Colegio de Postgraduados

Canopy rainfall interception by pine (*Pinus hartwegii* Lindl) and oyamel [*Abies religiosa* (Kunth) Schltdl. y Cham.] at the Zoquiapan Experimental Forest Station, Mexico

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ABSTRACT

Objective: To quantify and characterize the canopy rainfall interception of two dominant forest species of a coniferous forest in Mexico, in order to determine its magnitude and importance in the hydrological cycle and have a source of estimation of interception to improve the accuracy of water balance calculation.

Methodology: Twenty-one rainfall events in the period May-June 2018 were analyzed in two 0.25-ha experimental plots, one with pine (*Pinus hartwegii*) and the other with oyamel (*Abies religiosa*), at the Zoquiapan Experimental Forest Station (EFEZ), located in the Sierra Nevada in the State of Mexico. Rainfall was measured with an automated weather station and interception was recorded by placing collectors under the canopy and collars on the trunks.

Results: The pine tree *P. hartwegii* intercepted 16.37% of the precipitation, 79.86% of the throughfall, and 3.74% of the stemflow. For *A. religiosa*, recorded interception was 24.68%, throughfall 72.42%, and stemflow 2.90%. Precipitation had a linear relationship with both throughfall and stemflow, and an exponential one with canopy rainfall interception.

Implications: The analysis should be extended to other rainy periods to strengthen the study.

Conclusions: The intercepted volume depends on the forest measurement characteristics and leaf area index (LAI) of the species, and the rainfall amount. The fraction of rainfall intercepted is considerable and should be included in hydrological balances.

Keywords: canopy effect, throughfall, rainfall interception, stemflow, water balance.

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INTRODUCTION

Forest ecosystems retain part of the rainfall (rainfall interception) through foliage, branches, leaves and trunks of their trees. A fraction of this captured water returns to the atmosphere as evaporation; the remaining water drains down the canopy structure (throughfall) or the trunk (stemflow), and reaches the ground producing superficial flows through which it finally integrates into the soil as infiltration. This process presents great complexity and is part of the water cycle; its importance lies mainly in the relationship between the effect of the tree cover and the modifications that the latter exerts on water balance (Santiago-Hernández, 2007). Because of this, several authors have conducted studies to identify and account for rainfall intercepted by tree cover. The forest covers of temperate climates and those formed by conifers are the most frequently studied ecosystem types (Návar-Cháidez *et al.*, 2008). According to Besteiro and Rodríguez (2012), interception ranges from 12.2% to 27.2% in temperate forest plantations, agreeing with León *et al.* (2010) and Fan *et al.* (2014) who report 19.0, 22.4 and 22.9%, respectively, for similar species. However, Chen *et al.* (2013), Pérez *et al.* (2015) and Gavazzi *et al.* (2016) differ, reporting 33.2, 29.6 and 33.4% for conifer forests of *Pinus tabulaeformis*, *Pinus pinea*, and *Pinus taeda* L., respectively.

Sadeghi *et al.* (2015) reported variations in rainfall interception between deciduous forests and perennial forests, with 25% and 40%, respectively. For tropical forests, values close to 39% are reported (Crockford and Richardson, 2000). For species of semi-arid ecosystems, percentages vary from 2% to 5% of total rainfall (Oyarzún *et al.*, 1985; Carlyle, 2004); this type of environment is the least studied due to the methodological complexity involved in its measurement and its low annual precipitation.

Although in recent years rainfall interception has become important in hydrological and forest hydrology studies, the increase in studies in different covers and ecosystems is not enough to establish a constant fraction of precipitation as rainfall interception, because the distribution varies according to each cover's specific characteristics and to the zone's particular weather conditions. For this reason, the objective of this study was to estimate canopy rainfall interception, through the quantification of these hydrological process components in the *P. hartwegii* and *A. religiosa* forest species, by using experimental plots and collectors to directly measure rainfall interception. The relationship between throughfall and stemflow, and the volume of canopy rainfall interception as a function of incident precipitation was analyzed. The behavior of the two types of flow and the retention of rainfall by the canopy of both forest species was analyzed based on their forest measurement characteristics, since these species were subjected to the same experimental conditions.

MATERIALS AND METHODS

The experimental area is located in the EFEZ, which has an area of 1638 ha and elevations ranging from 3200 to 3500 m a.s.l. (DICIFO, 2005). It is located in the southeast of the State of Mexico, and enclosed within the orographic system of the Sierra Nevada. The climate is temperate cold with summer rains, and the rainfall ranges from 900 to 1200 mm per year. The main forest species in the EFEZ are *Abies religiosa*, *Pinus hartwegii* and *Alnus firmifolia* (DICIFO, 2005). Two experimental plots of 0.25 ha (50 × 50 m) each were selected: one for *A. religiosa* and one for *P. hartwegii*; both plots were in the central area of the EFEZ and 600 meters apart.

Characterization of experimental plots

The LAI and forest measurement parameters were obtained from measurements made in 64 *P. hartwegii* and 50 *A. religiosa* randomly selected trees.

Instrumentation for the components of Interception

To obtain throughfall, several 3 L plastic bottles were placed on wooden bases (1.20 m high) and used as collectors. Previously, these collectors were calibrated with a weather station ($P<0.05$). Throughfall was obtained based on the following equation:

$$TH = \frac{vm}{ac} \quad (1)$$

where TH is the throughfall (mm); vm is the volume captured by each collector (ml); and ac is the capturing area of the collector (cm^2).

Several collar-type implements were attached to the trunks in order to measure the stemflow. They were made out of plastic hoses, and attached around the trunks 2.5 times their circumference to form a downwards spiral. The rainfall guttered by these implements was collected in 3 L plastic bottles, and at the end of each event, the volume was measured with a 100 ml plastic test tube. To estimate the depth of the stemflow, the Price and Carlyle (2003) equation was used:

$$FC = \frac{n \times FC(a)}{FA} \quad (2)$$

where FC is the stemflow (mm); n is the number of tree samples; $FC(a)$ is the mean volume measured from the trees sampled (ml); and FA is the basal area of the canopies of n number of trees sampled (m^2).

Gross precipitation and meteorological variables

Twenty-one rainfall events that took place in May and June 2018 were analyzed. That year was very dry: there were few precipitation events and the most representative ones occurred in those months indicated above. The sole condition for these twenty-one events to be classified as such was the absence of rainfall events between them, for at least 6 hours. (Hosseini *et al.*, 2012). The gross rainfall (incident precipitation) (P, mm) was recorded every 10 minutes by a DAVIS® weather station, model Vantage Pro2™ Wireless.

Experimental design

Throughfall was measured with 39 collectors randomly distributed in 13 measurement sites with different coverage characteristics (LAI and forest measurement variables), which are associated with this type of flow (Flores-Ayala *et al.*, 2016). Stemflow was quantified in five trees from each species using one collar per tree (Figures 1a and 1b); the trees selected had vertical trunks and no bifurcations below 1.3 m. The behavior of the throughfall of the sampling sites was statistically analyzed to show the variation of the canopy characteristics and justify their selection.

Mathematical modeling of rainfall interception

Different empirical mathematical models were tested to obtain throughfall, stemflow, and canopy rainfall retention, as a function of the gross rainfall depth (liquid precipitation rainfall falling on the canopy) of each precipitation event. Linear models were tested as suggested by Leyton *et al.* (1967), and Gash and Morton (1978).

RESULTS AND DISCUSSION

Forest measurement characteristics of the species at plot level

The results showed forest measurements and leaf cover differences between the *P. hartwegii* and *A. religiosa* forests. *P. hartwegii* presented a lesser tree height (H), LAI and Diameter at breast height (DBH), but a greater trunk height (Hf) than *A. religiosa*. On the other hand, *A. religiosa* presented greater dimensions in the higher and lower diameters of its canopies (DM and Dm), providing a greater foliage cover area and lower gap fraction between canopies than *P. hartwegii*. The mean values of H, (DBH), Hf, DM and Dm for *P. hartwegii* were 21.1 m, 15.1 m, 37.6 cm, 7.8 m and 4.6 m, and for *A. religiosa*, they were 23.2 m, 11.6 m, 50.5 cm, 8.4 m and 5.9 m. The LAI values obtained from *P. hartwegii* (2.83) and *A. religiosa* (2.99) corresponded to previously reported ranges for forest species (Peduzzi, 2007; Muzylo *et al.*, 2009; Pérez-Arellano *et al.*, 2015).

Characteristics of rainfall events

The events analyzed are light and moderate rains, according to the CONAGUA criterion (Fan *et al.*, 2014). Approximately 57.2% of the rainfall events corresponded to precipitation of up to 5 mm, 9.5% to 5-10 mm, 23.8% to 10-15 mm, and 9.5% to 15-20 mm.

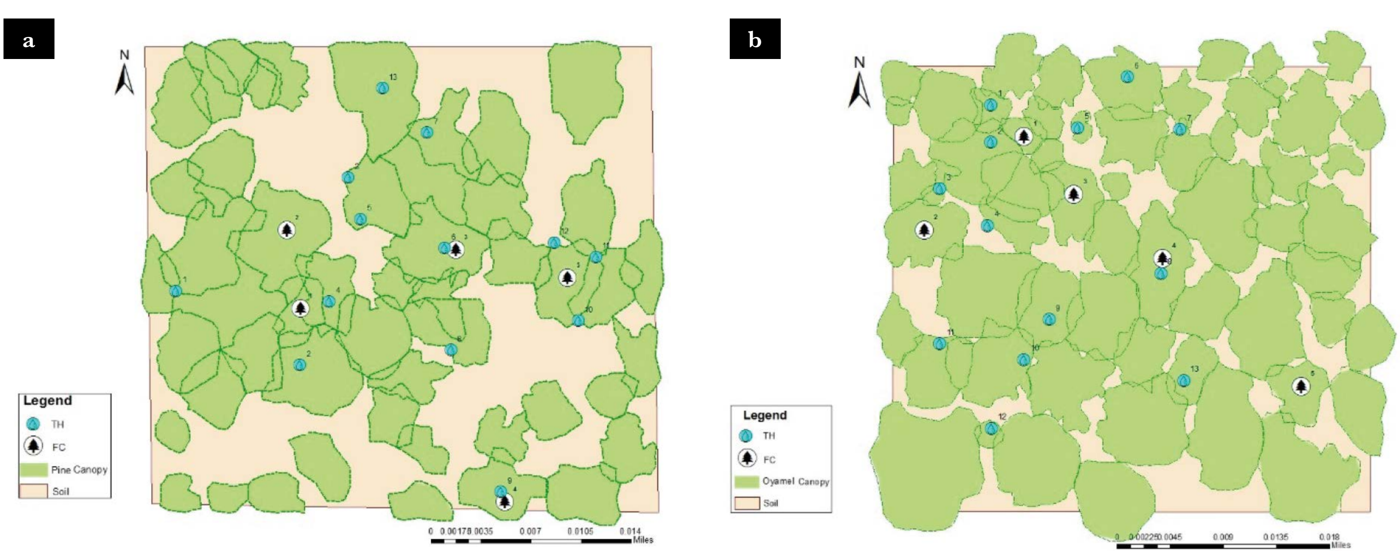

Figure 1. General instrumentation arrangement in the experimental plot for throughfall and stemflow: a) *P. hartwegii*, b) *A. religiosa*.

Rainfall interception and its components

The throughfall of *P. hartwegii* was 100.8 mm, which is 79.86% of the total rainfall depth of the 21 events analyzed (126.2 mm). This percentage was similar to that reported by Santiago-Hernández (2007) (79%) for mountain forests, to that observed by Ghimire *et al.* (2012) (76.2%) for pine forests, and to that found by Pérez *et al.* (2015) (70%) for *Pinus pinea*. However, it was lower than the 89% observed by Gavazzi *et al.* (2016) in *Pinus taedea* L. The differences were attributed to the fact that the rainfall events and the meteorological conditions were different, as well as the characteristics of the trees studied.

The throughfall in *A. religiosa* was lower than that in *P. hartwegii*, with 72.42% of total rainfall. The differences found between the two species were explained by their morphology, LAI and canopy-covered area. *A. religiosa* is a tree with a conical canopy in multi-layers that presents insertion of its leaves in a spiral shape (Arriola-Padilla *et al.*, 2014); this type of structure and geometry allowed retaining more canopy rainfall than *P. hartwegii*, which is a tree with hemispherical round canopy, and lower LAI and foliage thickness values (Tivo-Fernández, 2004).

The throughfall obtained in *A. religiosa* was similar to some of the results reported in species with similar canopy geometry and morphology. Iroume and Huber (2000), and Besteiro and Rodríguez (2012) observed 60% and 60%-75%, respectively. However, Oyarzún *et al.* (1985), Valente *et al.* (1997) and León *et al.* (2010) reported higher percentages of 74%-80%, 82.6% and 81%, respectively.

The stemflow recorded in the *P. hartwegii* plot was 3.74% of total rainfall, agreeing with the results of Ghimire *et al.* (2012) who reported 3.1%. It was higher than what was found by Pérez *et al.* (2015) who reported 0.3%, and it was lower than the 6.7% reported by Santiago-Hernández (2007). The differences among these results can be explained by differences in the morphology of the branches and trunks of the trees.

In the *A. religiosa* plot a stemflow of 2.90% was obtained, a percentage lower than what was obtained in the *P. hartwegii* plot, due to higher water retention by the trunk because its surface is more exposed and rougher. The percentage recorded for *A. religiosa* does not agree with that found in other studies in similar species, and it is attributed to the differences in morphological and phenological characteristics of the trunks of the species (Oyarzún *et al*, 1985; Iroume and Huber, 2000; Léon-Peláez *et al.*, 2010; Besteiro and Rodríguez, 2012).

A linear behavior between throughfall (TH, in mm) and gross precipitation (P, in mm) for both studied species was found (Equation 3 for *P. hartwegii* and Equation 4 for *A. religiosa*), as reported by other authors (Carlyle, 2004; Návar-Cháidez *et al.*, 2008; Carlyle and Gash, 2011; Pérez-Arellano *et al.*, 2015).

$$TH = 0.8452\,P - 0.2795 \tag{3}$$

$$TH = 0.8441\,P - 0.7209 \tag{4}$$

The coefficients of determination obtained were 0.99 and 0.98, and the RMSE values were 0.50 and 0.61 mm for *P. hartwegii* and *A. religiosa*, respectively.

In both species, a positive linear relationship was observed between stemflow (FC, in mm) and gross precipitation (P, in mm); this is a trend similar to those reported in other studies (Carlyle, 2004; Návar-Cháidez *et al.*, 2008; Carlyle and Gash, 2011). Equation 5 corresponds to *P. hartwegii* and equation 6 to *A. religiosa*, with coefficients of determination of 0.77 and 0.86, and RMSE values of 0.11 and 0.10 mm, respectively:

$$FC = 0.0382\,P - 0.0043 \quad (5)$$

$$FC = 0.0398\,P - 0.0646 \quad (6)$$

The analyses of variance conducted on the means of the throughfall depths collected from the rainfall events indicated a highly significant difference ($P<0.05$). Therefore, it is inferred that the chosen sampling sites were suitable since the characteristics of the canopy were both different and representative of the experimental plots.

Canopy rainfall interception

The interception calculated for *P. hartwegii* and *A. religiosa* was 20.66 mm and 31.15 mm, respectively, corresponding to 16.37 and 24.68% of total rainfall. Flores-Ayala *et al.* (2016) reported different total values in a study conducted on the same species as in this study, with 19.20% in *P. hartwegii* and 26.10% in *A. religiosa*. The difference in results between these two studies can be attributed to the fact that Flores-Ayala *et al.* (2016) did not consider stemflow in their calculation of rainfall interception, since it was calculated by subtracting the throughfall from the incident precipitation. If stemflow is not considered, although it apparently has small percentages in large areas with high depth rainfall, this omission can generate important errors in water balances. Previous studies in similar *P. hartwegii* species report values similar to those obtained in this research (Santiago-Hernández, 2007; Ghimire *et al.*, 2012; Pérez-Arellano *et al.*, 2015). For *A. religiosa*, there are similarities with what was reported by Iroume and Huber (2000) and Besteiro and Rodríguez (2012), but there are differences with what was obtained by Oyarzún *et al.* (1985), Valente *et al.* (1997) and León *et al.* (2010). The discrepancies in the rainfall intercepted between species confirm that the redistribution of canopy rainfall is a function of the morphological and structural characteristics of the vegetation type, the characteristics of the rainfall, and the meteorological conditions during the events (Iroume and Huber, 2000).

The relationship between the percentage of rainfall interception and gross rainfall was expressed through a negative exponential function for both plots, with coefficients of determination (R^2) of 0.78 and 0.89, and RMSE values of 4.89 and 7.05 mm for *P. hartwegii* and *A. religiosa*, respectively (Figure 2). Some authors reported a similar relationship between these two components (Oyarzún *et al.*, 1985; Carlyle, 2004; Carlyle and Gash, 2011; Besteiro and Rodríguez, 2012). It was observed that as the amounts of rainfall increases, the rainfall interception decreases, with a fast decline in small amounts and with asymptotic behavior in large amounts, saturating the *P. hartwegii* canopy with smaller precipitation amounts than in the *A. religiosa* canopy. Flores-Ayala *et al.* (2016) found a potential relationship for *A. religiosa* and a logarithmic relationship for *P. hartwegii*,

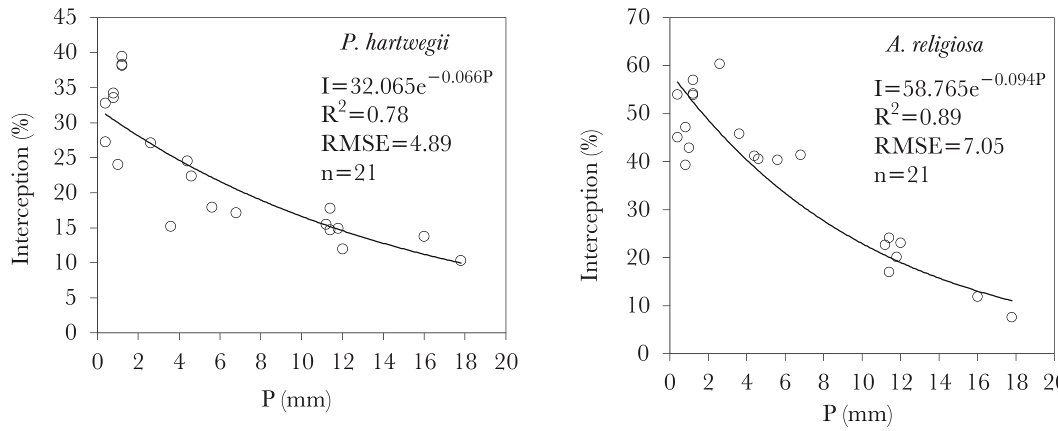

Figure 2. Canopy rainfall interception as a function of gross precipitation on *P. hartwegii* and *A. religiosa*.

with R^2 values much lower than those found in our study, since they obtained 0.58 and 0.42, respectively. In our study, the linear relationships (first-order polynomials) presented values of R^2 equal to 0.89 and 0.78 for *A. religiosa* and *P. hartwegii*, respectively, which are also higher than the values found by Flores-Ayala *et al*. (2016).

CONCLUSIONS

Canopy rainfall interception in the *A. religiosa* plot was higher than that in the *P. hartwegii* plot (24.86% and 16.37%, respectively). The difference is associated with the different characteristics of the canopy in the two species, reflected in the LAI values obtained and in the forest measurement parameters reported, primarily in terms of canopy size.

The *A. religiosa* plot presented canopy density and canopy diameter values higher than those in *P. hartwegii* plot, which led to a lower water contribution through the plant cover toward the ground, since throughfall was 72.42% and 79.86%, respectively. Instead, it generated higher water retention in the trunk, showing a lower stemflow (2.90 and 3.74, respectively), due to its rougher and thicker bark, and greater exposed surface.

Canopy rainfall interception percentage is related to incident precipitation with a negative exponential function, with R^2 greater than 0.78 in both species. Throughfall and stemflow were found to have a linear function with incident precipitation in both species, with R^2 greater than 0.98 and 0.77, respectively.

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