FOG PRECIPITATION IN RELATION TO PINE FOREST STRUCTURE IN LA PALMA, CANARY ISLAND

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Abstract

Aim: Fog is a cloud with physical contact to the earth's surface. Fog precipitation is the most important freshwater provisioning resource in water stressed island of the Canaries La Palma Island. Pine forest structural diversity and stratification plays a critical role in influencing the largest amount of fog precipitation on this Island but it's crucial to know the most important elements of forest structure for targeting high fog precipitation harvesting.

Methods: We investigated the relationship between pine forest stand structure and fog precipitation and chose a location within a high elevated pine forest, where cloud occurs frequently, on the island La Palma of Spain. Up to 73 throughfall gauges were set-up for collecting fog precipitation during eight (8) days (13^{th} – 22^{nd} April 2019). Three (3) sites corresponding natural dense and heterogeneity structure both on the wind and leeward side of the hill. The third site on the open forest on leeward side and last an additional site on leeward side of the hill, represented natural managed forest with homogenous structure. Several forest structural parameters were measured individually for under each gauge. Statistical visualization through boxplots and regression analysis were performed to test the hypothesis.

Results: Analysis of the forest structure showed that there was a clear relationship between fog precipitation and pine forest structure. Our findings suggest that there can be no fog precipitation harvesting without pine forest. The most efficient forest structure parameters for fog precipitation in the pine forests of La Palma Island are the following: DBH, Height, Canopy density, and Basal area. A more homogenous structure allows more free wind movement, pushing clouds against the huge surface area of the pine trees and facilitating higher fog precipitation harvesting. The windward side of a hill produces more fog precipitation than the leeward side. Hence, forest management should target tree planting at the windward side instead of the leeward side of a hill. Forest conservation efforts should emphasize the maintenance of the natural pine forest structure in order to optimally utilize forest resources. Excessive deforestation or logging would have indirect negative effects on water provisioning.

Keywords: *Cloud forest, fog precipitation, humid pine forest, trade winds, water collection, fog drip, La Palma, Canary Island*

1. Introduction

Fog is a cloud with physical contact to the earth's surface (Corell, et al, 2012). Fog precipitation is the most important freshwater provisioning resource for drinking water and irrigation on the water stressed island of the Canaries La Palma (Marzol 1988; Cerezal and Martín 2013). This precipitation is derived from a precipitating layer of stratocumulus clouds that have their source in the combination of the orography and the particular vertical structure of the atmosphere influenced by Atlantic anticyclone, subsidence inversion and cold oceanic current (Marzol et al. 2011). When humid air from the ocean moves over the volcanic mountains of La Palma, it is forced to ascend to a higher altitude by the topography of the island. As it cools and its pressure decreases, at a certain height, water precipitates and cloud is formed. Since the air is ascending along the mountain, the clouds are often formed at ground level and flow through the Canary forests as they continue to rise. Forest vegetation in La Palma Island influences the total fog precipitation collected, runoff and consequently, infiltration through fog interception (Zinke 1967). The three main forest types can be found in the fog belt layer transcending top down as follows: Pine forest, Laurel forest and Fayal Brezal. Pine forest (*Pinus canariensis*) which is an archipelago endemic and the largest, can comb out the fine fog of the cloud layer with its long-shaped needles and therefore, plays an important role in collecting water for La Palma. This process is called fog precipitation, where intercepted fog droplets fall to the forest floor (Holder 2004). Interception is the ability of vegetation to temporarily store precipitation on its surface, which can be evaporated directly or, in case of a plant canopy, leave the canopy as stemflow or throughfall and finally infiltrates into the soil (Bonan 2016).

Structure refers to the spatial arrangement of the various components of the ecosystem, such as the heights of different canopy levels and the spacing of trees (McElhinny et al. 2005). A number of studies have shown that managed forests have less structural complexity compared with primeval forests (Fujimori 2001). The arrangement, density, type, and size of the foliage play an important role in the amount of fog precipitation collected (Azad et al. 2015). Plants having "needlelike" structures, e.g., pine, redwood, and fir, are reported to collect a good amount of fog whereas the "leaflike" impermeable structures (no regular void space on the surface) allow the moisture to flow around the surface of the leaf and evaporate (Limm et al. 2009; Simonin et al. 2009). Increased branchiness of plant species, such as narrow leaf syndrome, is reported to be an important trait to collect fog (Stanton and Horn 2013). A description of stand structure is important for the understanding and management of forest ecosystems (McElhinny et al. 2005).

Several studies on fog precipitation harvesting have focused on fog water collection using passive mesh system for cloud water interception (CWI) (Holwerda et al. 2010; Corell, et al., 2012) or biomimetic fog Collectors (Azad et al. 2015). More projects were realized in Chile (Osses et al. 2000); Peru, Ecuador, Guatemalan, Islands in the Caribbean, S. Africa, Namimbia, Eastern Africa and the Arabian Peninsula, Eritrea, Tanzania, Oman, Macaronesian archipelagos (the Azores, Madeira, the Canary Islands, and the Cape

Verde Islands), NW. Africa and desert archipelago of Cape Verde. In Europe, Croatia and Spain on the eastern fringe of the Iberian Peninsula. In Asia, fog precipitation collection projects occur in Nepal (Corell, et al., 2012). So far there are no studies aimed unravelling the efficiency of pine forest structural parameter on fog precipitation harvesting. Therefore, this study attempted to perform a robust characterization of the effect of pine forest structure to gain understanding on the potential efficiency of a combination of pine forest structural parameter on fog precipitation harvesting, which could subsequently guide sustainable forest management practices and freshwater provisioning. Furthermore, this study answers the question of which forest structure type yields the highest amount of fog precipitation? We hypothesize that a more dense or heterogeneous structure of the pine forest translates into the highest quantity of fog precipitation compared to other forest structure types. In addition, we also addressed the following question: what are the most relevant parameters of pine forest structure for efficient fog precipitation harvesting? Here, we think canopy density and basal area are the most efficient parameters.

2. **Materials and Methods**

2.1 Study area

La Palma as a volcanic island, located 28°26'N, 18°00'W to 28°51'N, 17°43'W, is the most north-western island of the canaries, Spain (Irl and Beierkuhnlein, 2011). With an elevation of 2426m at its peak Roque de los Muchachos and an area of 708km^2 it has a unique topography with different climate conditions within the Island (Irl et al. 2015). Annual precipitation ranges from about 170mm to almost 1400mm, excluding fog drip (Irl and Beierkuhnlein, 2011). Fog drip can however lead to a significant increase of total precipitation locally, especially in summer (Marzol et al. 2011). As fog precipitation and rain are highly correlated to topography the overall precipitation pattern does most likely not change including fog precipitation (Walmsley et al. 1996). Cloud layer is mainly formed of orographic origin and occurs between 800m and 1600m in altitude (Prada et al. 2009), where the endemic canary pine forest can be found (Irl and Beierkuhnlein, 2011). Our study sites were located close together on the ridge of Cumbre Nueva (center of La Palma), where similar climates, high occurrence of clouds, high elevation, a negligible altitudinal gradient and a pine forest was given.

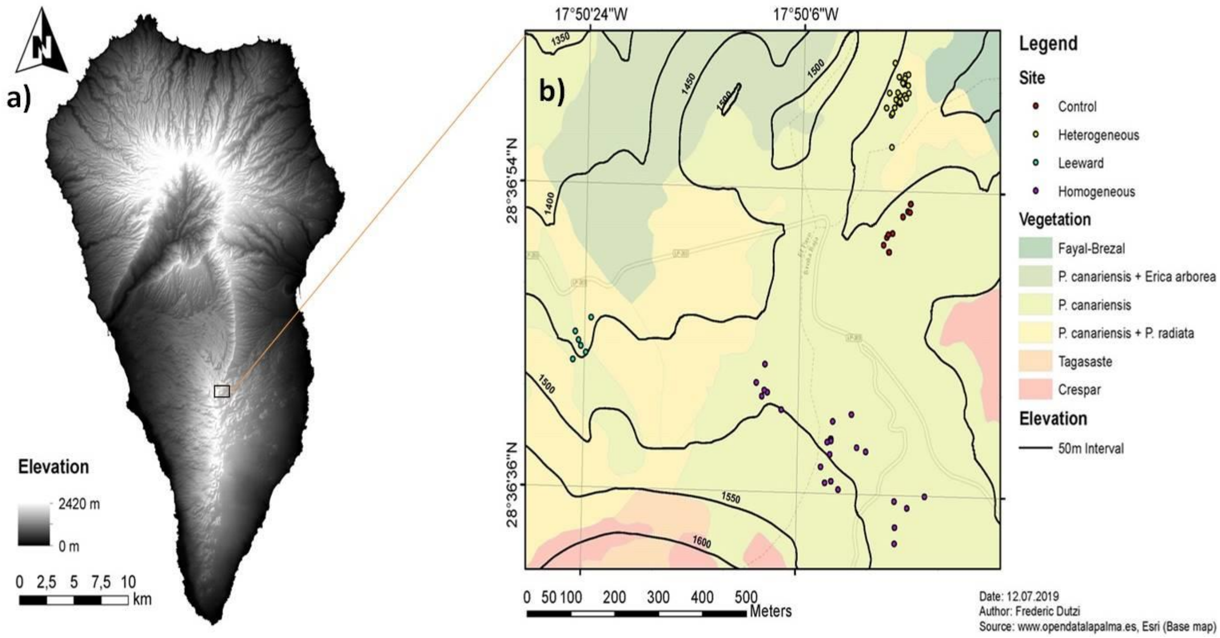

Figure 1. Maps of La Palma, Canary Islands and Study Area. a) Map of La Palma with spatial distribution of elevation. b) Sample design with location of the collector devices grouped by sites, vegetation and elevation.

Table 1. List of environmental variables given for each gauge grouped by data classes

Environmental Variables at each gauge

Data class	Variable	Abbreviation	Unit
Fog precipitation	Fog precipitation		ml/m2/24h
Forest structure	Basel area		-
	Canopy density		%
	Diameter of breast height	DBH	cm
	Tree height		M
	Lowest crown limit	LCL	m
	Lowest ramification height	LRH	m
	Point-centered-quarter	PQM	1/m^2
	Vertical pole interception	VPI	-
Vegetation	*Litter depth*		cm
Weather	*Dew point*		°C
	Rain		mm/h
	Temperature		°C
	Wind speed		m/s

Note: Point quota method (PQM) describes the number of trees per square meter; vertical pole interception (VPI) describes the number of interceptions a vertical pole would have with the tree. Weather data was collected on similar elevation and climatic conditions located on Cumbre Nueva; cursive was thrown out.

2.2 Data Collection

Fog precipitation data was recorded in 73 throughfall gauges across four sites. The number of gauges varied between the sites due to different functioning and difficulties of access. The four sites were chosen according to the characteristic of forest stand density and heterogeneity structure. The first and second site represented natural dense and heterogeneity structure (Fig.2. a) both on the wind and leeward side of the hill. The third site on the open forest on leeward side field tested occurrence of rainfall events and evaporation (Fig.2. b) and last an additional site on leeward side of the hill, represented natural managed forest with homogenous structure (Fig.2. c). Within the sites the gauge locations were randomly distributed. Each gauge, consisting of a gauge shaped soccer-cone and a 1.5 l water bottle, that was read daily to record the amount of water during 15th to 22nd of April 2019. In two out of eight (8) days it was measured twice a day. To avoid evaporation the gauges, the bottles were dug into the ground (Fig. 2. b). Several forest structure parameter and weather variables (see Table 1; Popma et al., 1988) were measured at each location of the gauge and weather data was collected from close weather station. Evaporation and interception at gauges surface was tested in the control site and assumed to be zero for the whole measuring period. Evaporation was tested throughout two gauges, filled with 10 and 20 ml, within 24 hours with a clear, sunny sky during the day. Interception was tested by installing a roof upon three gauges which allowed air mass movement underneath the roof at the gauges surface.

Fig. 2. Photographs of sites. a) Heterogeneous, b) Control (Cloud event visible, dug in collector device), C) Homogenous forest structure

2.3 Data analysis

For this study, fog precipitation was the dependent variable while the independent variables include the forest structure parameters as well as some climate variables. Fog precipitation among sites was visualized using a boxplot and relationships between sites were tested using the non-parametric Kruskal-Wallis test, after a Shapiro-Wilk normality test was performed. We also tested for collinearity among independent variables to separate variables that are highly correlated.

A generalized linear model (GLM) was constructed to identify the most predictive variables for fog precipitation. Using the vegan package in R, a hierarchical partitioning test among independent variables was also performed to identify specific variables that contribute mostly to fog precipitation. Furthermore, for the calculation of structural index among sites, we used the Gini coefficient from the ‘ineq’ package in R. This index was calculated using data on the distribution of tree basal areas among the forest structure sites. Results of the calculation are index numbers in the range [0,1] where 0 represents perfect homogeneity and 1 complete heterogeneity. These results were then inputted as predictive variables for fog precipitation in a GLM regression model to compare how significant they are for fog precipitation among forest sites.

All data analysis was performed using the R statistical software version 3.6.1

3. Results

3.1 Variability of fog precipitation among pine forest structures

Results on the variability of fog precipitation are presented below using a boxplot. Fog precipitation varied between sites and was highest in the homogenous forest, followed by the heterogenous forest and the lowest values in the control plot and homogenous-leeward forest (Fig. 3). According to Kruskal-Wallis test, there was no significance difference in fog precipitation between the heterogenous forest and the homogenous forest as well as between the control plot and the heterogenous-leeward forest. But a significant difference between the heterogenous-leeward forest and the two forest types of heterogenous and homogenous forest on the windward side of the hill (Table 2).

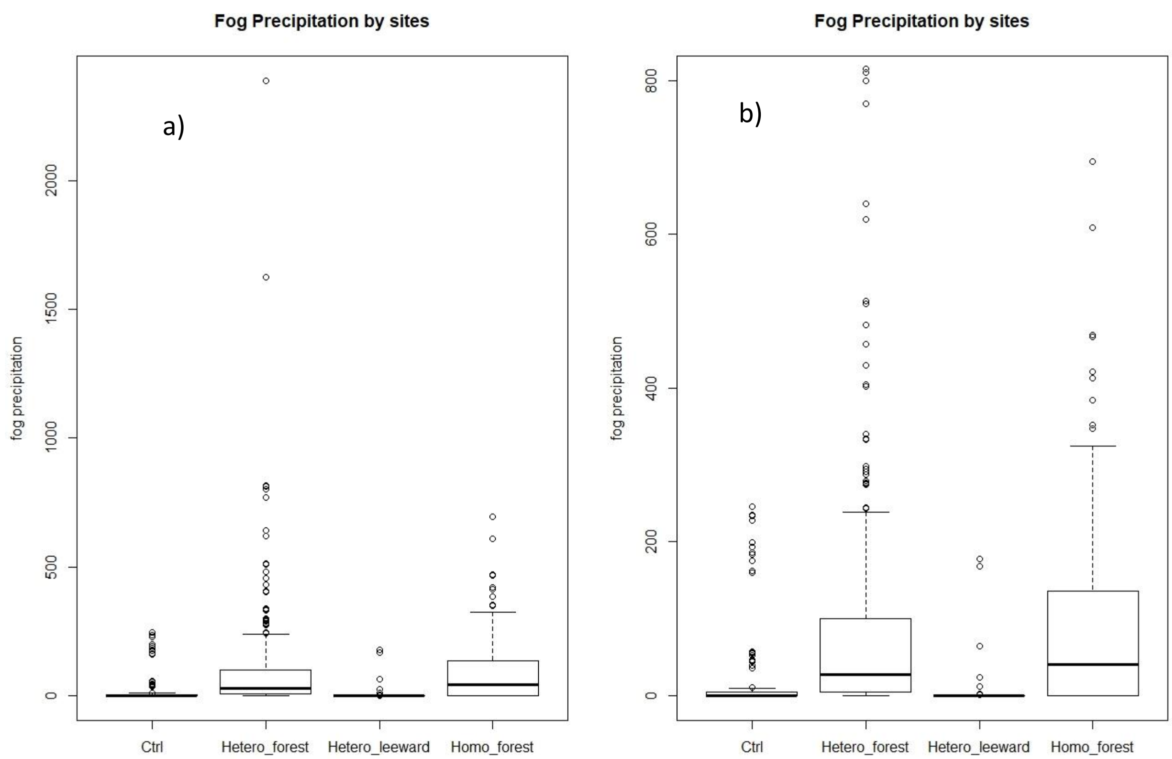

Figure 3: Variability of fog precipitation among sites (a) Full scale of boxplot (b) reduced scale (0-800mm)

Table 2: Variability of fog precipitation as tested by the Kruskal-Wallis test

Multiple comparison test after Kruskal-Wallis			
p.value: 0.05			
Comparisons			
	obs.dif	critical.dif	Difference
Ctrl-Hetero_forest	179.73	59.47	TRUE
Ctrl-Homo_forest	168.45	58.29	TRUE
Ctrl-Homo_leeward	48.56	83.99	FALSE
Hetero_forest-Homo_forest	11.28	46.69	FALSE
Hetero_forest-Homo_leeward	228.29	76.39	TRUE
Homo_forest-Homo_leeward	217.01	75.48	TRUE

3.2 Structural characteristics of the pine forest by sites

3.2.1. Forest structure index

In this study, the Gini-coefficient was used as a forest structure index to characterize structural heterogeneity. It is being recommended by Nyman (2018) and it fits perfectly into our study as it is not sensitive to variation in sample sizes when compared to other structural indices. A homogenous structure is defined for coefficient values that are closer to 0, while those that are closer to 1 are more heterogenous structures (Table 3).

The results of a linear regression model relationship between fog precipitation and the Gini coefficient values for each site shows that the dense forest structure is the most important structure for fog precipitation harvesting (see Table 4,5,6,7). The most significant relationship at $P<0.05$ was found for the GLM between fog precipitation and the Gini coefficient values of the heterogenous and homogenous forest (Table 5 and 6). While there was no significant relationship observed for the control plot and the heterogenous-leeward forests. (Table 4 and 7).

Table 4: Characterizing forest structure using the GINI index

Sites	Mean basal area (m2/ha)	GINI coefficient	Definition
Control plot	10.01	0.35	Heterogenous
Heterogenous forest	51.55	0.04	Homogenous
Homogenous forest	34.73	0.08	Homogenous
Heterogenous-leeward forest	28.0	0.10	Homogenous

Table 5: GLM model of fog precipitation as explained by the homogenous forest

Call: glm(formula = F.Precipitation ~ dmg_G, family = gaussian(link = "identity"),data = dense_managed)				
Deviance Residuals:				
Min 1Q Median 3Q Max				
-123.38 -70.78 -43.86 47.78 595.39				
Coefficients:				
	Estimate Std.	Error	t value	Pr(>|t|)
(Intercept)	65.78	11.02	5.97	7.32e-09 ***
dmg_G	62.40	29.65	2.10	0.0363 *
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1				
(Dispersion parameter for gaussian family taken to be 12861.65)				
Null deviance: 3568175 on 274 degrees of freedom				
Residual deviance: 3511229 on 273 degrees of freedom				
AIC: 3386.5				
Number of Fisher Scoring iterations: 2				

Table 6: GLM of fog precipitation as explained by the heterogenous forest

Call: glm(formula = F.Precipitation ~ dmx_G, family = gaussian(link = "identity"),data = dense_mixed)				
Deviance Residuals:				
Min 1Q Median 3Q Max				
-188.18 -86.21 -45.43 -2.20 2261.00				
Coefficients:				
.	Estimate Std	Error	t value	Pr(>|t|)
(Intercept)	22.51	31.41	0.72	0.47425
dmx_G	173.34	60.67	2.86	0.00465**
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1				
(Dispersion parameter for gaussian family taken to be 51605.75)				
Null deviance: 12806673 on 241 degrees of freedom				
Residual deviance: 12385380 on 240 degrees of freedom				
AIC: 3316.8				
Number of Fisher Scoring iterations: 2				

Table 7: GLM of fog precipitation as explained by the control plot

Call: glm(formula = F.Precipitation ~ ops_G, family = gaussian(link = "identity"),data = open _sparse)				
Deviance Residuals:				
Min 1Q Median 3Q Max				
-28.645 -26.734 -23.868 -3.224 218.266				
Coefficients:				
	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	18.73	6.17	3.04	0.00294 **
ops_G	-28.67	20.55	-1.40	0.16574
Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1				
(Dispersion parameter for gaussian family taken to be 3457.557)				
Null deviance: 407803 on 117 degrees of freedom				
Residual deviance: 401077 on 116 degrees of freedom				
AIC: 1300.4				
Number of Fisher Scoring iterations: 2				

Table 8: GLM of fog precipitation as explained by the homogenous-leeward forest

Call: glm(formula = F.Precipitation ~ htrl_G, family = gaussian(link = "identity"),data = heter o_leeward)				
Deviance Residuals:				
Min 1Q Median 3Q Max				
-15.911 -15.911 -3.559 -1.089 163.559				
Coefficients:				
	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	14.38	5.58	2.58	0.0125 *
htrl_G	-14.82	9.28	-1.60	0.1156
Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1				
(Dispersion parameter for gaussian family taken to be 1052.545)				
Null deviance: 63733 on 59 degrees of freedom				
Residual deviance: 61048 on 58 degrees of freedom				
AIC: 591.78				
Number of Fisher Scoring iterations: 2				

3.3 The best combination of pine forest parameters for efficient fog precipitation harvesting

3.3.1 Test of collinearity among independent variables

Figure 4 presents a collinearity tests among predictive variables. A collinearity test was performed among forest structure parameters and a correlation coefficient threshold of 0.7 was picked as a basis for variable selection. We found out that Canopy density and Basal area showed significant correlation coefficients higher than 0.7 (Fig. 4). Subsequently, a suitable test decision of separating these variables into two predictive models was made.

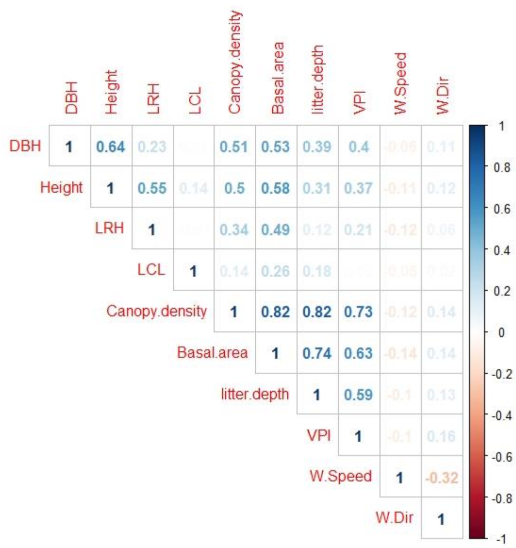

Figure 4. Collinearity test among forest structure parameters

3.3.2 Predictive models of fog precipitation as influenced by forest structure parameters

After the test of collinearity, we constructed two GLM predictive models of fog precipitation while separating canopy density and basal area. The models showed that all forest structure parameters are significant for fog precipitation. Thereafter, a comparison test of the two models was performed, where the model with the lowest AIC value was chosen. Therefore, the model that includes canopy density had the lowest AIC value and was retained for further analysis (Table 9).

Table 9: GLM model of fog precipitation explained by forest structure parameters

Call: glm(formula = F.Precipitation ~ (DBH + Height + LRH + LCL + Canopy.density + litter.depth + VPI), family = poisson(link = "log"), data = cloudV_data)				
Deviance Residuals: Min 1Q Median 3Q Max -23.13 -11.34 -7.20 2.16 78.85				
Coefficients:	Estimate	Std.Error	z value	Pr(>|z|)
(Intercept)	3.07	0.02	147.94	< 2e-16 ***
DBH	-0.01	0.00	-32.20	< 2e-16 ***
Height	0.06	0.00	42.45	< 2e-16 ***
LRH	0.02	0.00	11.27	< 2e-16 ***
LCL	-0.00	0.00	-5.32	1.02e-07 ***
Canopy.density	0.06	0.00	63.73	< 2e-16 ***
litter.depth	-0.05	0.00	-29.81	< 2e-16 ***
VPI	-0.03	0.00	-17.08	< 2e-16 ***
Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1				
(Dispersion parameter for poisson family taken to be 1)				
Null deviance: 111743 on 634 degrees of freedom				
Residual deviance: 98982 on 627 degrees of freedom				
AIC: Inf				
Number of Fisher Scoring iterations: 6				

In addition, the results of the variance partitioning shows that canopy density explains the highest variation in fog precipitation (Figure 3). Other important variables are height, litter depth, lowest ramification height (LRH), diameter breast height (DBH) and vertical pole interception (VPI).

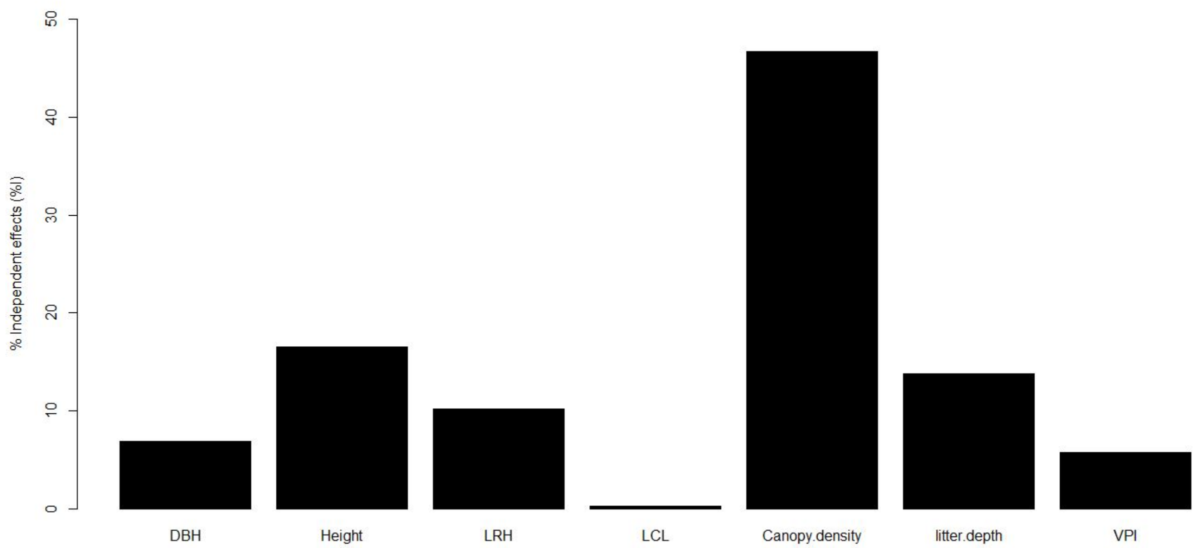

Figure 2: Variance Partitioning

3.3.3. Predictive models of fog precipitation as influenced by forest structure parameters by sites

Results for predictive GLM model of fog precipitation and forest structure parameters for the homogenous site showed a strong relationship (P<0.05) with fog precipitation for the following parameters: DBH, Height, LRH, Canopy density, litter depth and VPI. While LCL was found not to be significant for fog precipitation (P>0.05) in this site. The strongest relationships were found for DBH, Height, Canopy density and VPI (Table 9).

Table 9: GLM model of fog precipitation explained by forest structure parameters in the homogenous forest

Call: glm(formula = F.Precipitation ~ (DBH + Height + LRH + LCL + Canopy.density + litter.depth + VPI), family = poisson(link = "log"), data = dense_managed)				
Deviance Residuals:				
Min 1Q Median 3Q Max				
-14.433 -12.242 -5.323 5.098 39.927				
Coefficients:				
	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	4.15	0.07	63.77	< 2e-16 ***
DBH	0.00	0.00	4.75	2.03e-06 ***
Height	0.01	0.00	6.37	1.92e-10 ***
LRH	-0.01	0.00	-2.29	0.02201 *
LCL	-0.00	0.00	-0.79	0.43233
Canopy.density	-0.03	0.00	-11.02	< 2e-16 ***
litter.depth	0.02	0.01	2.90	0.00373 **
VPI	0.05	0.00	10.46	< 2e-16 ***
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1				
(Dispersion parameter for poisson family taken to be 1)				
Null deviance: 37031 on 274 degrees of freedom				
Residual deviance: 36696 on 267 degrees of freedom				
AIC: Inf				
Number of Fisher Scoring iterations: 6				

Furthermore, for the heterogenous forest structure, fog precipitation showed a highly significant relationship with the following parameters: DBH, Height, LRH, LCL, Canopy density, litter depth and VPI (Table 10).

Table 10: GLM model of fog precipitation explained by forest structure parameters in the heterogeneous forest

Call: glm(formula = F.Precipitation ~ (DBH + Height + LRH + LCL + Canopy.density + litter.depth + VPI), family = poisson(link = "log"), data = dense_mixed)				
Deviance Residuals:				
Min 1Q Median 3Q Max				
-27.112 -11.577 -7.239 1.832 69.992				
Coefficients:				
	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	2.83	0.08	35.36	<2e-16 ***
DBH	-0.03	0.00	-38.48	<2e-16 ***
Height	0.11	0.00	33.35	<2e-16 ***
LRH	-0.04	0.00	-12.24	<2e-16 ***
LCL	-0.00	0.00	-14.50	<2e-16 ***
Canopy.density	0.09	0.00	50.08	<2e-16 ***
litter.depth	-0.07	0.00	-30.20	<2e-16 ***
VPI	-0.07	0.00	-20.34	<2e-16 ***
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1				
(Dispersion parameter for poisson family taken to be 1)				
Null deviance: 56638 on 241 degrees of freedom				
Residual deviance: 47793 on 234 degrees of freedom				
AIC: Inf				
Number of Fisher Scoring iterations: 6				

In the control forest, significant parameters for fog precipitation were only DBH and Height. While the other variables were insignificant (P>0.05) for fog precipitation. (Table 10). While in the heterogenous-leeward forest, structural parameters that were significant include: DBH, Height LRH, LCL, and canopy density (Table 11).

Table 11: GLM model of fog precipitation explained by forest structure parameters in the control forest

Call:				
glm(formula = F.Precipitation ~ (DBH + Height + LRH + LCL + Canopy.density +				
litter.depth + VPI), family = poisson(link = "log"), data = open_sparse)				
Deviance Residuals:				
Min 1Q Median 3Q Max				
-7.489 -7.111 -6.484 -4.743 26.655				
Coefficients: (2 not defined because of singularities)				
	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	2.25	0.17	13.28	< 2e-16 ***
DBH	0.02	0.01	2.39	0.016748 *
Height	0.09	0.03	3.61	0.000302 ***
LRH	-0.20	0.14	-1.39	0.164815
LCL	-0.18	0.14	-1.33	0.184855
Canopy.density	-0.06	0.04	-1.67	0.095358 .
litter.depth	NA	NA	NA	NA
VPI	NA	NA	NA	NA
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1				
(Dispersion parameter for poisson family taken to be 1)				
Null deviance: 9955.2 on 117 degrees of freedom				
Residual deviance: 9869.5 on 112 degrees of freedom				
AIC: Inf				
Number of Fisher Scoring iterations: 7				

Table 12: GLM model of fog precipitation explained by forest structure parameters in the heterogenous-leeward forest

Call: glm(formula = F.Precipitation ~ (DBH + Height + LRH + LCL + Canopy.density + litter.depth + VPI), family = poisson(link = "log"), data = hetero_leeward)				
Deviance Residuals:				
Min 1Q Median 3Q Max				
-5.950 -5.779 -3.578 -1.483 22.283				
Coefficients: (2 not defined because of singularities)				
	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	13.22	1.45	9.09	< 2e-16 ***
DBH	-0.095	0.02	-5.05	4.50e-07 ***
Height	0.60	0.09	6.73	1.65e-11 ***
LRH	-0.82	0.15	-5.44	5.44e-08 ***
LCL	-0.20	0.05	-3.94	8.09e-05 ***
Canopy.density	-0.78	0.09	-8.49	< 2e-16 ***
litter.depth	NA	NA	NA	NA
VPI	NA	NA	NA	NA
Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1				
(Dispersion parameter for poisson family taken to be 1)				
Null deviance: 2626.1 on 59 degrees of freedom				
Residual deviance: 2316.8 on 54 degrees of freedom				
AIC: 2369.2				
Number of Fisher Scoring iterations: 7				

4. Discussion

Firstly, we found out that there can be no fog precipitation harvesting without the pine forest. A high amount of fog precipitation was collected compared to an open forest structure which is the control. Similarly, we found that fog precipitation is more efficient in forest stands that are located at the windward side of the hill. We recorded very insignificant amounts of precipitation in the leeward side of La Palma. Similar results were reported by Prada et al., (2009) who studied fog precipitation collected by forest vegetation.

Moreover, the natural heterogenous forest is the best forest structure type for harvesting fog precipitation. Our findings suggest that the most efficient forest structure parameters for fog precipitation in pine forests of La Palma are the following: DBH, Height, Canopy density, Basal area and VPI although the importance of these parameters differs by sites. 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 (Prada et al., 2009). 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. Although the structure of the homogenous forest with less complex structure than a heterogenous forest intercepted more fog precipitation, this could be explained by the wind dynamics between two structures. Open structure could be allowing more free wind movement that replenishes the open forests with more fresh clouds hence more fog precipitation. The wind direction also explains the quantity of water collected by the pine trees. Our results are similar to those obtained by Kittredge (1948) and Prada et al. (2009).

In order to target more fog precipitation harvesting, forest management should maintain natural pine forest status with limited logging and pruning to achieve a similar forest stand observed in this study. This type of forest management should allow wood consumption and high fog harvesting to occur at the same time. It is important to note that too much logging would lead to less precipitation as observed in the open sparse forest. Since the forest height is important for fog precipitation, under climate change, conservation of trees under high elevations would be important for water harvesting.

Further studies using a larger number of gauges per forest structure type and long time series of for precipitation collection will refine the present findings.

5. Conclusion

The pine trees of La Palma island are important for fog water harvesting through their efficient leaf structure. This study compared fog precipitation among different pine forest structural forest types. Our findings suggest that the most efficient forest structure parameters for fog precipitation in the pine forests of La Palma are the following: DBH, Height, Canopy density, Basal area and VPI. These parameters are highly evident in the heterogenous forest and they become more significant with a denser forest structure. Other contributing factors to fog precipitation are wind direction and wind velocity. The combination of wind flow pattern and wind speed are important factors which to a large extent brings about the combing out of water from clouds by the pine needles. A more open forest structure allows more free wind movement, pushing clouds against the huge surface area of the pine trees and facilitating the fog precipitation process.

The windward side of a hill produces more fog precipitation than the leeward side. Hence, forest management should target tree planting at the windward side instead of the leeward side of a hill. Forest conservation efforts should emphasize the maintenance of the natural pine forest structure in order to optimally utilize forest resources. Excessive deforestation or logging would have indirect negative effects on water provisioning.

Changes in climatic conditions may not affect land-atmosphere interactions on an endemic island. With increasing temperature, there will be more evaporation into the atmosphere which means more clouds and higher freshwater provisioning. There could be also a reverse effect of vegetation on the atmosphere. Evapotranspiration into the atmosphere and cloud thickness would reduce with the removal of vegetation cover.

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