies between 0.1 g/m^3 and 0.25 g/m^3 (Frisch et al., 1995).

Recently, Madeira's vegetation was described by Capelo et al. (2004). Above 300 m on the North slope a humid laurissilva forest, dominated by stink laurel (*Ocotea foetens*), islands laurel (*Laurus novocanariensis*) and *Clethra arborea* is the climax vegetation. However, mainly due to human actions (fire and grazing) this multi-stratified forest up to 30 m high was replaced by a secondary tree heath forest dominated by the heath *Erica platycodon* subsp. *maderincola* and the madeiran blueberry (*Vaccinium padifolium*). Above 1400 m a high altitude tree heath forest, dominated by *Erica arborea* trees, corresponds to the climax vegetation. This high altitude tree heath forest was severely damaged by overgrazing and fire and only a few small woods still stand.

Precipitation under a canopy (throughfall) and rainfall in a nearby clearing were compared at three sites representing three different types of vegetation (Table 1) selected on the northern slope of "Paul da Serra" massif (Fig. 1).

This area was selected because it has a well-preserved vegetation cover (included in the Madeira Natural Park, and part of Natura 2000 NET), is exposed to the predominant winds from northeast and has a high annual rate of fog days (235 days). Mean slope is 50%, from at about 600 m to the summit at 1600 m at Bica da Cana. Following the bioclimate classification proposed by Rivas-Martínez (2004) and according to the bioclimate map proposed by Mesquita et al. (2004) the sites correspond to a temperate macrobioclimate, to a mesotemperate termotype (superior to inferior) and to ultra to inferior hyperhumid ombroclimate.

The first site is a high altitude tree heath forest at 1580 m ("Bica da Cana", Fig. 2) exposed to winds from all directions, with prevailing north-eastern direction (36% of the time) in a 5.6 ha homogenous stand. This site bioclimate corresponds to a superior mesotemperate termotype and to a ultrahyperhumid ombroclimate (Mesquita et al., 2004). Data were collected with two gauges for 955 days between October 1996 and September 1999.

The second site is a secondary tree heath forest at 1385 m ("Fonte do Rentroia", Fig. 3) exposed to the northern winds in a large area (about 50 ha) of continuous vegetation. It is bioclimatically similar to the first site, but the ombroclimate is dryer (inferior hyperhumid, Mesquita et al., 2004). Data were collected with two gauges for 394 days between May 21, 2004 and July 13, 2005. Gauges malfunctioned for 25 days between November 23 and December 17, 2004.

The third site is a humid laurissilva forest at 1055 m (Fig. 4) exposed to northern winds in large area (about 50 ha) of

Table 1
Geographical and ecological characteristics of sites.

	Location	Altitude	Vegetation type	Exposition	Data registry
Site 1	Bica da Cana	1580 m	High altitude tree heath forest	Winds from all directions	October 1996–September 1999
Site 2	Fonte Rentroia	1385 m	Secondary tree heath forest	Northern winds	May 2004–July 2005
Site 3	Montado dos Pessegueiros	1055 m	Humid laurissilva forest	Northern winds	June 2004–April 2005

Fig. 2. High altitude heath tree.

continuous vegetation. The bioclimate corresponds to a inferior mesotemperate termotype and inferior hyperhumid ombroclimate (Mesquita et al., 2004). In this site due to flaws in the two gauges used, the data records represent five months during dry season (153 days between June 1, 2004 and October 31, 2004) and three months during rainy season (97 days between January 15, 2005 and April 21, 2005).

The location of the open-rain gauge is extremely important, as close distance to vegetation, slope, and gauge type are among the main factors contributing to common estimation errors (Crockford and Richardson, 2000). Rainfall was measured with identical gauges but in open-rain sites at the same altitude. In the first site (high altitude heath forest), the rain gauge was located in a forest clearing of about 5000 m^2. Due to canopy continuity in the secondary tree heath forest and the laurissilva (sites 2 and 3, respectively) the open-rain gauges were placed in a clearing at least 5 m away from the canopy edge.

There is always some percentage of interception in the forest canopy. In fact interception is heavily influenced by the tree crown storage capacity and its variation throughout the seasons, as well as other species dependent factors such as leaf area index (LAI), foliar angle and coverage, and hydrophobic characteristics of the different aerial plant parts (Crockford and Richardson, 2000; Holder, 2007). Interception is also related to other factors such as those related to understory type and cover as well as epiphytic storage capacity (Holder, 2004 and references therein). Climatic factors also play a major role in water interception, including rain quantity and intensity, wind direction and speed during the rainfall and air temperature and moisture (Crockford and Richardson, 2000). An open-rain gauge normally receives a larger quantity of water (gross precipitation) than a gauge under a forest canopy (net precipitation). As such, the canopy interception has a positive value. However, when net precipitation is higher than

Fig. 3. Secondary tree heath forest.

Fig. 4. Humid laurisilva forest.

gross precipitation (negative canopy interception), the additional water is considered to come from the fog filtered by the canopy.

Fog precipitation is not, however, equal to the difference between net and gross precipitation (when the first exceeds the second), since evaporation and storage of fog water during canopy interception is not taken into consideration. Fog precipitation is often underestimated, because fog contribution to throughfall is only quantified whenever net precipitation is higher than gross precipitation. Fog water volume present in the days when canopy interception is positive is ignored, as well as fog water volume that compensates for rain water intercepted by vegetation in the days when the canopy interception value is negative.

Throughfall was measured with two aerodynamic rain gauges (Environmental Measurements Ltd., model ARG100) with a digital magnetic counter (Data Taker 5—Data Electronics, Australia), placed at each site. To obtain a better representation of water drip under a canopy one gauge was placed near a tree trunk, where the foliage and branch cover is much denser, and the other(s) in an area of branch convergence, with a less dense canopy. Forest edges were avoided. The arithmetic means of the data registered by the gauges were calculated at each site.

Fog precipitation values were determined by using the canopy interception formula (Crockford and Richardson, 2000) but stemflow was not determined. Throughfall was considered equal to the net precipitation (Bruijnzeel, 2001), the water that reaches soil underneath a forest canopy, accordingly:

$$I = P_{\text{gross}} - P_{\text{net}}$$

where I is interception, P_{gros} is gross precipitation, and P_{net} is net precipitation.

Whenever canopy interception is negative, fog precipitation is considered to have occurred and its value equalled the absolute value of I. Using the absolute canopy interception mean values in those days when fog drip is considered to have occurred, the input of fog precipitation in the ecosystem can be inferred, by the formula:

$$F_{\text{prec}} = \text{mean}|I\ \text{value in the days when it is negative}|$$

in which F_{prec} is fog precipitation (mm/day).

3. Results

Fog precipitation was approximately 30 mm/day in the high altitude tree heath forest at Bica da Cana (daily measurements correlation between gauges 0.75). These values correspond to a total of 5100 mm/year (30 mm/day × 170 fog drip days—with simultaneous fog and wind), much higher than the mean annual rainfall for the same site (2966.5 mm/year). Fog water input is extremely high (73.4%), and total canopy interception is −225% (Fig. 5; Table 2).

Table 2
High altitude tree heath forest between 1996/1999.

	96/97	97/98	98/99	Total
Sampled days	267	351	337	955
Fog drip days	116	159	146	421
Gross precipitation (mm)	1267.8	2369.9	1650.3	5,288.0
Throughfall (mm)	4836.4	7283.5	5078.0	17,197.9
Fog water (mm)	3800.8	5111.5	3711.3	12,623.6
Canopy interception (%)	−282	−207	−208	−225
Fog water per fog drip day (mm/day)	32.8	32.1	25.4	30.0
Fog water input (%)	78.6	70.2	73.1	73.4

Table 3
Secondary tree heath and humid laurisilva forests during 2004/2005.

	Secondary tree heath forest	Humid laurisilva forest	
		Dry season	Rainy season
Sampled days	394	153	97
Fog drip days	69	21	23
Gross precipitation (mm)	1660	493.8	753.2
Throughfall (mm)	1155.3	171.2	331.2
Fog water (mm)	153.4	56.5	36.9
Canopy interception (%)	30	65	56
Fog water per fog drip day (mm/day)	2.2	2.7	1.6
Fog water input (%)	13	33	11

A total of 69 days with negative canopy interception (throughfall higher than rainfall) were registered in the secondary tree heath forest. Total rainfall was 1660 mm, and throughfall was 1155.3 mm, corresponding to a 30% canopy interception (daily measurements correlation between gauges 0.90). A total depth-equivalent of 153.4 mm of fog water was calculated, corresponding to 2.22 mm/fog drip days and a 13% extra water input in the ecosystem (Fig. 6; Table 3).

There were 21 negative canopy interception days during summer, and 23 negative canopy interception days during winter in the humid laurisilva forest (daily measurements correlation between gauges 0.88). Total rainfall during summer was of 493.8 mm and throughfall was 171.2 mm, corresponding to a 65% canopy interception. Total fog precipitation depth-equivalent was 56.5 mm, corresponding to 2.7 mm/fog drip day and a 33% extra water input in the ecosystem (Fig. 7; Table 3). As for the winter period, total rainfall was 753.2 mm whereas throughfall was 331.2 mm. Canopy interception was 56% whilst total fog water

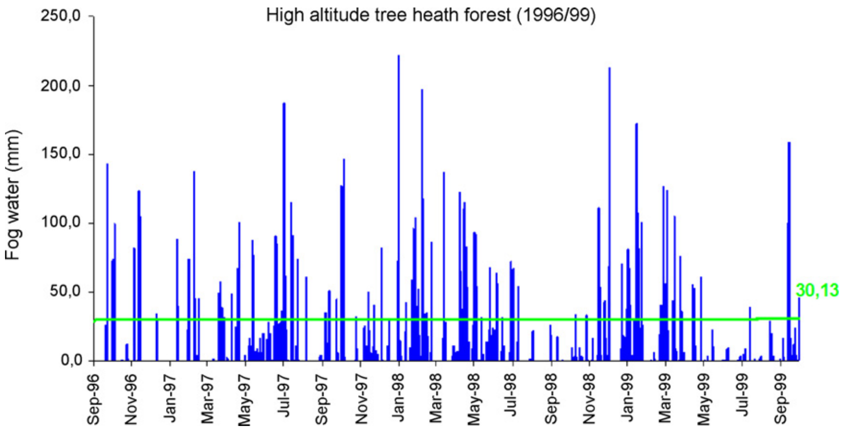

Fig. 5. Fog water collected by high altitude tree heath forest.

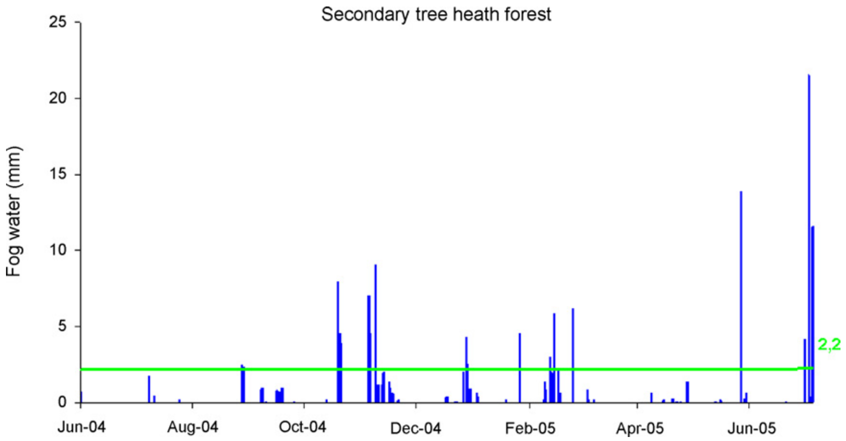

Fig. 6. Fog water collected by secondary tree heath forest.

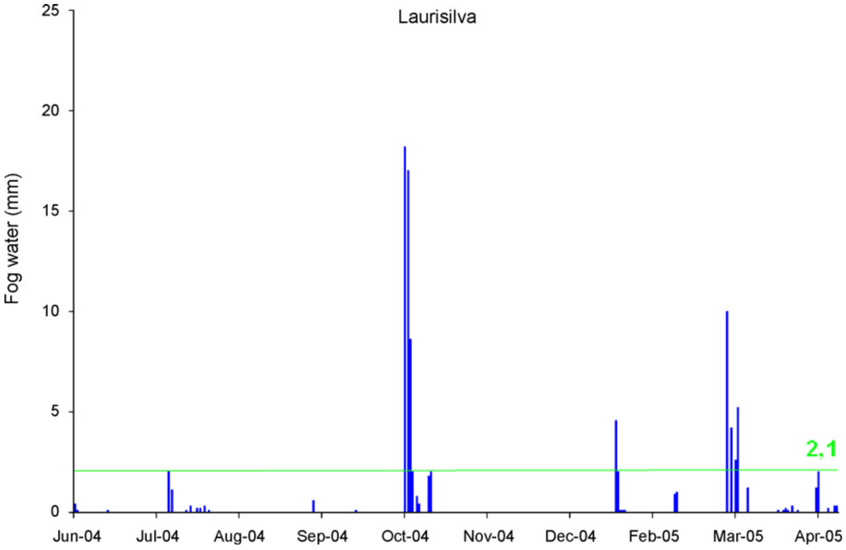

Fig. 7. Fog water collected by laurisilva.

was 36.9 mm, which represents 1.6 mm/fog drip day. This volume represents an extra 11% of water in measured throughfall.

4. Discussion

4.1. Fog precipitation

The amount of fog water contribution to the system is a function of: (a) the size, shape and structure of the trees intercepting the fog droplets and (b) wind velocity (Parsons, 1960). In addition, Went (1955) verified that very small needle-like leaf surfaces are much more efficient in capturing fog water. According to Goodman (1985) variations in the amount of fog drip are not only due to the type and size of foliage but also to the actual location and density of the foliage. Fig. 8 and Table 4 summarize plant morphology and architecture for the main trees in the 3 types of vegetation studied.

Fog precipitation in the high altitude tree heath forest is extremely high, an average of 30 mm/day, which corresponds to a 73.4% input in the system. The large quantity of fog precipitation may be explained by: (1) large canopy of heath trees, around 6 m × 6 m; (2) branches with high leaf density, creating a large capture surface (Fig. 8a); (3) needle-like form of leaves (Table 4); (4) wind exposure from all directions; and (5) high wind velocity. Our results are similar to those obtained by Kittredge (1948), in that fog drip may increase precipitation by 2 or 3 times compared with in the open. The canopy interception value of −225% is similar to the ones obtained by Holder (2004) for a Guatemala tropical mountain cloud forest.

In the secondary tree heath forest (Fig. 8b), despite the 25 days registry loss, data are still sufficient to be considered representative of the 2004/2005 hydrological year. Even though fog water captured by this vegetation corresponds to 13% of all water that had dropped into the soil, the mean 2.2 mm/day of fog drip is a much lower value than that registered under high altitude tree heath forest. This may happen due to:

1. Climax heath forest in which a very dense, needle-like leaves species is dominant *vs.* substitution heath forest whose dominant species have loose needle and loose elliptical leaves (Table 4). Another factor affecting secondary vegetation data is partial leaf fall in the shrub *V. padifolium* (Table 4). As stated by Crockford and Richardson (2000), in deciduous trees autumn–winter *vs.* spring–summer balance is influenced by the barrier reduction in the first period, so that water interception would be more extensive in the spring–summer period, and less so in the

Fig. 8. (a) Plant architecture in high altitude tree heath forest (site 1). (b) Plant architecture in secondary tree heath forest (site 2). (c) Plant architecture in the humid laurisilva (site 3).

Table 4
Tree size and structure, leaf type, shape and size, in the main trees of studied vegetation types.

	Forest	Plant size	Plant structure	Leaf type and shape	Leaf size
Ocotea foetens (Aiton) Baill.[a]	Humid laurisilva	40 m	Tall tree with a pyramidal to rounded crown, distal branching parallel to the ground.	Coriaceous, elliptic to elliptic-ovate	6–18 cm × 2–7 cm
Clethra arborea Aiton[a]	Humid laurisilva	9 m	Tree with distal branching, upright branching but leafs crowded in the distal part of the branches (a shrubby crown).	Stiff, oblanceolate to obovate	9–20 cm × 4–7 cm
Laurus novocanariensis Rivas Mart., Lousã, Fern. Prieto, E. Dias, J.C. Costa & C. Aguiar[a]	Humid laurisilva	20 m	Tall tree with distal branching parallel to the ground.	Coriaceous, elliptic to obovate or ovate	5–17 cm × 3-6 cm
Erica arborea L.b	High altitude tree heath forest	Up to 8 m	Old trees with distal branching and a well defined trunk, apical part of the branches dropping; young trees similar to *E. platycodon* but with less steep branching.	Leaves linear with revolute margins	3–4 mm × 1 mm
Erica platycodon (Webb & Berthel.) Rivas Mart., Wildpret, del Arco, O. Rodr., P. Pérez, García Gallo, Acebes, T.E. Díaz & Fern. Gonz. subsp. *maderincola* (D.C. McClint.) Rivas Mart., Capelo, J.C. Costa, Lousã, Fontinha, R. Jardim & M. Seq.[b]	Secondary tree heath forest	Up to 4 m	Shrub-tree much branched from the base, branches almost erect to steep.	Leaves linear with revolute margins	10–12 mm × 1 mm
Vaccinium padifolium Sm.[b]	Secondary tree heath forest	Up to 6 m	Semi-evergreen shrub or small tree.	Leathery, oblong to elliptic	2.5–7 cm × 1–2.5 cm

[a] Short (1994) and Jardim et al. (2007).
[b] McClintock (1994) and Jardim et al. (2007).

autumn–winter. Comparison between the two heath vegetations studied would also be affected by this factor since *V. padifolium* does not occur in the climax heath vegetation.

2. Experimental site at 1580 m and experimental site at 1385 m are influenced by different wind exposure and wind speed.
3. Different weather conditions during the different periods in which data were recorded. According to Goodman (1977) cited by Goodman (1985), there is a variation in the collection rate that is a function of the liquid water content which varies with time and elevation.
4. Less frequency and duration of the fog episodes. According to Schemenauer and Cereceda (1991), the production of water depends not only on the vegetation characteristics, but also on fog liquid water content and wind speed.
5. Fog water underestimation due to stemflow. Plant structure (Table 4 and Fig. 8b) would cause this effect to be more pronounced in the secondary vegetation, due to erect or steep branching.

In the humid laurisilva forest the most common leaf shape in dominant tree species (*O. foetens* and *L. novocanariensis*) is broad and coriaceous (Table 4). According to Went (1955), when fog moves through large leaves, it is deflected and the water droplets flow with air around the surface and prevent contact with it. Went (1955) further states that fog interception occurs along leaf edges and not over their surfaces. This makes leaf shape and size in the humid laurisilva dominant species less fog water capture effective.

Data were registered in the humid laurisilva forest, during 2004–2005, a below-average dry year, in which frequency and fog hours per day were low. Fog precipitation results in laurissilva show a divergence between recorded values in summer and winter. Low rainfall during summer seems to be compensated by fog precipitation, whose water input is relatively high (33%). This result has obvious implications on summer sustainability of ground water resources (Prada et al., 2005).

4.2. Rainfall interception

Essential to interception estimation are reliable data for rainfall, throughfall, and stemflow (Crockford and Richardson, 2000). Since stemflow was not measured in this study, canopy interception loss is obviously overestimated. However, interception losses can be neglected since the main goal was to estimate the differences between net fog interception between the 3 sites.

Under high altitude heath forest, the average canopy interception was -225% of gross precipitation, indicating the importance of fog precipitation input. This value is probably underestimated due to stemflow.

Stemflow affects fog precipitation more than throughfall; in fact the occurrence of fog without simultaneous precipitation could result in estimating no water input because of branching type and angle favouring stemflow (Table 4), this is the case in site 2. In this site the dominant plant, *E. platycodon*, is a shrub-tree with almost erect branching, this pattern is clearly related to its ecological role, being a fast growing plant that, with *V. padifolium*, constitutes the typical secondary vegetation in humid laurissilva clearings after disturbance.

A very distinct situation occurs in the laurisilva forest (site 3), which is composed mainly of *O. foetens*, *L. novocanariensis* and *C. arborea* [Table 4 and Fig. 8c; other trees also occur and the reader should refer to Capelo et al. (2004) for a full description]. In this climax forest trees can reach 30 m high (or even 40 m), they have imposing trunks and almost parallel to the ground branching. This architecture seems to favour true canopy interception instead of stemflow. Other morphological characters, such as broad and large leaves (Table 4), could also facilitate interception instead of throughfall.

In the humid laurissilva (site 3) during the dry season canopy interception (65%) is higher than in the rainy season (56%), this could be due to rainfall duration and intensity (see Crockford and Richardson, 2000 and references therein).

Canopy interception is higher in humid laurisilva (60% average) than in secondary tree heath forest (30%) and high altitude tree heath forest (-225%), which may be explained by laurisilva's dominant species morphology. Their branches form a denser and continuous canopy, whilst their broad, large and horizontally displayed leaves can sustain smaller rain drops thus decreasing the amount of water that reaches the ground, since the increased air exposure facilitates evaporation. The other types of forests have less dense canopy coverage, and tree leaves do not have a large surface area, easing the water access to the soil and decreasing evaporation of crown water.

Comparing high altitude heath tree forest with these two types of vegetation (secondary tree heath and humid laurissilva forests) is risky. This is due to the fact that study periods were not the same and meteorological conditions were distinct. High altitude heath trees present peculiar architecture and branching as well as other morphological characteristics (needle-like small leaves) that could explain the higher amount of fog precipitation.

The stemflow values summarized by Bruijnzeel (2001) range between less than 2% and 18% but White et al. (2002) measured 31% of total water input in coconut trees during extreme rain events due to stemflow. These variations correspond to different types of vegetation. Examples similar to the studied vegetation at site 3 are the evergreen cloud forest stemflow values given by Brown et al. (1996) corresponding to less than 2%. In fact this type of vegetation, is comparable to site 3 (laurisilva forest). Other stemflow estimations are those of David (2002) for *Quercus ilex* trees and Valente et al. (1997) for *Eucalyptus* and *Pinus* trees that range between 0.26–1.7% and 0.3%, respectively. Bruijnzeel (2001) refers to as much as 18% for upper mountain cloud forest in Jamaica and except for the values given by White et al. (2002), these are the larger references found. Vegetation type including tree architecture as well as field observations suggest that site 1 and also 2 have larger stemflow values, possibly closer to the ones referred by Bruijnzeel (2001). In fact vegetation structure in these sites broadly corresponds to the description given by the author for upper mountain cloud forest in having smaller trees and smaller leaves among other characteristics. Accordingly, overestimation of canopy interception and consequent underestimation of fog precipitation will be larger in sites 1 and 2. This means that differences in fog precipitation between sites would be even larger than suggested by our results.

Another factor that could introduce uncertainty to our results is the small number of gauges. Bruijnzeel (2001) states that a large number of gauges should be used for a proper quantification of net precipitation amounts in order to account for the spatial variability of rain forest canopies. However, the same author refers to a number of similar experiments that used a variable number of gauges (from only 2 to 58). In fact, the correlation values between the different gauges at the same sites were usually high (daily measurements correlation between gauges range between 0.75 and 0.90). The lower value obtained in the high altitude forest (0.75) is related to the different positions of the gauges and variability, due to location, of the prevailing winds. As previously discussed by Prada and Silva (2001), the different values obtained in the two gauges are related to differences in wind exposure.

A *F-Snedcor* test and *t-Student* test (Morrison, 1990) was applied to data from all the rain gauges, in order to analyse the accuracy from each site. Descriptive statistical data are presented in Table 5.

The *F-Snedcor* test results form data field's statistical analysis enable to state that variances of all sampling plot are highly

Table 5
Descriptive statistical data of water collected at each site.

	Average	Variance	*N*
Site 1, gauge 1	18.506	1629.953	766
Site 1, gauge 2	9.469	618.977	766
Site 2, gauge 1	1.095	17.434	164
Site 2, gauge 3	2.013	40.638	164
Site 3, gauge 1	1.980	48.033	219
Site 3, gauge 2	1.439	18.372	219

different, which is due to number of null rain catch in some of the rain gauges:

- Site 1 (climax heath forest)—$F_{\text{stat}} = 2.6333$; $F_{\text{critical}} = 1.1264$; p-value = 1.01E−39; $n = 766$.
- Site 2 (secondary tree heath forest)—$F_{\text{stat}} = 0.4290$; $F_{\text{critical}} = 0.7723$; p-value = 5.28E−08; $n = 164$.
- Site 3 (laurisilva forest)—$F_{\text{stat}} = 2.6144$; $F_{\text{critical}} = 1.2502$; p-value = 1.74E−12; $n = 219$.

The previous present results leaded to apply a *t-Student* test for unequal variances (Morrison, 1990), in order to analyse differences in average of water collected in each site. The *t-Student* test results enable to state that no significant differences were found for site 2 (secondary tree heath forest) and site 3 (laurisilva forest), as below presented:

- Site 3: gauge 1 *vs*. gauge 2: $t_{\text{stat}} = 0.983$; $t_{\text{critical}} = 1.967$; p-value = 0.3260; $n = 219$.
- Site 2: gauge 1 *vs*. gauge 2: $t_{\text{stat}} = 1.543$; $t_{\text{critical}} = 1.968$; p-value = 0.1239; $n = 164$.

However, differences from average of water collected by the two gauges at site 3 are highly significant; $t_{\text{stat}} = 5.274$; $t_{\text{critical}} = 1.962$; p-value = 1.57E−07; $n = 765$.

Although the average differences found, and high correlation, based on daily measurements between gauges, absolute values per gauge show some overlapping mainly between sites 2 and 3, this uncertainty on our results could derive from the small number of gauges and canopy spatial variability. In fact, canopy spatial variability was already discussed and related to the detected differences between sites, canopy variability is possibly higher in site 3 and caution should be used when differences between sites 2 and 3 are to be established.

Leaf area index was not measured but it will be larger in the laurissilva (site 3) and smaller in the *E. arborea* stands (with smaller needle shaped leaves, site 1). Further studies should estimate LAI and its possible correlations with interception values and take into account the rain regimes (intensity and duration) in order to evaluate its effects on interception, throughfall and fog precipitation.

5. Conclusions

Our data confirm an important input of fog liquid water. Results further showed that high altitude heath vegetation is related to the higher fog water input (per fog drip day) among the vegetation types studied, and that secondary heath and laurissilva show much lower inputs. However, the secondary heath forest fog water input is larger than in the laurisilva. These results are related to structural and morphological aspects of the dominant trees. Nonetheless, further studies with larger number of gauges could refine our results mainly on the quantification of differences between the similar values found in secondary heath and laurissilva.

Vegetation cover is not homogeneous and important areas such as the Paul da Serra plateau formerly covered with altitude tree heath forest are nowadays pastures of annual and biannual plants. In fact, grazing and fire largely destroyed most of the climax vegetation cover. This means that a large proportion of fog water content is not being intercepted by vegetation. However, actual fog precipitation amounts are believed to be larger than reported because stemflow was not measured and precipitation was measured only when throughfall exceeded precipitation. Further studies using a larger number of gauges per forest type, stemflow measurements, as well as LAI, will refine the present data.

Santos and Aguiar (2006) showed using prediction models that mean annual precipitation in Madeira will be reduced in the near future. As already suggested by Prada et al. (2006) and according to our results, reforesting with indigenous tree species is the most adequate measure to guarantee sustainability to Madeira's groundwater resources (Prada et al., 2006).

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