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Hydrological impact of pine species and plantation age in the semi-arid *Mixteca alta*, Oaxaca

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TECHNOLOGY OF FOREST PRODUCTS

ABSTRACT

Background: Rainfall redistribution by forest canopies is a key hydrological process influencing water availability in semi-arid ecosystems. However, information remains limited on how pine species and stand development affect rainfall partitioning in reforested landscapes of the Mixteca Alta region of Oaxaca, Mexico. This study evaluated throughfall, stemflow, and interception in *Pinus pseudostrobus* and *Pinus greggii* plantations ranging from 6 to 56 years old.

Results: Rainfall partitioning was monitored throughout the rainy season using throughfall collectors and stemflow collars installed in seven pine plantations. Throughfall generally decreased with stand age, whereas interception increased as canopy development progressed. *Pinus pseudostrobus* consistently allowed greater throughfall and exhibited lower interception losses than *P. greggii*, particularly in younger stands. In contrast, *P. greggii* showed greater canopy retention of rainfall, reflecting differences in canopy structure and density. Stemflow contributed only a small proportion of total precipitation and declined with increasing stand age in both species. Log-linear models indicated significant relationships between incident precipitation and rainfall redistribution components, while structural attributes such as crown diameter and basal area were associated with observed hydrological responses

Conclusions: Species identity and stand age significantly influenced rainfall partitioning in semi-arid pine plantations. The greater interception observed in older stands and in *P. greggii* highlights the importance of canopy structure in regulating water inputs to the forest floor. These findings provide useful guidance for species selection and reforestation planning aimed at sustaining hydrological ecosystem services in water-limited environments.

Keywords: *Canopy structure; Rainfall interception; Restoration hydrology; Stemflow; Throughfall.*

HIGHLIGHTS

Pine species affected rainfall partitioning in semi-arid plantations.
Throughfall decreased as pine plantations became older.
Canopy traits should guide reforestation in water-limited regions
Interception increased with canopy structural development.

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INTRODUCTION

Forests play a crucial role in the generation of fresh water supply, contributing significantly to the water cycle and the provision of water resources; they are responsible for guiding water into rivers, lakes, and groundwater, making them a vital source of water for various ecosystems and human populations (Valente *et al.*, 2020). The trees absorb moisture from the soil and release it into the atmosphere through a process called transpiration, which increases the capacity of the ground to store water and promotes cloud formation, leading to rainfall and the continuation of the water cycle (Wani e Sahoo, 2021). However, deforestation and forest degradation can disrupt the water cycle by altering transpiration, decreasing precipitation, and promoting increased runoff (Wu *et al.*, 2021; Xu *et al.*, 2022). In this sense, forest regeneration and plantation can positively contribute to local hydrological ecosystem services, including reducing water erosion of soils and the risk of moderate floods, improving infiltration rate and sediment yield, and enhancing water quality and flood resilience (Heckel *et al.*, 2020).

Reforestation with pine trees has been found to impact rainfall interception. Studies have shown that exotic pine forests intercept more rainfall than native forests, resulting in reduced rainfall reaching the forest floor (Francis, Wuddivira e Farrick, 2022). The higher interception in pine forests can be attributed to their higher storage capacity and the role of understory vegetation in the interception process (Ma *et al.*, 2019). Pine plantations have been found to have higher interception losses compared to native forests, resulting in a decrease in net rainfall input in forested ecosystems (Cortés *et al.*, 2020). Pine reforestation can also lead to a decline in dry season streamflow, affecting water availability in the region (Au *et al.*, 2022).

Although forest plantations play a crucial role in hydrological ecosystem services, several research gaps need to be addressed, such as the lack of readily available knowledge on defining thresholds for the ideal relationship between natural ecosystems and land uses to ensure the supply of water ecosystem services (Bispo *et al.*, 2023), the need to evaluate the effects of forest plantations on water regulation ecosystem services, such as water yield, soil water, surface runoff, groundwater recharge, and evapotranspiration (Kristanto *et al.*, 2022).

In Mexico, as in many other regions of the world, one of the main problems of reforestation is the decrease in water availability they cause during early growth (Hua *et al.*, 2022). Due to the inadequate selection of species, this impact is generally more noticeable in exotic than in native species. The amounts of water required throughout the growing season and between years for these species' correct functioning (establishment, early growth, and morphological development) are still being determined (Egginton, Beall e Buttle, 2014). However, there are indications that reforestation with inappropriate, fast-growing species usually reduces groundwater levels and river flows due to increased transpiration. Despite increasing reforestation efforts in semi-arid regions, limited information is available on how pine species and stand development modify rainfall redistribution in degraded tropical dryland landscapes. This knowledge gap is particularly relevant in the Mixteca Alta region of Oaxaca, where water scarcity, soil degradation, and reforestation programs coexist.

We hypothesised that rainfall partitioning differs between pine species and stand ages due to species-specific canopy architecture and age-related structural development. Specifically, we expected that: (i) older stands would show greater interception and lower throughfall due to increased canopy storage capacity; and (ii) *Pinus greggii* would intercept more rainfall than *P. pseudostrobus* because of its denser canopy structure.

Therefore, this study aimed to quantify throughfall, stemflow, and interception in *Pinus greggii* and *Pinus pseudostrobus* plantations of different ages in the semi-arid Mixteca Alta region of Oaxaca, Mexico.

MATERIAL AND METHODS

Study area

This study was conducted in the community of Tlacotepec Plumas, located in the district of Coixtlahuaca, Oaxaca, Mexico (Fig. 1). The dominant vegetation type of the study area is pine-oak forests, with ornamental, edible, fruit, and medicinal plants, despite water scarcity (Rzedowski, 2006). The average annual rainfall ranges from 600 to 700 mm. December is the driest month in Tlacotepec Plumas, with 9 mm of precipitation. June is the rainiest month, with an average rainfall of 263 mm. May is the warmest month, and January is the coldest. The study area belongs to the Mixteca Region, one of the poorest regions of Mexico that has suffered serious environmental deterioration (soil degradation, high levels of deforestation and water scarcity) that began more than 500 years ago (Figure 1).

Experimental design

We selected seven monoculture pine plantations (S1…S7) representing two species (*Pinus pseudostrobus* and *Pinus greggii*) and a chronosequence ranging from 6 to 56 years of age. All stands were located within similar topographic conditions (slope <15%, southwest-facing exposures) to minimise environmental heterogeneity (Table 1).

At each stand, 20 throughfall collectors were installed in a stratified random layout covering the projected crown area. Three trees per stand were equipped with stemflow collars and collection containers to capture water flowing down the stems. Tree structural variables, including diameter at breast height (DBH), total height, crown diameter, and basal area, were measured for all instrumented trees. These variables were used to interpret hydrological differences among species and age classes (Table 2).

Because the study was conducted in existing operational plantations, the experimental design was observational rather than fully factorial. Stand age and site identity were partially confounded, and age classes

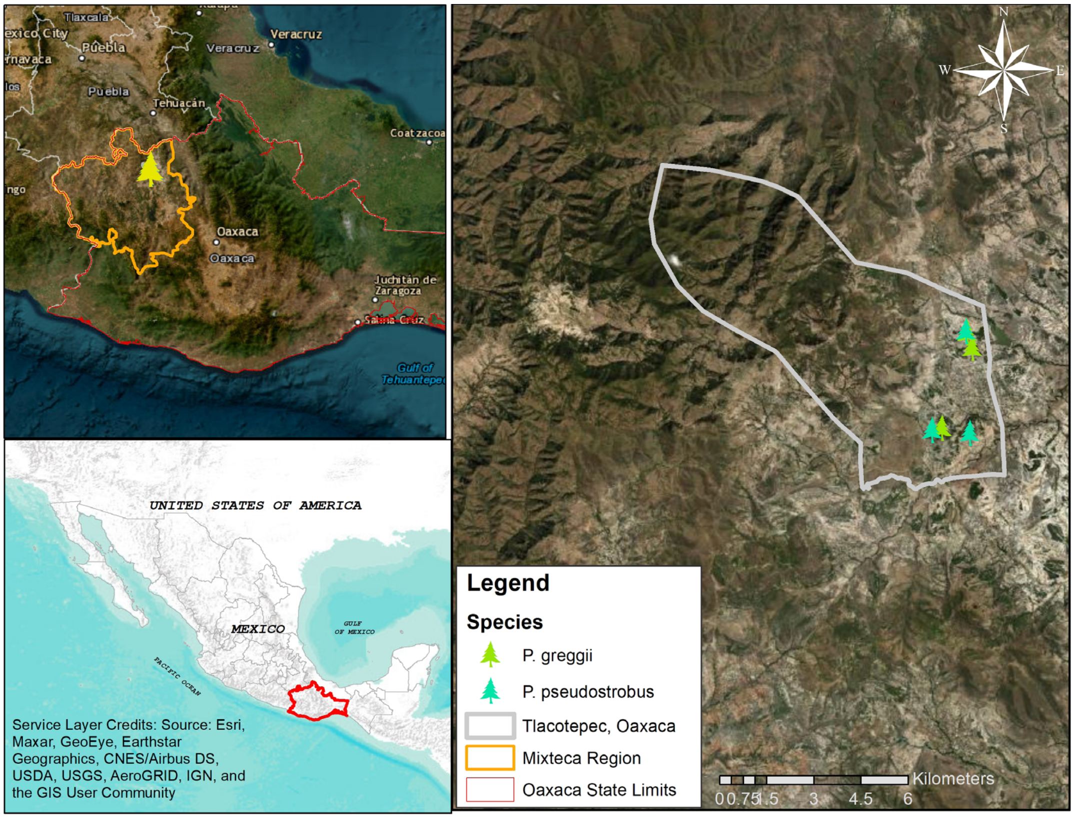


Figure 1: Localisation of the study area.

were not completely balanced between species. Therefore, statistical results should be interpreted as ecological trends associated with species and stand development rather than as strictly causal effects. This limitation was considered when interpreting the results.

Incident Precipitation and Throughfall Measurement

To measure incident precipitation (P, mm), 14 standard Tenite® plastic rain gauges (range up to 280 mm) were installed at seven strategic locations, free of vegetation but near the sample sites, at 0.70 m above ground.

Also, three automated rain gauges (ONSET Rain Gauges) were installed to measure rainfall frequency and intensity, strategically distributed across the experimental strip. Rainfall data were downloaded at 8-day intervals, capturing 23 events in 2021 and 26 in 2022, with rainfall ranging from 0 to 47.3 mm. The data collection period was from 25 August to 27 October 2021 and from 21 June to 20 September 2022. Although data on incident precipitation, throughfall, and stem flow collected in 2021 were not included in the analysis due to inconsistent and unreliable methods. In the 2022 measurement period, cumulative precipitation of 238.5, 254.1, 257.8 and 210 mm was recorded at the 6, 21, 25 and 56-year-old sites of *Pinus pseudostrobus* var. *apulcensis* and 212.9, 241.4 and 234 mm of precipitation at the 25, 16 and 6-year-old plantation of *Pinus greggii* var. australis, respectively.

Throughfall

We used 20 collectors with a 2.8-litre capacity each and placed them under the trees' canopy to measure throughfall, randomly distributed over an area of 78.54 m^2 at sites 1, 2, 3, 4, 5, 6, and 7. The data collection period was

Table 1: Species used at each experimental site.

Experimental Site	Species	Location	Elevation (masl)	Age (years)
S1	*Pinus greggii*	N17° 52′12.6″ W096° 26′ 12.2″	2115	25
S2	*Pinus pseudostrobus*	N17° 52′12.2″ W 097° 26′18.9″	2066	25
S3	*Pinus greggii*	N17° 51′54.0″ W 097° 26′12.2″	2125	16
S4	*Pinus pseudostrobus*	N17° 52′12.2″ W 097° 26′18.9″	2068	21
S5	*Pinus pseudostrobus*	N 17° 50′ 30.2″ W097°26′54.0″	2147	6
S6	*Pinus greggii*	N17° 50′32.2″ W097° 26′43.8″	2131	6
S7	*Pinus pseudostrobus*	N 17° 50′27.2″ W 097°26′14.9″	2183	56

Table 2: Mean values of dasometric variables of sampled pines in Tlacotepec Plumas, Oax.

Site	Species	Age (years)	DBH (cm)	Total height (m)	Canopy (m)	Crown height (m)	TSF (%)
1	*Pinus greggii*	25	18.6(4.45)	17.5(2.4)	4.54(0.9)	15.5(2.23)	50.83(13.6)
2	*Pinus pseudostrobus*	25	21.38 (5.02)	15.51(2.44)	4.47(1.31)	13.21(1.43)	55.83(10.1)
3	*Pinus greggii*	16	17.29(4.55)	12.52(0.7)	6(0.91)	11.43(0.96)	48.33(11.7)
4	*Pinus pseudostrobus*	21	17.52(4.49)	13.83(1.95)	4.61(1.09)	11.42(1.75)	59.04(6.82)
5	*Pinus pseudostrobus*	6	8.6(2.4)	4.74(0.81)	2.75(0.63)	3.78(0.94)	49.16(8)
6	*Pinus greggii*	6	8.9(1.4)	5.94(0.7)	3.12(0.89)	5.07(0.61)	49.16(3.76)
7	*Pinus pseudostrobus*	56	38.5(11.3)	19.33(4.02)	9.8(2.95)	18.16(4.09)	50(13.1)

TSF: Transparency scale of the tree's foliage. Standard deviation in brackets.

from 25 August to 27 October 2021 and from 21 June to 20 September 2022. During this period, data were collected immediately after each rainfall event.

Stemflow

At each research site, six representative trees were selected for stem-flow measurement: two dominant (D), two co-dominant (C), and two suppressed (S). For each chosen tree, a section of bark was carefully removed in an undamaged manner, extending about 80 cm above the ground in a spiral pattern. A clear plastic hose with a ½-inch diameter was then fitted to the tree, with lengths ranging from 100 to 135 cm, depending on the tree's diameter. The hose was longitudinally slit and affixed to the tree's trunk in a spiral configuration using 16 mm staples and nails, directing the collected water into a 20-litre container for subsequent analysis. For data analysis, the volume of stem flow collected in millilitres was converted to millimetres by dividing the total volume by the average crown area of the six selected trees.

Interception

Interception is the fraction of water retained on the canopy and evaporated after or during rainfall events (Lian *et al*., 2022). In this study, we calculate the interception by using the incident precipitation, throughfall and stem flow measurements into the following formula 1:

$$I_c = P_i - (P_d + S_f) \quad (1)$$

Where:

I_c= interception; P_i=incident precipitation; P_d=Throughfall; S_f= Stemflow

Statistical analysis

Rainfall partitioning components were analysed at the rainfall-event level. Throughfall, stemflow, and interception were evaluated as response variables, while species, stand age, rainfall amount, and sampling month were considered explanatory variables. Log-linear models were used to describe the relationship between incident precipitation and rainfall partitioning components.

Model assumptions were assessed using residual-versus-fitted plots and Q–Q plots.

Normality and homoscedasticity were verified before interpreting model outputs. Analysis of variance was used to compare throughfall, stemflow, and interception among stand ages and tree strata, followed by Bonferroni-adjusted multiple comparisons when significant effects were detected (Quinn e Keough, 2002). Pearson correlation analysis was used to examine associations between dasometric variables and rainfall partitioning components. Due to the observational design and limited site replication, statistical inference was interpreted cautiously, emphasizing patterns and hydrological trends rather than broad causal generalization.

All statistical analyses were executed using RStudio (R Core Team, 2020) version 4.1.3.

RESULTS

Dasometric variables from each sample site.

Tree structure varied notably across sites and species. The oldest stand—56-year-old *Pinus pseudostrobus* (site 7)—averaged 19.0 m in height, 38.5 cm in diameter, and 10 m crown diameter (TSF = 50%), and is considered mature. In contrast, 25- and 21-year-old *P. pseudostrobus* stands (sites 2 and 4) were smaller (~15.5 m height, ~21 cm diameter, ~4.5 m crown), with slightly higher TSF (55%). The youngest *P. pseudostrobus* stand (site 5, 6 years) had much smaller trees (4.7 m height, 8.6 cm diameter, 2.7 m crown; TSF = 49%). *Pinus greggii* showed similar age-related patterns. At 25 years (site 1), trees averaged 17.5 m height, 18.6 cm diameter, and 4.5 m crown (TSF = 50.8%). The 16-year-old stand (site 3) was shorter (12.5 m), with 17 cm diameter and 6.0 m crown (TSF = 48%). The youngest stand (site 6, 6 years) averaged 5.9 m height, 8.9 cm diameter, and 3.0 m crown (TSF = 49%). At similar ages, *P. greggii* generally had denser crowns (lower TSF) than *P. pseudostrobus*.

Incident precipitation

During the 2022 measurement period, cumulative precipitation measurements recorded at sites aged 6, 21, 25, and 56 years for *Pinus pseudostrobus* var. *apulcensis* ranged from 238.5 mm to 257.8 mm. Additionally, cumulative precipitation at sites with *Pinus greggii* var. australis plantations aged 25, 16, and 6 years was measured as 212.9 mm, 241.4 mm, and 234 mm, respectively (Figure 2).

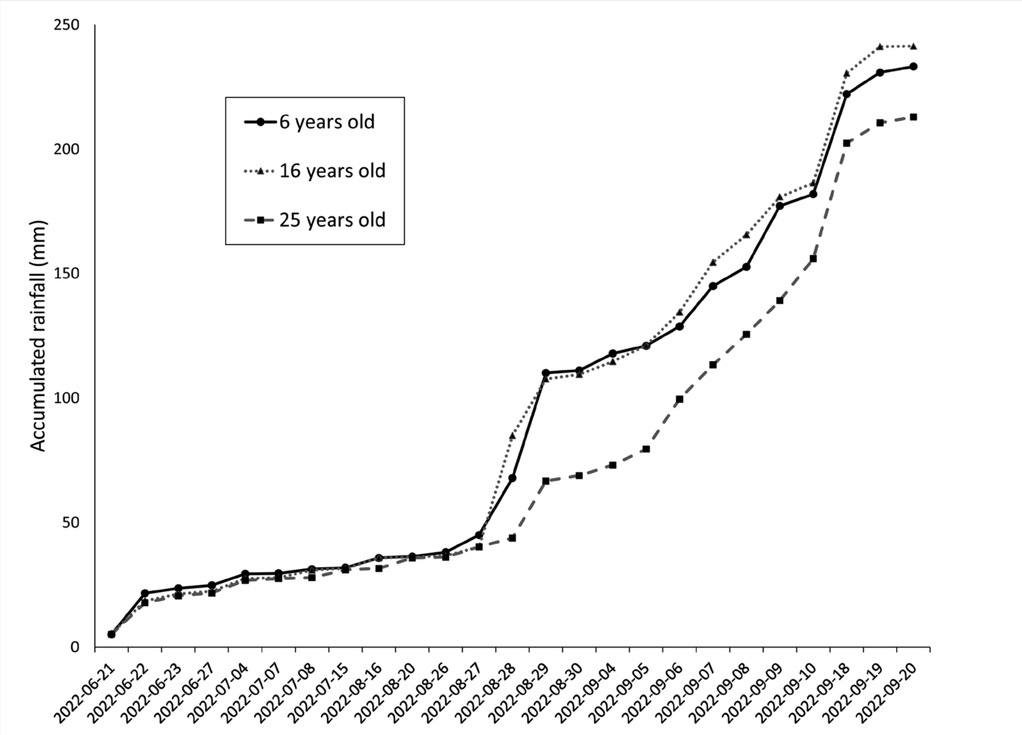


Figure 2: Accumulated rainfall in the reforestation of *Pinus greggii*.

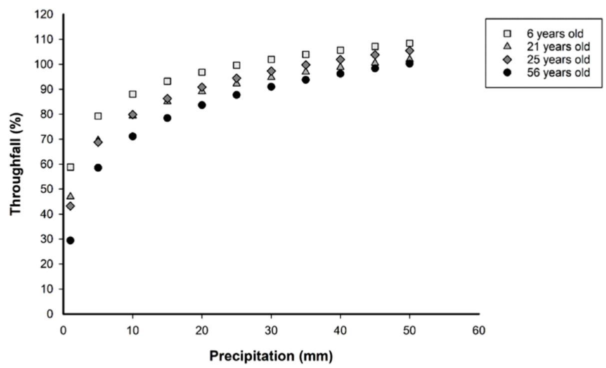
During the study period, direct precipitation for *Pinus pseudostrobus* var. *apulcensis* was 78.1%, 68.4%, 68.0%, and 53.6% for stands aged 6, 21, 25, and 56 years, respectively. A logarithmic model best described the relationship between direct and incident precipitation (Table 3, Figure 3), showing that as incident rainfall increases, direct precipitation also rises. Younger stands (especially the 6-year-old) allowed more rainfall to reach the forest floor, with throughfall decreasing with stand age (Figure 3).

For *Pinus greggii*, throughfall was 72.6% (6 years), 69.2% (16 years), and 59.8% (25 years), following similar logarithmic trends (Table 3). Canopy saturation occurred around 45 mm of rainfall. As with *P. pseudostrobus*, older *P. greggii* stands allowed less water to reach the ground (Figures 3–4).

Table 3: Log models for the estimation of throughfall as a function of incident precipitation.

	Stand age (years)	Model	R^2
P. pseudostrobus	6	*y = 12.686 ln (x) + 58.821*	0.66
	21	*y = 14.056 ln (x) + 46.972*	0.75
	25	*y = 15.906 ln (x) + 43.212*	0.61
	56	*y = 18.103 ln (x) + 29.42*	0.80
P.greggii	6	*y = 12.595 ln (x) + 54.803*	0.61
	16	*y = 14.876 ln (x) + 47.906*	0.78
	25	y = 18.47 ln (x) + 32.653	0.68

x = incident precipitation (mm); y = estimated throughfall (%)



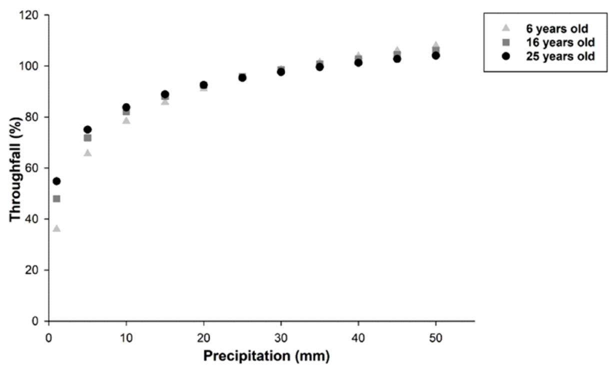


Figure 3: Throughfall as a function of incident precipitation for *P. pseudostrobus*; right: *P. greggii*.

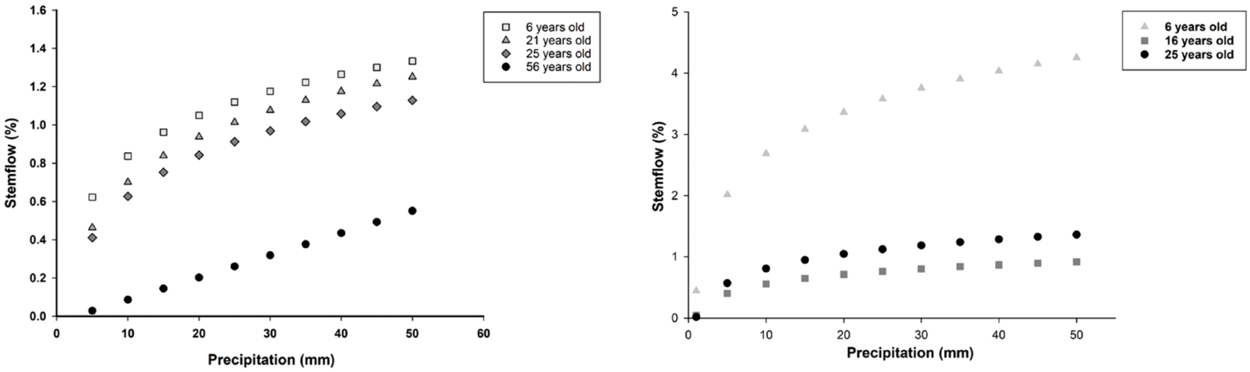


Figure 4: Estimated stemflow as a function of incident precipitation by stand age for *P. pseudostrobus* (left) and *P. greggi* (right).

The results of the analysis of variance indicate highly significant differences between throughfall and stand age ($p < 0.01$) for *P. pseudostrobus* (Table 4). For *P. greggii*, we found no significant differences ($p>0.05$); however, between direct rainfall and months ($p<0.01$), and in the interaction between age and month, there were no significant differences ($p>0.05$) (Table 4).

Table 4: Analysis of variance of the throughfall as a function of incident precipitation.

Species	Source of variation	Degrees of freedom	Sum of squares	Mean squares	F-value	p-value
	Age	3	7598	2532.54	4.375	<0.01**
P. pseudostrobus	Month	3	9134	3044.78	5.260	<0.005**
	Age*month	9	948	105.38	0.182	0.995
	Stand age	2	224.3	1124.62	1.8689	0.1661
P. greggii	Month	3	9358	3119.42	5.1978	0.028**
	Age*month	6	778	129.64	0.216	0.970

A multiple-comparison using the Bonferroni test showed that the throughfall values for the 6-year-old reforestation were 24 units higher than the average of the 56-year-old reforestation ($p<0.01$). On the other hand, the direct precipitation values presented by the 6- and 21-year-old reforestations and the 25-year-old plantation were similar ($p>0.05$) (Table 5).

Table 5: Bonferroni multiple tests for contrasting throughfall by age.

Contrast age (years)	Estimators	Standard error	Descriptive statistics	*p-value*
6 - 21	8.787	7.266	1.209	1
6 - 25	9.874	7.206	1.370	1
6 - 56	24.007	7.266	3.303	0.008
21 - 25	1.086	7.140	0.152	1
21 - 56	15.219	7.201	2.113	0.225
25 - 56	14.133	7.141	1.979	0.306

Stemflow

Stem flow data from the 6-, 21-, and 25-year-old *Pinus pseudostrobus* sites fit best to a logarithmic model, while the 56-year-old reforestation was better described by a linear model (Table 6). During the study period, stem flow accounted for 0.6% of incident precipitation in the 6-year-old stand, 0.4% in both the 21- and 25-year-old sites, and just 0.1% in the 56-year-old forest (Figure 4).

Similarly, total water reaching the ground via stem flow was highest in the 6-year-old reforestation (1.8%), followed by the 25-year-old plantation (0.5%) and the 16-year-old site (0.4%). Stemflow decreased with increasing stand age across both pine species (Table 6).

Table 6: Log-Models for stem flow estimation by stand age.

Species	Stand age (years)	Model	R^2
	6	$y = 0.3088 \ln(x) + 0.1254$	0.75
P. pseudostrobus	21	$y = 0.3423 \ln(x) - 0.0876$	0.70
	25	$y = 0.3119 \ln(x) - 0.0919$	0.63
	56	$y = 0.0116x - 0.0299$	0.84
	6	$y = 0.9729 \ln(x) + 0.4469$	0.76
P. greggii	16	$y = 0.2238 \ln(x) + 0.0428$	0.66
	25	$y = 0.3437 \ln(x) + 0.0168$	0.63

The 6-year-old reforestation exhibited the highest stemflow, with the suppressed stratum capturing 1.56%, followed by the co-dominant (0.77%) and dominant (0.41%) strata. A similar pattern was observed in the 25-year-old plantation, where the suppressed, co-dominant, and dominant strata accounted for 0.91%, 0.59%, and 0.18%, respectively. In contrast, the 21-year-old reforestation showed greater stemflow in the dominant stratum (0.76%), followed by co-dominant (0.36%) and suppressed (0.21%) strata. The 56-year-old site had the lowest values overall, with suppressed and co-dominant strata each at 0.07% and the dominant stratum at 0.04%. ANOVA results indicated significant differences in stemflow by age ($p < 0.001$), tree stratum ($p < 0.001$), and their interaction ($p < 0.001$) (Table 7)

Table 7: Analysis of variance of stemflow as a function of the strata.

Species	Source of variation	Degrees of freedom	Sum of squares	Mean squares	F-value	*p-value*
P. pseudostrobus	Stand age	3	59.56	19.852	27.454	<0.001***
	Strata	2	22.67	11.336	15.677	<0.001***
	Age/strata	6	36.03	6.005	8.304	<0.001***
P. greggii	Stand age	2	484	241	45.672	<0.001***
	Strata	2	71.52	35.761	6.749	0.001**
	Age/strata	4	111.2	27.8	5.246	<0.001***

Multiple comparisons using the Bonferroni test showed no significant differences in stemflow among dominant trees across all sites, including the 6-, 21-, and 56-year-old reforestations and the 25-year-old plantation ($p > 0.05$). In contrast, co-dominant trees in the 6- and 21-year-old reforestations exhibited stemflow values 0.72 units higher than those in the 56-year-old reforestation ($p < 0.001$), while co-dominant trees in the 25-year-old plantation showed values 0.52 units higher than the 56-year-old site ($p < 0.05$). However, no significant differences were observed among the co-dominant trees of the 6-, 21-, and 25-year-old sites ($p > 0.05$), nor between the 21- and 25-year-old reforestations ($p > 0.05$).

For the suppressed stratum, the 6-year-old reforestation had significantly higher stemflow than all other sites: 1.34 units higher than the 21-year-old reforestation, 0.71 units higher than the 25-year-old plantation, and 1.54 units higher than the 56-year-old site (all $p < 0.0001$). Suppressed trees in the 21-year-old reforestation had stemflow values 0.63 units lower than those in the 25-year-old plantation ($p < 0.001$), while the 25-year-old plantation's suppressed trees had values 0.83 units higher than those in the 56-year-old reforestation ($p < 0.0001$). No significant difference was found between the suppressed trees in the 21- and 56-year-old reforestations ($p > 0.05$) (Table 8)

Table 8: Bonferroni test for assessing stem flow by stratum and stand age.

Stratum	Contraste (stand ages)	Estimators	Standard error	Descriptive statistics	*p-value*
		P. pseudostrobus			
D	6 – 21	0.061086	0.1700	0.359	1
D	6 – 25	0.25371	0.168425	1.506	1
D	6 – 56	0.389839	0.170068	2.292	0.400
D	21 – 25	0.192623	0.168425	1.143	1
D	21 – 56	0.328753	0.170068	1.933	0.966
D	25 – 56	0.13613	0.168425	0.808	1
C	6 – 21	0.000895	0.170068	0.005	1
C	6 – 25	0.203086	0.168425	1.205	1
C	6 – 56	0.725334	0.170068	4.264	0.000419
C	21 – 25	0.202191	0.168425	1.200	1
C	21 – 56	0.72444	0.170068	4.259	0.000428
C	25 - 56	0.522248	0.168425	3.100	0.036388
S	6 - 21	1.346251	0.170068	7.915	<0.001**
S	6 - 25	0.710992	0.168425	4.221	<0.001**
S	6 - 56	1.546332	0.170068	9.092	<0.001**
S	21 - 25	-0.63526	0.168425	-3.77	0.00321
S	21 - 56	0.20008	0.170068	1.176	1
S	25 - 56	0.835339	0.168425	4.959	<0.001**
		P. greggii			
C	6 - 16	1.909		4.187	0.0003
C	6 - 25	1.706		3.742	0.0019
C	16 - 25	-0.203		-0.441	1.0000
D	6 - 16	1.063		2.331	0.1816
D	6 - 25	1.219		2.674	0.0699
D	16 - 25	0.156		0.340	1.0000
S	6 - 16	3.798		8.331	< 0.0001***
S	6 - 25	3.301		7.240	< 0.0001***
S	16 - 25	-0.497		-1.080	1.0000

D is dominant; C is codominant, and S is suppressed

Interception

Interception rates for *P. pseudostrobus* were 21.3%, 31.1%, 31.6%, and 46.3% for the 6-, 21-, 25-, and 56-year-old stands, respectively. These rates were modelled logarithmically to illustrate interception trends relative to incident precipitation for each forest condition. For *P. greggii*, interception varied with tree age: the 6-year-old reforestation intercepted 25.5% of rainfall, the 16-year-old reforestation intercepted 30.4% on average, and the 25-year-old plantation intercepted 39.7% of rainfall during the study period (Table 9 and Figure 5).

The analysis of variance indicates significant differences between intercept and tree age ($p < 0.01$) for *P. pseudostrobus*. On the other hand, the results of the analysis of variance (ANOVA) for *P. greggii* indicate no significant differences in interception mean values across plantation ages ($p > 0.05$). However, between interception values and months, there were significant statistical differences ($p<0.001$) and between age and month interaction, there were no significant statistical differences ($p>0.05$) (Table 10).

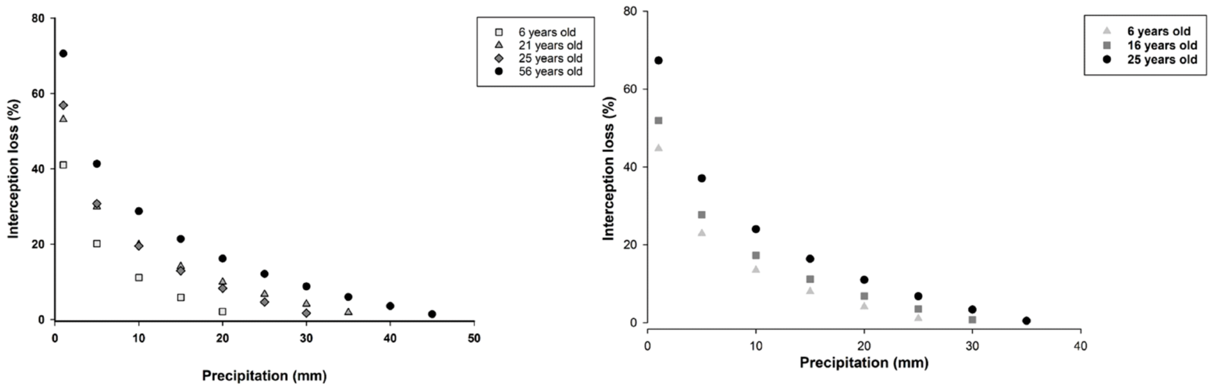


Figure 5: Estimated interception loss as a function of incident precipitation by stand age: *P. pseudostrobus* (left) and *P. greggii* (right).

Table 9: Log-Models for interception loss estimation by stand age.

	Stand age (years)	Model	R^2
P. pseudostrobus	6	$y = -12.99 \ln(x) + 41.054$	0.68
	21	$y = -14.4 \ln(x) + 53.116$	0.76
	25	$y = -16.22 \ln(x) + 56.88$	0.62
	56	$y = -18.17 \ln(x) + 70.604$	0.80
P. greggii	6	$y = -13.57 \ln(x) + 44.75$	0.64
	16	$y = -15.05 \ln(x) + 51.941$	0.78
	25	$y = -18.81 \ln(x) + 67.33$	0.68

where x is precipitation in mm; y is the interception expressed in percentage.

The Bonferroni multiple comparison test indicated that the interception values of the 6-year-old reforestation were 24.94 units lower than those of the 56-year-old reforestation ($p<0.01$). However, there were no significant differences among the 6-year-old reforestation, the 21-year-old reforestation, and the 25-year-old plantation ($p > 0.05$). Additionally, the average interception values for the 21-year-old reforestation did not differ significantly from those of the 25-year-old plantation and the 56-year-old reforestation ($p>0.05$). Finally, the 25-year-old plantation's interception values did not differ significantly from those of the 56-year-old reforestation (Table 11).

Finally, linear correlation analysis showed no relationship between direct rainfall and interception with respect to the dasometric variables (Table 11).

On the other hand, strong negative correlations were observed between diameter at breast height (-0.80) and crown diameter (-0.89) and stem flow at age six years. At age 16, stem flow and dasometric variables were not correlated. Finally, at the age of 25, stem flow is only related to clear stem height (-0.77) (Table 12).

DISCUSSION

Species effects on rainfall partitioning

Rainfall redistribution differed between the two pine species, supporting our hypothesis that species-specific canopy architecture influences hydrological processes in semi-arid plantations. Across stand ages, *Pinus pseudostrobus* generally allowed a greater proportion of rainfall to reach the forest floor, whereas *P. greggii* exhibited higher interception losses. These differences are consistent with studies reporting that pine species vary considerably in canopy storage capacity and rainfall interception efficiency due to differences in crown architecture, needle arrangement, and foliage density (Demir *et al.*, 2024; Francis, Wuddivira e Farrick, 2022; Valente *et al.*, 2020). This concentrated moisture flux near the trunk generates significant lateral gradients in soil water content, often resulting in marked differences in infiltration rates compared to the open areas beneath the canopy edge (Şensoy *et al.*, 2026).

Table 10: Analysis of variance of interception loss as a function of the strata

Species	Source of variation	Degrees of freedom	Sum of squares	Mean squares	F-value	p-value
P. pseudostrobus	Stand age	3	7933	2644.27	4.4751	0.005**
	month	3	9416	3138.60	5.3117	0.002**
	age/month	9	951	105.64	0.1788	0.995
P. greggii	Stand age	2	2627	1313.6	2.0997	0.130
	month	3	9844	3281.3	5.245	0.002**
	age/month	6	787	131.1	0.2095	0.972

Table 11: Bonferroni test for assessment of interception loss by stand age of *Pinus pseudostrobus*.

Stand age	Estimators	Standard error	Descriptive statistics	p-value
6 – 21	-9.801	7.069	-1.386	1
6 – 25	-10.255	7.000	-1.464	0.877
6 – 56	-24.947	7.069	-3.529	0.004
21 – 25	-0.454	7.000	-0.064	1
21 – 56	-15.145	7.069	-2.142	0.208
25 – 56	-14.692	7.000	-2.098	0.230

The higher interception observed in *P. greggii* is likely associated with its denser canopy structure, which increases the surface area available for water storage and evaporation. Similar relationships between canopy density and interception have been reported in pine plantations and other forest ecosystems, where greater canopy complexity increases rainfall retention before water reaches the soil surface (Acharya *et al.*, 2020; Zhang *et al.*, 2022). In contrast, the more open canopy conditions observed in *P. pseudostrobus* likely facilitated greater throughfall, allowing a larger fraction of incident precipitation to reach the forest floor.

Influence of stand age and canopy development

Stand age exerted a strong influence on rainfall partitioning. Throughfall decreased and interception increased with plantation age in both species, supporting our expectation that canopy development modifies hydrological functioning. Older stands exhibited larger tree dimensions and crown development, which likely increased canopy storage capacity and prolonged water retention during rainfall events.

This pattern agrees with previous studies showing that interception generally increases as forests mature because larger crowns, greater leaf area, and more complex canopy structures provide additional surfaces for rainfall storage (Ma *et al.*, 2019; Eliades, Bruggeman e Djuma, 2022). The progressive decline in throughfall from the youngest to the oldest stands suggests that structural development can substantially alter water inputs to the soil in reforested semi-arid environments. Such changes may be particularly important in regions where water availability represents a major ecological constraint.

The logarithmic relationships observed between incident precipitation and both throughfall and interception indicate that canopy saturation becomes increasingly important as rainfall amount increases. Similar non-linear responses have been reported in interception studies where a greater proportion of small rainfall events is retained by the canopy, while larger storms exceed canopy storage capacity and generate proportionally greater throughfall (Fischer *et al.*, 2023; Lian *et al.*, 2022).

Stemflow responses and tree structural characteristics

Stemflow represented a relatively small component of the water balance in both species, accounting for less than 2% of incident precipitation. Nevertheless, stemflow exhibited clear differences among stand ages and canopy strata. Younger plantations generally produced higher stemflow than older stands, while suppressed trees often generated larger stemflow volumes than dominant individuals (Noren & Stan, 2026).

The low stemflow values observed are typical of coniferous species, whose crown architecture and branch arrangement tend to promote water retention and redistribution as throughfall rather than concentration along the stem (Attarod *et al.*, 2015; Xiao *et al.*, 2000). The higher stemflow recorded in younger stands may reflect smoother bark surfaces, smaller crown dimensions, and branch configurations that facilitate water channeling toward the trunk (Zhou *et al.*, 2025).

The negative correlations observed between stemflow and structural attributes such as diameter at breast height and crown diameter suggest that increasing tree size may reduce the efficiency of water concentration along stems. Similar relationships have been reported in studies showing that tree architecture strongly influences stemflow generation and rainfall redistribution pathways (Valente *et al.*, 2020; Xiao *et al.*, 2000).

Hydrological implications and study limitations

The observed differences among species and stand ages have important implications for reforestation planning in semi-arid regions. Species that promote greater throughfall may enhance soil moisture replenishment and potentially increase water availability for understory

Table 12: Correlation analyses between rainfall components and dasometric variables in *Pinus greggii*.

Dasometric variables	Rainfall	Throughfall	Interception	Stem flow		
				Six years	16 years	25 years
DBH (cm)	-0.0017	-0.1367	0.1866	-0.8066	0.0003	-0.5813
Total height (m)	-0.0146	-0.1564	0.2148	-0.3931	-0.3886	-0.6747
Crown diameter (m)	0.0239	-0.0568	0.0749	-0.8975	-0.4154	-0.5784
Crown height (m)	-0.0129	-0.1546	0.2122	-0.4122	-0.2135	-0.5780
Foliage transparency (%)	-0.0416	-0.0921	0.1299	-0.1645	-0.0193	0.0786

vegetation. Conversely, species with greater interception capacity may reduce net rainfall reaching the soil, particularly during small precipitation events that dominate many semi-arid climates (Francis, Wuddivira e Farrick, 2022; Ma *et al.*, 2019).

However, several limitations should be considered when interpreting these results. The study was based on existing plantations rather than a fully replicated experimental design, resulting in some confounding between stand age and site conditions. In addition, rainfall partitioning was evaluated during a single monitoring period, limiting assessment of interannual variability. Consequently, the findings should be interpreted as robust site-level patterns rather than universal responses of pine plantations. Future research should incorporate longer monitoring periods, replicated stands within age classes, and mixed-effects modelling approaches to improve inference and evaluate the consistency of these patterns under varying climatic conditions (Natalini *et al.*, 2024; Ordóñez *et al.*, 2024).

Despite these limitations, the study provides valuable evidence that species selection and stand development significantly influence rainfall redistribution in reforested semi-arid landscapes. Understanding these hydrological responses is essential for designing restoration strategies that balance forest establishment with the maintenance of water-related ecosystem services.

CONCLUSIONS

This study showed that pine species and stand age influenced rainfall redistribution in semi-arid plantations of the Mixteca Alta region. *Pinus pseudostrobus* allowed greater throughfall, whereas *P. greggii* showed higher interception, likely due to denser canopy structure. In both species, interception increased and throughfall decreased with stand age. Stemflow represented a small proportion of incident rainfall and generally declined in older stands.

These results suggest that species selection and canopy development should be considered when planning reforestation in water-limited regions. Pine species with more open canopies may favour water input to the forest floor, whereas denser canopies may reduce net rainfall reaching the soil, especially in semi-arid environments.

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DATA AVAILABILITY

The datasets analyzed during the current study are available from the corresponding author upon reasonable request.

AUTHORSHIP CONTRIBUTION

Project Idea: AHH; JFCB; FMA; NGA; BSR
Database: AHH; MERS; AGH; JFCB
Processing: AHH; JFCB; FMA; NGA; BSR
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Writing: AHH; MERS; AGH
Review: AHH; MERS; AGH; JFCB; FMA; NGA; BSR

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