

# Fog water capture in temperate forests

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## ABSTRACT

**Objective:** To develop a procedure for estimating fog water capture in temperate forests for three genera *Pinus*, *Abies* and *Quercus*, in locations lacking specialized instrumentation.

**Design/Methodology/Approach:** Three one hectare plots were established in temperate forest. Seventy-five rain gauges, with a precision of 0.1 mm, were randomly distributed across each plot. To analyze of fog water collection, precipitation events were recorded daily during the rainy season (June-September). From these data, events were selected only if at least one rain gauge showed no precipitation while a minimum volume of water was recorded in the remaining gauges.

**Results:** The *Abies* forest captured a total of 4.7 mm of fog water, followed by *Quercus* 2.89 mm, and *Pinus* 1.12 mm.

**Study Limitations/Implications:** The evaluation was to the rainy season, with data recorded on a daily basis. The accessibility challenge was overcome.

**Findings/Conclusions:** The proposed procedure provides reliable results, enabling the assessment of fog water contribution as an initial strategy when specialized instrumentation is unavailable.

**Keywords:** Fir, highland Pine, Oak, horizontal precipitation.

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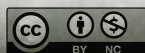
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## INTRODUCTION

Globally, water scarcity is one of the most important challenges for human development. Currently, 2.4 billion people live in countries affected by water stress. In addition, there has been an increase in the frequency and intensity of extreme weather events, including droughts and floods, which further exacerbates ecosystem degradation (UN, 2023), particularly forest ecosystems. In Latin America and the Caribbean, 34% of the world's total freshwater resources are available. However, despite this high value (28,000 m<sup>3</sup> per inhabitant per year) and an average annual precipitation of 1,600 mm, some regions experience water stress due to differences in precipitation patterns and water demand associated with economic activities (FAO, 2025).

In Mexico, hydrological basins must meet the high water demand of the population. Daily *per capita* water consumption is estimated at 366 liters (UN, 2025), which requires careful resource management beginning with rainwater capture in the country's forests and tropical ecosystems. In this regard, the National Water Commission (CONAGUA) and the Ministry of Environment and Natural Resources (SEMARNAT) aim to mitigate water supply limitations in the country. Both institutions work jointly under the National Water Program (PNH) 2024-2030 (CONAGUA, 2024) and the future Water Agenda 2030, promoting irrigation technification in agriculture and rainwater harvesting as key strategies for long-term water security.

Rainfall interception (I) is the capacity of the tree canopy to store or retain rainwater within its structure (leaves, branches, and stem) during and after a precipitation event. This amount can represent up to one quarter of total precipitation (Navar, 2020). Interception values (I) have mainly focused on comparing throughfall (Pd) with precipitation recorded outside the forest in experimental plots, which represents total or incident precipitation (Pi). However, an additional and scarcely evaluated fraction of water may originate from fog or horizontal precipitation captured by vegetation, which is rarely differentiated from water derived from Pi (Kavianpour *et al.*, 2025).

Fog consists of tiny suspended water droplets whose small size prevents their falling velocity from exceeding the upward force of air, thereby avoiding precipitation (Villegas *et al.*, 2008). When fog is transported by wind, droplets collide with vegetation surfaces, where they coalesce into larger droplets that eventually fall to the ground. This process, known as fog interception, constitutes an important water source for many ecosystems (Prada *et al.*, 2009). These fluxes can be quantitatively relevant for the local water balance (Tognetti, 2015), especially during dry seasons or along coastal altitudinal gradients (Weathers *et al.*, 2020). According to Baguskas (2016), fog promotes seedling survival and reduces mortality during summer droughts, with direct implications for natural regeneration and restoration success. Furthermore, authors such as Berry *et al.* (2015) report that fog influences tree physiology by increasing leaf water potential and reducing transpiration. Some epiphytes, mosses, and understory species strongly depend on this additional water input in the form of fog (Liu *et al.*, 2021), supporting biodiversity and microclimate regulation (Berrones, 2022).

Fog is not only a source of water; it also provides nutrients (N, P) and atmospheric pollutants (Jofre-Meléndez *et al.*, 2015) that influence soil and water fertility and chemistry, with consequences for species composition and biogeochemical processes, making it an important ecological vector (Weathers *et al.*, 2020). According to Zhan *et al.* (2020), fog interception can result in measurable contributions to soil moisture, which may vary considerably due to topography, forest edge effects, and canopy structure (Harr, 1982; Ewing *et al.*, 2009), as well as vegetation cover, which in turn depends on the type of silvicultural treatment applied (Monárrez-González, 2023). Fog interception is also influenced by fascicle size, with smaller fascicles being more efficient (Went, 1955; Praskievicz and Sigdel, 2023). Therefore, fog water capture is considered a viable technology to address water scarcity; however, its success depends on both technological and socioeconomic factors, including financing and maintenance (Sowmya *et al.*, 2025).

Dunne and Leopold (1978) point out that estimating I captured in forests in the form of fog remains a methodological challenge, particularly considering that this fraction is relatively small compared with Pi. In interception studies, conventional rain gauges are typically installed in open fields; therefore, they rarely capture fog drip water generated under the forest canopy (Vogelmann *et al.*, 1968; Kavianpour *et al.*, 2025). Consequently, fog interception is often quantified using indirect methods (Schmid *et al.*, 2011). Among the methods employed are mesh collectors and modeling techniques (Imteaz *et al.*, 2011). However, in both cases, the potential contribution of fog water captured by trees is being evaluated (Ritter *et al.*, 2008; Regalado and Ritter, 2010). Other approaches include the Standard Fog Collector and the Large Fog Collector, structurally improved designs such as the CloudFisher and the Warka Water Tower, as well as laboratory-scale innovations using biomimetic wettability-patterned surfaces, electrospun nanofibers, and Janus membranes (Sowmya *et al.*, 2025).

Fog precipitation represents a significant potential in forest ecosystems, as forests play a crucial role in improving water availability, particularly during dry periods. Integrating fog water inputs into regional water resource management and forest conservation strategies is essential to ensure the sustainability of these valuable ecosystems. Therefore, the objective of this study is to apply a procedure to identify fog water capture and estimate its contribution to the water balance in temperate forests dominated by the genera *Pinus*, *Abies*, and *Quercus* within a hydrologically important forested watershed.

## MATERIALS AND METHODS

### Study Area

This study was conducted within the Texcoco River watershed, located in the eastern part of the Valley of Mexico basin in the municipality of Texcoco, within the ejidal forest area of San Pablo Ixayoc (Figure 1). The watershed topography is composed of three well-defined zones: a lowland zone extending from the watershed gauging station to the 2,300 m a.s.l. contour line; a hilly zone between the 2,300 m and 2,500 m a.s.l. contour lines; and a mountainous zone, where this study was carried out, ranging from 2,500 m to over 4,000 m a.s.l., which marks the upper boundary of the watershed and covers an area of 14.74 km<sup>2</sup>.

The climate of the area is classified as Cb'(w2) temperate subhumid to semi-cold, with a mean temperature ranging from 5 °C to 12 °C. Average monthly precipitation ranges from 381.4 mm to 868 mm, with July being the wettest month. The mean annual temperature is 10.95 °C; January is the coldest month and May is the warmest. Regarding soil types, chromic Vertisols dominate, characterized by their high clay content. Vegetation is distributed in well-defined zones dominated by *Pinus* in the upper part, *Abies* in the middle zone, and *Quercus* in the lower zone (Carrillo, 2015).

The study was carried out using infrastructure installed under the research project “Rainfall Interception Study for Silvicultural Management Purposes” of the National Research Program on Sustainable Forest Management of the National Institute for Forestry, Agricultural and Livestock Research (INIFAP). Three representative sites were selected



**Figure 1.** Location of the plots within the Texcoco River watershed in the ejidal forest area of San Pablo Ixayoc, Texcoco.

along the altitudinal gradient and forest types. In 2009, the first site was established in a pure *Abies religiosa* (Kunth) Schlttdl. & Cham. forest at an altitude of 3,000 m a.s.l. In 2010, the second plot was established in an oak forest dominated by *Quercus rugosa* Née at an altitude of 2,850 m a.s.l., and in 2011, a third site was established in a pure *Pinus hartwegii* Lindl. forest at an altitude of 3,650 m a.s.l. (Figure 2).

The general characteristics regarding the location and year of establishment of the study areas are presented in Table 1.



**Figure 2.** (a) *Abies religiosa* (Kunth) Schlttdl. & Cham. forest, (b) *Quercus* spp. forest, and (c) *Pinus hartwegii* Lindl. forest.

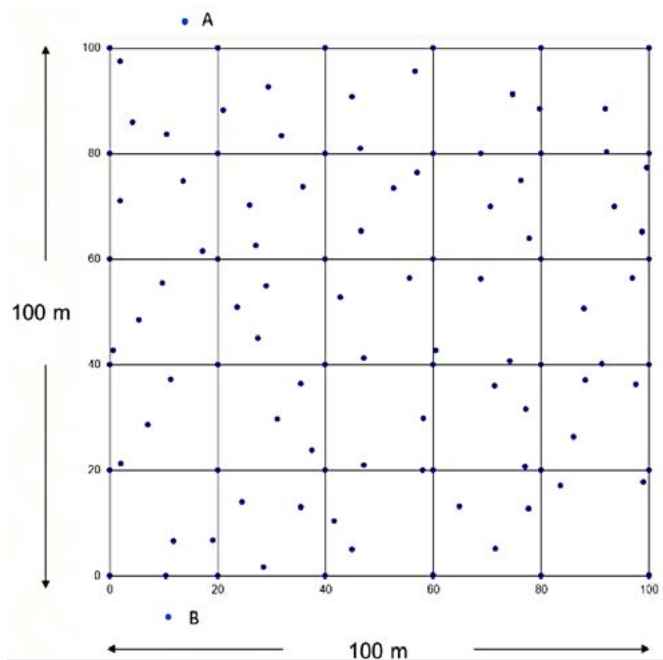
**Table 1.** Location of the plots within the ejido of San Pablo Ixayoc, Texcoco, State of Mexico.

Parcela	Coordenadas	Nombre del paraje/ altitud	Año
Oyamel: <i>Abies religiosa</i> (Kunt) Schlttl. & Cham.	19° 26' 16.92" 98° 45' 40.81"	Atlapulco: 3,000 m	2009
Encino: <i>Quercus rugosa</i> Née <i>Quercus deserticola</i> Trel. <i>Quercus laurina</i> Humb. & Bonpl.	19° 27' 09.11" 98° 46' 19.23"	Tlatzala: 2,900 m	2010
Pino: <i>Pinus hartwegii</i> Lindl.	19° 25' 09.85" 98° 44' 15.51"	Cañada Honda: 3,650 m	2011

### Experimental Plots

A detailed inventory of the dominant vegetation was conducted. Data collection included the following variables: species, diameter at breast height (DBH), clear bole height, total height, and spatial location using coordinates (x, y) within each plot. Botanical samples of all tree species were collected for identification at the Forest Herbarium of the Forestry Division of the Autonomous University of Chapingo.

Three plots of one hectare each (100 m × 100 m) were established. In each plot, 75 True Chek<sup>®</sup> direct-reading rain gauges were installed, with a capacity of 150 mm and a precision of 0.1 mm, randomly distributed under the tree canopy, along with two additional rain gauges placed in open conditions (A and B, outside the plot) (Figure 3). The rain gauges were mounted on supports at a height of 0.90 m above ground level to prevent splash effects.

**Figure 3.** Plot layout and distribution of rain gauges.

Daily precipitation measurements were conducted, and the amount of rainfall intercepted by the canopy was estimated as the difference between total precipitation measured under open conditions and the overall average obtained from the water volume recorded in rain gauges located under the canopy. To measure water captured from fog, the database generated from rainfall interception studies was used. To quantify fog water capture volumes, events were selected and analyzed in which at least one rain gauge showed no precipitation record and only a minimal water volume was recorded in the remaining rain gauges, which was attributed to the presence of fog. The rationale behind this procedure is that conventional rain gauges are not suitable for directly recording fog water. However, trees act as condensation elements that enable fog to be transformed into water. When tree foliage becomes saturated with condensed water, it drips and precipitates to the ground, where it is collected by the rain gauges.

Finally, the study considered only those events in which at least 10 rain gauges were empty for each studied species. For each selected event, it was verified that no previous precipitation event had occurred to avoid residual drip effects. This was proposed as a conservative criterion aimed at minimizing potential sources of error and allowing a more robust interpretation of horizontal precipitation capture. The working premise was that rain gauges showing any recorded water volume reflected fog drip resulting from fog particles intercepted by vegetation, which coalesce on canopy surfaces and, due to gravity, drip to the ground and/or are captured by the measuring equipment (Holder and Bruijnzeel, 2004).

### Data analysis

Information previously generated from the rainfall interception study was grouped by genus, analyzing precipitation data for each year and study period. The data were analyzed by rainfall period, constructing a database of rainfall events and considering events in which at least one rain gauge recorded no water volume.

## RESULTS AND DISCUSSION

A total of 74 rainfall events were recorded, with 27 events showing at least one empty rain gauge in *Abies religiosa*; 63 total rainfall events with 16 events showing at least one empty rain gauge in *Quercus* spp.; and 72 total rainfall events with 12 events showing at least one empty rain gauge in *Pinus hartwegii* (Table 2).

**Table 2.** Database by studied genus, analyzed rainfall period, and number of analyzed events.

Especie	Total rainfall events	Rainfall events	Fog events	Period analyzed
<i>Abies religiosa</i> (Kunt) Schltdl. & Cham	74	66	8	May 22 to September 30
<i>Quercus</i> spp.	63	56	7	May 27 to October 30
<i>Pinus hartwegii</i> Lindl.	72	68	4	June 24 to September 30

The analyzed results show that the *Abies* forest captured a total of 4.7 mm of fog-derived water, *Quercus* 2.89 mm, and *Pinus* 1.12 mm during the study periods, equivalent to 47.0, 28.9, and 11.2 m<sup>3</sup> ha<sup>-1</sup>, respectively. According to Palán and Křeček (2018), fragmented montane forests recorded an average fog drip of 81 mm year<sup>-1</sup>, equivalent to 7% of the annual gross precipitation. Although our data do not allow a direct annual comparison due to shorter observation periods and the exploratory nature of this study, the event-based estimates obtained (0.28-0.59 mm) are lower in magnitude; however, the comparison remains valuable, as even low fog inputs can represent a relevant fraction of the water balance. Berrones *et al.* (2022), using higher-precision equipment, reported fog capture values per event between 0.1 and 0.2 mm, while Praskievicz and Sigdel (2023) reported average total values per event ranging from 0.24 to 0.69 mm, which are very similar to those found in this study. This suggests that despite the use of an indirect and conservative method, the magnitude of fog water capture inferred from the rain gauge network is consistent with values reported in the literature.

Table 3 summarizes the volumes of fog water captured in *Abies*, *Quercus* spp., and *Pinus* forests, considering only events in which 10 or more rain gauges remained without precipitation records.

In all cases, these values represent additional water inputs that, although smaller than vertical precipitation, are concentrated within a specific subset of events and forest types. During the development of this study, one of the main difficulties was the daily data collection, as measurements had to be conducted during the rainy season, particularly in the *Pinus hartwegii* forest, which is located at the highest elevation and on the steepest terrain. This limitation was partially compensated by the type of rain gauges used, which allowed for rapid and easy data recording.

**Table 3.** Total and average amounts of water capture per event from fog.

Forest	TNE	TFWM	AWE (mm)
<i>Abies religiosa</i> (Kunt) Schlttdl. & Cham.	8	4.70	0.59
<i>Quercus</i> spp.	7	2.89	0.41
<i>Pinus hartwegii</i> Lindl.	4	1.12	0.28

TNE=Total number of events classified as fog (events with  $\geq 10$  rain gauges without records).

TFWM=Total amount of fog water measured according to TNE (mm).

AWE=Average amount of fog water per event (mm).

## CONCLUSIONS

This study documents and applies an exploratory procedure to infer fog water capture from a network of direct-reading rain gauges originally installed to evaluate rainfall interception in temperate forests of *Abies*, *Quercus*, and *Pinus*. The spatial criterion (events with  $\geq 10$  rain gauges without precipitation records and absence of prior rainfall) allowed the identification of a subset of fog events and the estimation of their minimum contribution to the water balance. The results should be interpreted as minimum estimates, conditioned by the indirect nature of the method and the absence of micrometeorological measurements and fog collectors. Nevertheless, the reanalysis of rainfall interception databases emerges

as a viable alternative to constrain the expected range of fog water capture in hydrological-forest watersheds and to guide future studies integrating rain gauge networks, fog collectors, and continuous atmospheric records.

Developing and validating practical methodologies for measuring fog water capture is essential to strengthen forest management, as it may serve as a basis for designing silvicultural treatments that conserve or enhance canopy structure, species composition, and the functional integrity of forest ecosystems. Furthermore, these results highlight a potential analytical approach and represent an opportunity to deepen the understanding of this process. Fog water capture in temperate forests represents a hydrological process of high ecological relevance whose understanding remains limited in Mexico, mainly due to the scarcity of local research and the lack of standardized, accessible, and field-adapted methodologies.

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