RA'EGA
O ESPAÇO GEOGRÁFICO EM ANÁLISE
https://revistas.ufpr.br/raega

ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.60, n.1, p. 92 – 112, 8/2024
http://dx.doi.org/10.5380/raega.v60i0.96238

Rainfall interception in *Pinus taeda* L. plantation in southern Brazil

Interceptação da precipitação em plantações de *Pinus taeda* L. na região sul do Brasil

Daniel Ribeiro Lange*, Irani dos Santos**

* Departamento de Geografia, Universidade Federal do Paraná, daniellage@ufpr.br
** Departamento de Geografia, Universidade Federal do Paraná, irani@ufpr.br

http://dx.doi.org/10.5380/raega.v60i0.96238

Abstract

The Santa Catarina plateau has undergone significant changes in the landscape in recent decades after the introduction of pine plantations, potentially altering the hydrological balance – although there are few local studies on this subject. In this context, this research aimed to evaluate the effects of the development of *Pinus taeda* L. plantations (with ages of 5, 7 and 10 years) on the interception process through hydrological monitoring. To quantify the components of the interception process, this study measured the external rainfall, throughfall and stemflow in *Pinus taeda* L. plantations in the municipality of Rio Negrinho (SC). The interception components were monitored in 54 events between September 2017 and January 2019. In addition, dendrometric parameters – such as vegetation density, diameter at breast height (DBH), cover index (C) and leaf area index (LAI) – were measured as a way to characterize the representative vegetation in each site. During the study period, the average throughfall rates (Tf) were 74%, 58% and 65%, and the stemflow rates (Sf) were 6.8%, 9.7% and 12.7% for the ages of 5, 7, and 10 years, with densities of 1,333 (ha-^{1}), 1,100 (ha-^{1}) and 1,666 (ha-^{1}), respectively. These results indicate that, in homogenous stands of *Pinus taeda* L., the increase in age is not directly related to the reduction of the Tf rate. This presents a better relation to the spacing patterns of the forests and the consequent alteration of the environmental characteristics that determine its development.

Keywords:
Hydrological monitoring, Throughfall, Stemflow.

Resumo

O planalto catarinense sofreu significativas alterações da paisagem nas últimas décadas com a introdução de povoamentos arbóreos de *pinus*. No entanto, não existem muitos estudos locais sobre como estas alterações interferem nos componentes do ciclo hidrológico. Neste contexto, a presente pesquisa buscou avaliar os efeitos do desenvolvimento de povoamentos arbóreos de *Pinus taeda* L. sobre processo de interceptação por meio do monitoramento hidrológico. Para tanto este trabalho mediu a precipitação total, precipitação interna e o escoamento de tronco em povoamento de *Pinus taeda* L. com idades de cinco, sete e dez anos, no município de Rio Negrinho-SC. Os componentes da interceptação foram monitorados em 54 eventos entre setembro 2017 e janeiro 2019. Adicionalmente, foram mensurados parâmetros dendrométricos como, densidade da vegetação, diâmetro à altura do peito (DBH), índice de cobertura (C) e índice de área foliar (LAI) como forma de caracterizar a vegetação representativa em cada idade. Durante o período de estudo as taxas

RA'EGA
O ESPAÇO GEOGRÁFICO EM ANÁLISE
https://revistas.ufpr.br/raega
ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.60, n.1, p. 92 – 112, 8/2024
http://dx.doi.org/10.5380/raega.v60i0.96238

de precipitação interna (Tf) médias mensuradas foram de 74%, 58% e 65% e as taxas de escoamento de tronco (Sf) foram de 6,8%, 9,7% e 12,7% para as idades de 5, 7, 10 anos com densidades 1333 (ha^{-1}), 1100 (ha^{-1}) e 1666 (ha^{-1}) respectivamente. Estes resultados indicam que, em povoamentos homogêneos de *Pinus taeda* L., a idade explica parcialmente a dinâmica hidrológica do dossel, a qual responde também aos padrões de espaçamento dos povoamentos e consequente alteração das características ambientais que condicionam seu desenvolvimento.

Palavras-chave:
Monitoramento hidrológico, Precipitação interna, Escoamento de tronco.

I. Introduction

Rainfall interception is the first phase of the terrestrial part of the hydrological cycle and can be defined as the process of vegetation interfering with rainfall, causing its spatial and temporal redistribution (TUCCI; CLARKE, 1997; GIGLIO; KOBIYAMA, 2013). During interception, rainfall is divided into three portions: 1) some rainfall is intercepted and stored by the vegetation and later evaporates (interception loss); 2) some of it falls freely on the ground, without interference from the vegetation, or after being intercepted and dripping; and 3) a portion reaches the ground through the stems (LIMA, 1975). This process is conditioned by meteorological conditions (intensity of precipitation, total volume precipitated, wind, humidity, air temperature and solar radiation) and vegetation (density of cover, shape and position of leaves and branches) (TSIKO et al., 2012; SÁ et al., 2015).

Interception is recognized as a fundamental component of the forest's hydrological cycle and as a parameter when estimating the ecosystem's total evapotranspiration and water- balance development in the watershed. In general, interception losses can vary from 8% to 35% of gross precipitation, and 25% to 100% of evaporation from a forest (DAVID; GASH, 2009; GAVAZZI, et al., 2016), which indicates its considerable importance for the water balance. Furthermore, a large part of the efficiency of hydrological modeling depends on the values of water entering the basin, and the neglect or miscalculation in estimating interception losses introduces errors into rainfall-runoff modeling (SANTOS, 2009).

Most of the studies on interception in Brazil take place in tree stands (pine and eucalyptus) due to the homogeneity of these plantations and, therefore, the ease with which the characteristics of the vegetation can be parameterized. Giglio and Kobiyama (2013) carried out a review of interception studies in Brazilian forests and, according to the studies listed by the authors, the net precipitation values for *Pinus* plantations vary between 71.2% and 90.4%. The aforementioned study indicates that this variability seems to be associated with the age of the plantations, with a decrease in the percentage of throughfall according to the age of the stand.

ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.60, n.1, p. 92 – 112, 8/2024
http://dx.doi.org/10.5380/raega.v60i0.96238

According to Breuer et al. (2003), in addition to the age of the vegetation, other dendrometric parameters should be taken into account in interception studies, such as leaf area index (LAI), vegetation density and basal area. As data acquisition is costly in terms of time, effort and finances, researchers often use approximate parameter ranges instead of considering measured data sets.

According to Swank et al. (1972) individual interception studies should be analyzed taking into account the specificities of each location, including climatic conditions, and their results should be compared with otherregions with caution. However, when taken collectively, the data can support establishing general conclusions about the behavior of the process and the management of these systems.

The study area is located on the Santa Catarina plateau. This region was subject to logging between the end of the 19th century and the mid-1980s, during the so-called "timber cycle". This process was responsible for the significant alteration of almost all of its original forest cover. In the municipality of Rio Negrinho, as in much of the western region of Santa Catarina, forestry continues to play an important role in the economy, however it is no longer carried out in an extractive manner, but with tree stands generally planted with *Pinus taeda* L. (PINHEIRO; ROSA, 2010). These changes may be responsible for alterations in the water balance (RUTTER et al., 1971; GAVAZZI et al., 2016).

The present research surveyed and evaluated the data obtained by previous studies on precipitation interception in pine plantations, described the method for measurement, and evaluated the effects of homogeneous tree stands with *Pinus taeda* L. at ages of five, seven, and ten years, and different planting densities, on the precipitation-interception process by means of hydrological monitoring. The measurements include gross precipitation, throughfall and stemflow. The monitoring used automatic weighbridges and data-loggers, developed specifically for estimating these components, which took instantaneous measurements of throughfall and stemflow and made it possible to obtain a series of high temporal resolution data (ten-minute intervals). The components evaluated were monitored during precipitation events between September 2017 and January 2019. The experiments were conducted on sample plots located in the municipality of Rio Negrinho, SC.

II. Materials and Methods

Study site

The monitored plots are located in the municipality of Rio Negrinho-Santa Catarina, in the Sagui and Saci experimental watersheds, and are embedded in the Upper Rio Negro basin. The area has an average altitude of

RA'EGA
O ESPAÇO GEOGRÁFICO EM ANÁLISE
https://revistas.ufpr.br/raega
ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.60, n.1, p. 92 – 112, 8/2024
http://dx.doi.org/10.5380/raega.v60i0.96238

960 m and the predominant soils are of the Cambissolos type, originating from sedimentary rocks (claystones and siltstones) formed in a glacial and periglacial environment (SILVA; BORTOLUZZI, 1987). The native vegetation is characterized as a transition between the phytogeographic units of Mixed Ombrophilous Forest and Dense Ombrophilous Forest (KLEIN, 1978). According to Rio Negrinho City Hall (2017), the region's main economic activity is the reforestation of the *Pinus taeda* L. species.

According to Köppen, the climate is class Cfb, with an average annual temperature of between 15.5 °C and 17.0 °C. Humidity varies between 80% and 86%. The average rainfall in the study region is 1519 mm/year, obtained from data from a rain-gauge station located about three kilometers from the experiments, with data series between 1976 and 2019, summarized in figure 1. The average rainfall in the study region is 1519 mm/year. This value was obtained from a series of 41 years of data between 1976 and 2013 using data from the Corredeira rain gauge station (ANA) code (2649055), located about 10 km from the study area, and data between 2014 and 2019 from the feio weather station (LHG). The average historical monthly rainfall shows little seasonality, with monthly maximums being more than double the average observed for the period, and extreme events can occur at any time of the year. Historical daily maximums are around 100 mm in all months.

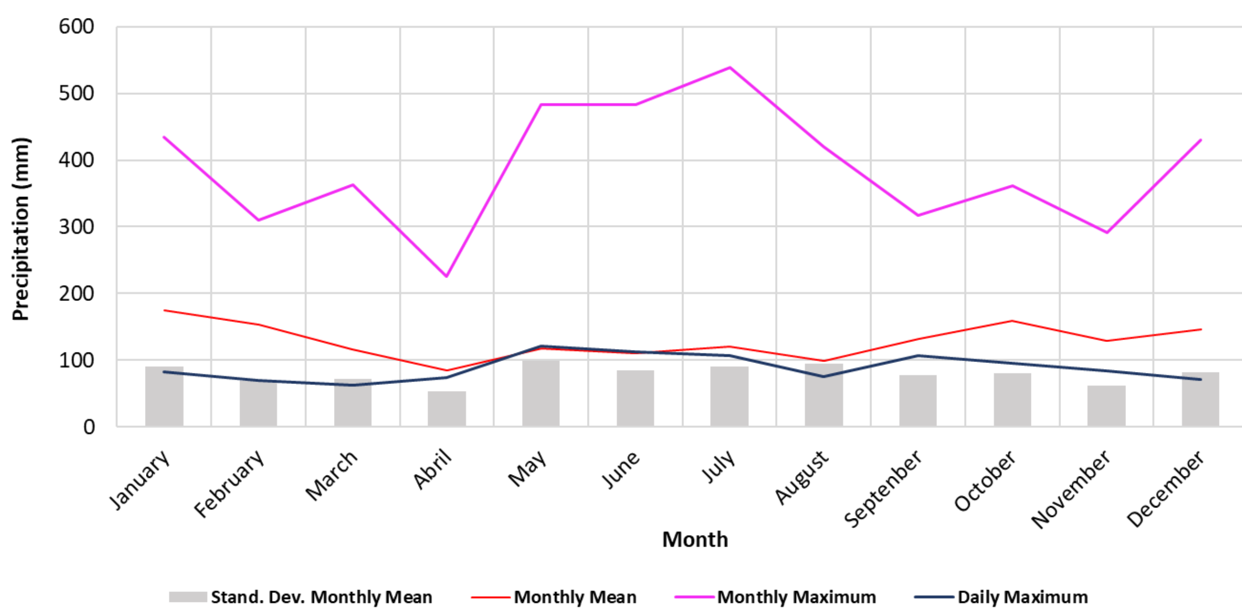


Figure 1 - Variation in monthly rainfall over a long period (1976-2019). Source: Corredeira rain gauge station (ANA - 2649055). Authors' production (2024).

The experimental basins of the Sagui and Saci rivers have had intensive hydrological monitoring since 2005, and the data obtained supported a thesis on hydrology (SANTOS, 2009). The experiments for this research

RA'EGA
O ESPAÇO GEOGRÁFICO EM ANÁLISE
https://revistas.ufpr.br/raega
ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.60, n.1, p. 92 – 112, 8/2024
http://dx.doi.org/10.5380/raega.v60i0.96238

were carried out in these basins, on plots called E1 (5 years), E2 (7 years) and E3 (10 years), as shown in Figures 2 and 3.

Relevant events for the study were those whose gross precipitation (*Pg*) was at least 5 mm. The definition of the temporal amplitude of each event was a minimum interval of six hours without precipitation (WISHMEIER; SMITH, 1958).

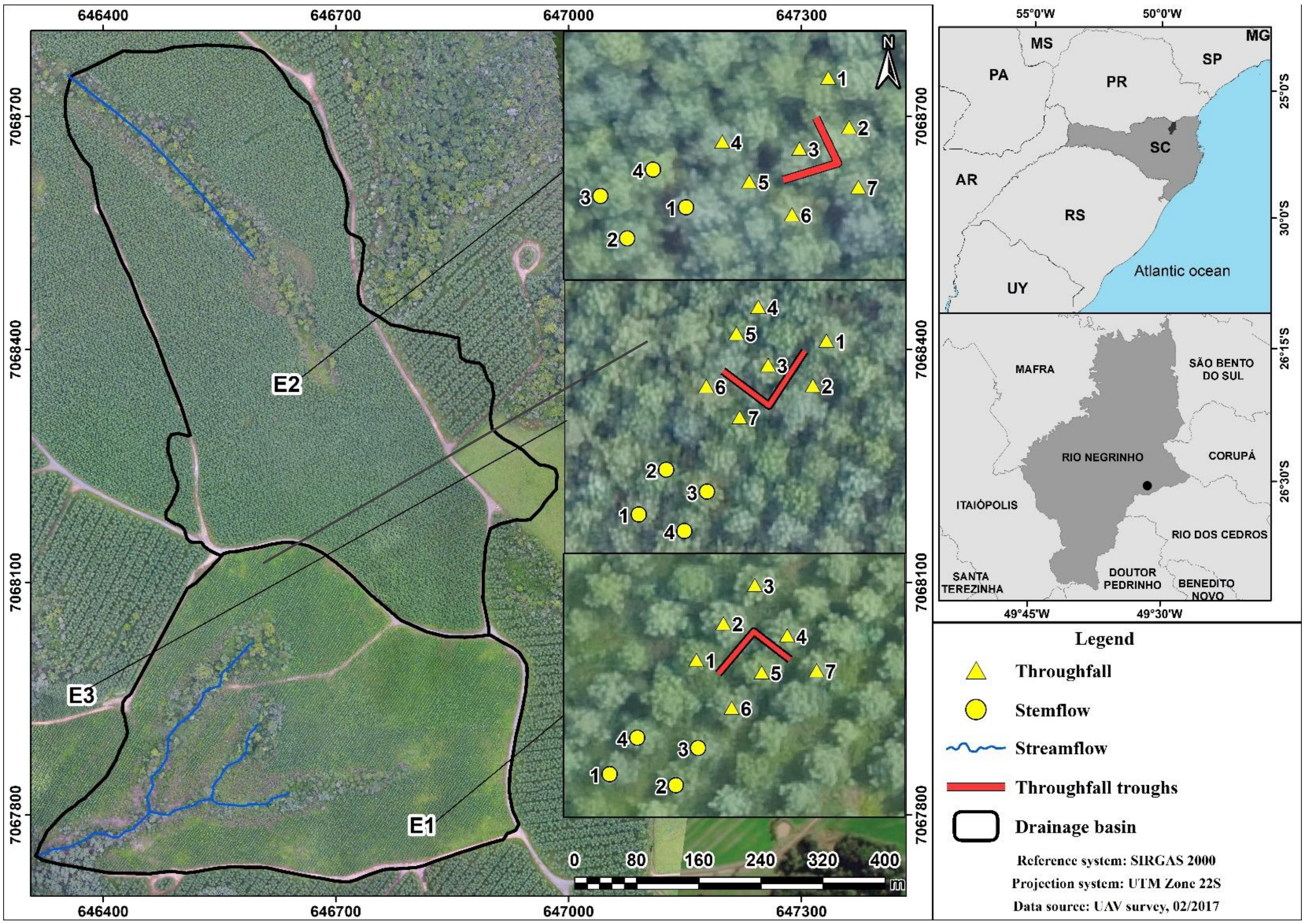


Figure 2 - Cartogram showing the location of the experiments. E1: 5-year-old plantation (Sací Basin). E2: 7-year-old plantation (Sagui Basin). E3: 10-year-old plantation. Authors' production (2024).

RA'EGA
O ESPAÇO GEOGRÁFICO EM ANÁLISE
https://revistas.ufpr.br/raega
ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.60, n.1, p. 92 – 112, 8/2024
http://dx.doi.org/10.5380/raega.v60i0.96238

Figure 3 - Images of the three experiments and their respective stemflow collection systems, throughfall collection troughs, and tipping bucket shelters. A) E1 (5-year-old plantation), B) E2 (7-year-old plantation) and C) E3 (10-year-old plantation). Authors' production (2024).

In each experiment, the sampled plot is based on a theoretical area of occupation, assuming a size of 6 m² for each plant at ages seven and ten, and 7.5 m² for those at age five, in the stemflow measurements. This theoretical area results from spacing the pine trees three meters apart and two meters apart in the same row for the seven- and tem-year-old pines, and two and a half meters by three meters (respectively) for the five-year-old pines. Although the seven-year-old stand underwent thinning three years after planting, in which approximately one third of its individuals were removed (Table 3), the specific location of the experiment was not directly affected, with the theoretical area of 6 m² being maintained for stemflow.

According to Santos (2009), the best way to obtain the interception rates of a forest is to carry out a canopy water balance. This can be expressed by the following equation:

$$I = Pg - Tf - Sf \quad (1)$$

Where I is the interception loss, Pg is the gross precipitation (mm), Tf is throughfall (mm), and Sf is the stemflow (mm); therefore, the sum of Tf and Sf is considered the portion that actually reaches the ground, called net precipitation.

RA'EGA
O ESPAÇO GEOGRÁFICO EM ANÁLISE
https://revistas.ufpr.br/raega
ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.60, n.1, p. 92 – 112, 8/2024
http://dx.doi.org/10.5380/raega.v60i0.96238

The planting density, diameter at breast height (DBH), basal area (G), cover index (C) and leaf area index (LAI) of the trees near the experiments were estimated as a way of characterizing the representative vegetation at each site. A cell phone application called VitiCanopy was used to estimate C and LAI. This application uses the camera and GPS of smartphones and tablets to automatically implement image analysis algorithms. Similar to the hemispherical image method, the app receives photos taken from above the canopy and calculates canopy architecture parameters. The results obtained by the app correlate well with traditional methods for estimating LAI, with the R^2 for MatLab being 0.97 and the R^2 for Licor-2000 being 0.95 (DE BEI et al., 2016).

As the pine plantations have a certain homogeneity in the size and distribution of the individuals, measurements were taken on the six trees sampled for throughfall and four for stemflow.

The gross precipitation (*Pg*) used for the interception balance was measured at ten-minute intervals at the rain gauge station located about 1 km from the plots. The equipment is adjusted for the correction of high-intensity events (WATERLOG H-500 logger and H-340 rain bucket).

The components of the interception process evaluated were monitored in precipitation events between September 2017 and January 2019. For the five-year experiment, 52 events were validated with a gross precipitation of 1072 mm; for the seven-year experiment, there were 50 events with a total Pg of 1156 mm; and for the ten-year experiment there were 41 events with a total Pg of 989 mm.

The consistency of the events took into account physical flaws in the experiments, such as troughs for measuring throughfall and tipping bucket gauges, as well as malfunctions in the pulse sensors responsible for counting the number of tilts. The criteria for selecting valid events accounted for those that did not have negative interception rates (throughfall greater than gross precipitation). This problem has been reported by Horton (1919), Valente et al. (1997), and Gavazzi et al. (2016) and according to the authors is probably caused by equipment errors, water input from other sources not measured by conventional rain gauges (fog and wind-driven precipitation), canopy characteristics or variability in the amount of precipitation around the area.

Equipment development and calibration

The high cost or lack of equipment for measuring hydrological parameters makes it necessary to create alternative instrumentation. One of the research stages was the development of customized equipment to monitor interception, like troughs for measuring throughfall (Figure 4-A1 and A2), tipping bucket gauges (Figure 4-A2 and B), and a system of collector rings for measuring stemflow and shelters for the rain gauges (Figure 4-C). The throughfall troughs were coupled to data-loggers for automatic data acquisition and recording (Figure 4-D). After testing and calibration, the equipment was qualified for installation in the field.

O ESPAÇO GEOGRÁFICO EM ANÁLISE
https://revistas.ufpr.br/raega
ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.60, n.1, p. 92 – 112, 8/2024
http://dx.doi.org/10.5380/raega.v60i0.96238

The system for measuring throughfall (Tf) consisted of two collection troughs with a total catchment area of 0.6 m². The collector troughs were installed at a height of one meter above the ground. The volumes of water captured by the troughs were measured in tipping-bucket gauges with a resolution of 0.1 mm (BRAGA et al., 2009).

The tipping-bucket gauges were calibrated at the Water, Soil and Sediment Analysis Laboratory (LAASS) of the Federal University of Paraná. Initially, the weighbridge rain gauges were adjusted to calculate an exact volume of 60 ml. A test was then carried out in which each weighbridge was subjected to ten different intensities (which simulated rainfall) in order to establish the error (Figure 5). The volumes of the ten tippers for each simulated situation were collected and weighed on a precision scale. An example of the test result for a tipping bucket is shown in Table 2. Each point on the graph represents the average result of collecting ten tippers at a given rainfall intensity.

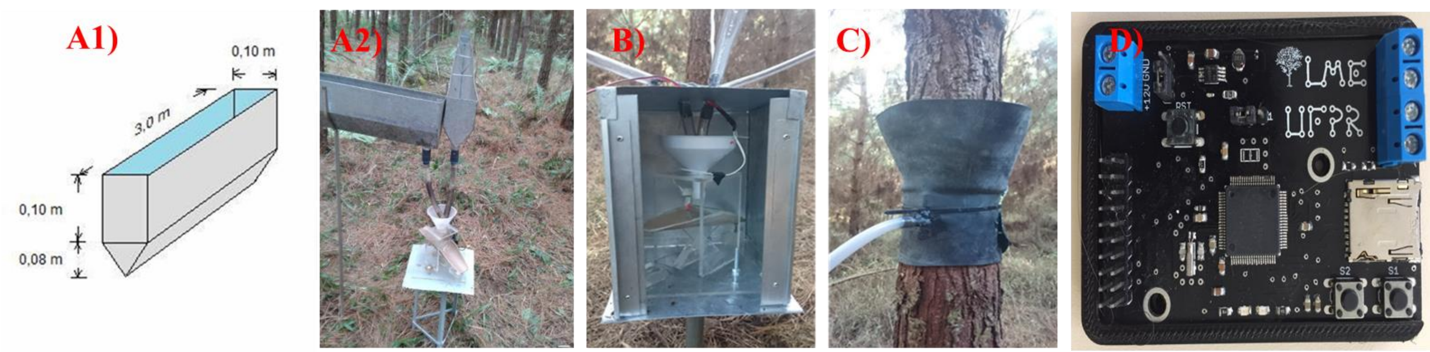


Figure 4 - Apparatus used for automatic monitoring of interception components (throughfall and stemflow). A1) dimensions of the throughfall troughs for collecting throughfall, A2) gutters and weighbridge, B) tipping bucket and shelter, C) stemflow collection ring, D) data-logger. Authors' production (2024).

The parameters of the linear regressions are shown in Table 2. The linear coefficient showed little variation (1.7%) and the angular coefficient showed the greatest variation (11.6%), justifying the adoption of individual correction equations. The coefficient of determination shows that the linear correlation is very good for all the scales, allowing measurement errors to be corrected a posteriori.

RA'EGA O ESPAÇO GEOGRÁFICO EM ANÁLISE
https://revistas.ufpr.br/raega
ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.60, n.1, p. 92 – 112, 8/2024
http://dx.doi.org/10.5380/raega.v60i0.96238

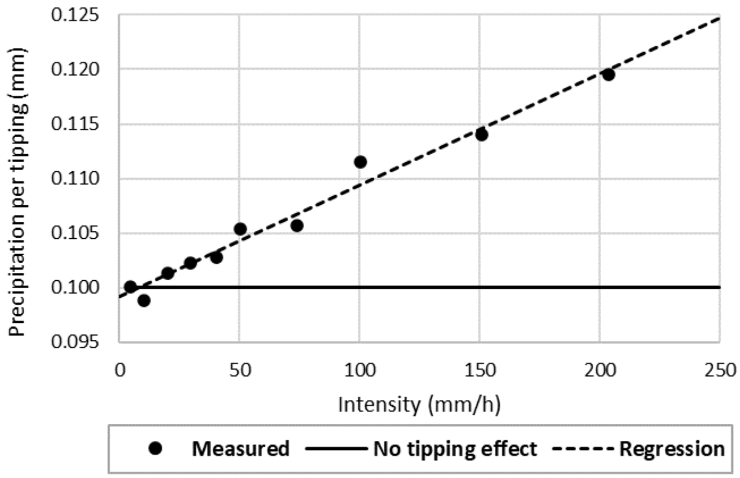


Figure 5 - Example graph of the test to establish the correction value for tipping-bucket rain gauges. Authors' production (2024).

Table 2 - Parameters of the linear regression for calibrating the scales used to monitor throughfall (*Tf*) and stemflow (*Sf*).

Tipping bucket	Angular coefficient	Linear coefficient	R^2
1	0.000100650	0.103	0.94
2	0.000095808	0.107	0.95
3	0.000101310	0.108	0.95
4	0.000091843	0,.105	0.96
5	0.000107759	0.105	0.97
6	0.000075810	0.104	0.98
Mean	**0.000095530**	**0.105**	**0.96**
Stand. dev.	**0.000011061**	**0.001**	**0.01**
C.v. %	**11.578**	**1.701**	**1.379**

Stand. dev. = Standard Deviation, C.v.= coefficient of variation. Authors' production (2024).

III. Results and Discussion

For the purposes of generalization, it can be assumed that pine trees of different species have similar physical characteristics and, therefore, the values can be used for comparison (Table 1). This idea can be seen in the work of Lima and Niconielo (1983) who measured interception in two species of pine of the same age and obtained little variation between them.

Table 1- Studies measuring interception in pine stands

Vegetation type	*D* (ha $^{-1}$)	*G* (m² h^{-1})	Age (years)	*I* (%)	*Tf* (%)	*Sf* (%)	Studies	Local
Pinus taeda L.	654	22.5	-	15.1	82.5	2,4	Lawson (1967)	
Pinus taeda L.	1760	23.6	10	4.6	73.2	22,2	Hoover (1953)	
Pinus taeda L.	904	23.1	18	-	81	-	Gavazzi et al. (2016)	USA
Pinus taeda L.	-	-	9. 5	-	-	9	Swank et al. (1972)	
Pinus taeda L.	2077	29.6	11	-	82	-	Stogsdill et al. (1989)	
Pinus sylvestris L.	800	-	44	32	66.4	1.6	Gash; Morton (1978)	Europe

ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.60, n.1, p. 92 – 112, 8/2024
http://dx.doi.org/10.5380/raega.v60i0.96238

Pinus sylvestris L.	-	-	-	24,7	73.9	1.3	Llorens et al. (1997)	
Pinus halepensis L.	-	-	32	30	66,7	3,3	Rodriguez et al. (2016)	
Pinus pinea L.	521	38,05	62	40	58,9	1,1	Mazza et al. (2011)	
Pinus taeda L.	1660	60,04	30	21,4	71,2	7,4	Santos (2009)	Brazil
Pinus oocarpa	-	-	13	-	88	-	Lima; Nicolielo (1983)	
Pinus caribaea	-	-	13	-	88.3	-		
Pinus caribaea	1666	13.5	6	6.6	90.4	3	Lima (1976)	
Pinus elliottii	1994	63.2	-	-	73.1	-	Gênova et al. (2007)	
Pinus elliottii	2100	-	8	-	73.4	-	Calux; Thomaz (2012)	
Pinus sp.	-	-	12	-	-	1.2	Shinzato et al. (2011)	
Pinus sylvestris	-	-	-	22.1	71.4	5.7	Liu et al. (2015)	Asia
Pinus elliottii x caribae	840	23.6	12	21.1	77.9	1	Fan et al. (2015)	Oceania

D = Density, *G* = Basal Area, *I* = Interception losses, *Tf* = throughfall, *Sf* = stemflow. Authors' production (2024).

Among the studies listed in Table 1, it can be seen that the experimental definition does not always simultaneously include the variables throughfall (*Tf*) and stemflow (*Sf*), which are necessary for determining interception. Throughfall stands out as the variable generally measured experimentally, and the values obtained show a direct relationship with the age of the vegetation, resulting in an $R^2 = 0.654$ for the studies shown in Table 1. In other words, there is a relative tendency between the two variables for age to be an explanatory parameter of the throughfall rate. However, the relatively low value of the coefficient of determination indicates considerable variation between the values described in the studies. This can be attributed to non-standardized measurement methods, different spacing patterns between trees, varying ages or different rainfall regimes.

It can also be seen from Table 1 that studies on stemflow rates are scarce and heterogeneous, and therefore insufficient for generalizations. This reduces the possibility of making inferences about the relationships between the components of the process. This means that, in some cases, interception rates are overestimated. Hoover (1953) highlighted the fact that stemflow in *Pinus taeda* L. has higher rates than those reported in the literature for various other pine species. This is due to the shape of the canopy and the pointed branches formed by a cluster of long needles. This arrangement forms an efficient system for carrying water to the stem. This redistribution of rainwater helps to increase soil moisture near the roots. Therefore, it is important to measure this component for interception studies for this species.

Santos (2009) carried out a study in the experimental basin of the Saci River, the same basin as one of the experiments in this study, with pine trees at the age of thirty years, and the new plantation is currently five years old. High values for stemflow were measured (7.4%) compared to the average (4.9%) obtained from Table 1.

ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.60, n.1, p. 92 – 112, 8/2024
http://dx.doi.org/10.5380/raega.v60i0.96238

The linear regression between basal area and throughfall, obtained from Table 1, showed a value of R^2 = 0.325. However, the basal area variable is closely related to planting density, and consequently the purpose of production and planting techniques, which explains the low value of the coefficient of determination and indicates caution when using basal area to infer the behavior of interception components (SANQUETTA et al., 2003; LIMA et al., 2013). On the other hand, the value obtained by linear regression between basal area and interception, based on data from studies on pine trees (n = 7) described in the review by Breuer et al. (2003), shows a good correlation (R^2 = 0.7898). In the same study, the correlation between interception and vegetation age resulted in R^2 = 0.1867.

To characterize the vegetation in the areas of the three experiments, with different planting ages (five, seven, and ten years), dendrometric variables of interest, commonly used in similar studies, were determined (n = 10 for each experimental plot) (Table 3).

Table 3 - Dendrometric variables for the different ages of the *Pinus taeda* L. stands.

	Stand age (years)		
	5	**7**	**10**
	Spacing (m)		
	2.5x3	2x3	2x3
	N.⁰ of trees (ha^{-1})		
	1333	1666/1100*	1666
	Height - *H* (m)		
Mean	9.625	13.625	16.775
Stand. dev.	0.479	0.359	0.340
C.v.	5%	3%	2%
	Diameter at breast height - *DBH* (cm)		
Mean	16.658	20.987	19.618
Stand. dev.	1.714	2.733	1.986
C.v.	10%	13%	10%
	Basal area- *G* (m^2 h^{-1})		
	29.36	39.05	50.88
	Coverage factor - *C* (%)		
Mean	77.900	79.600	80.900
Stand. dev.	5.152	2.591	2.644
C.v.	7%	3%	3%
	Leaf area index - *LAI* (m^2 m^{-2})		
Mean	1.909	2.185	2.35
Stand. dev.	0.166	0.161	0.125
C.v.	9%	7%	6%

*The stand was thinned three years after planting, reducing the number by approximately 35%, from 1666 to 1100 individuals per hectare. Authors' production (2024).

As expected, the coverage factor - *C* between the five-, seven- and ten-year-old plantations increased as they developed. However, the values varied little from one another (2.3% between the five- and seven-year-

ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.60, n.1, p. 92 – 112, 8/2024
http://dx.doi.org/10.5380/raega.v60i0.96238

old pines and 1.6% between the seven and ten-year-old pines). On the other hand, the *DBH* values for the ten-year-old plantation were lower than those for the seven-year-old plantation, probably due to the smaller spacing in the plantation and, therefore, a change in the environmental conditions necessary for its development.

Lima et al. (2013) carried out a study based on measuring *DBH* in nine spacing treatments in *Pinus taeda* L. stands (between 1.0 m² and 16.0 m² per tree). Their results indicate that spacing significantly influences growth in volume per hectare. At high densities (spacing between 1 and 5 m²), more crooked and smaller stems and smaller diameters were produced than at lower densities (> 5 m²). Therefore, wider spacing promotes larger diameters with lower volumetric production, while smaller spacing promotes taller trees, smaller diameters and higher volumetric production per unit area. This corroborates the data measured in this study: the ten-year-old stand (1666 individuals per hectare) had a lower *DBH* than the seven-year-old stand (1100 individuals per hectare) (Table 3 and Figure 19).

Gavazzi et al. (2016) showed changes in interception rates, *LAI* and *G* during continuous monitoring over ten years. Shortly after the removal of 36% with selective felling/thinning, the maximum interception rate values decreased by 5% and the reduction in *G* was 44%, indicating how management and planting techniques affect dendrometric parameters and the interception process. *Pinus* stands therefore take on different patterns in their densities, requiring caution when using comparisons and indirect and generalized data presented in studies. The choice of pine spacing can vary according to the interest in growth and development of dendrometric variables (production objective); tolerance and adaptability of the species to the planting area; market conditions; harvesting methods; availability of machinery; among others (LIMA et al., 2013).

Gavazzi et al. (2016) highlight the role that plantation managers play in managing water availability through vegetation management and control. In this specific case, reducing plant density and consequently the leaf area index also reduces the storage capacity of the canopy, resulting in lower interception rates and greater water availability in the basin.

Figure 6 shows the relationship between gross precipitation (*Pg*) and throughfall (*Tf).* As the trend line for the three ages shows, the correlation is high, which confirms that the rates obtained by linear regression are consistent with the measurements. For all the events analyzed,throughfall resulted in an average of 74%, 58% and 65% of gross precipitation, for E1, E2 and E3, respectively.

RA'EGA O ESPAÇO GEOGRÁFICO EM ANÁLISE
https://revistas.ufpr.br/raega
ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.60, n.1, p. 92 – 112, 8/2024
http://dx.doi.org/10.5380/raega.v60i0.96238

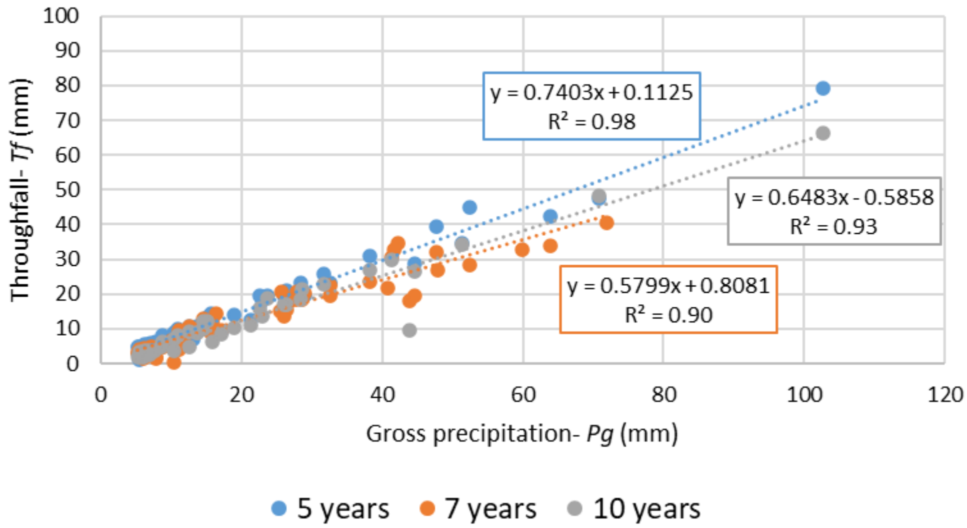


Figure 6 - Relationship between gross precipitation (*Pg*) and throughfall (*Tf*). Authors' production (2024).

Considering the data from the three experiments together, *DBH* was the dendrometric parameter that was most relevant to explaining throughfall rates (R^2 = 0.98). The correlation was lower for throughfall and the parameters coverage factor - *C* (R^2 = 0.39), leaf area index - *LAI* (R^2 = 0.09) and pine age (R^2 = 0.21). The *DBH* variable as an explanatory factor for interception rates was also described in the articles by Sanguetta et al. (2003), Lima et al. (2013) and Gavazzi et al. (2016).

In commercial *Pinus taeda* L. stands, development seems to be more related to environmental conditions than to the age of the plantations. Therefore, information related solely to planting age is insufficient as a conditioning factor for the interception process.

Figure 7 shows the relationship between gross precipitation (*Pg*) and stemflow (*Sf*). It can be seen that stemflow shows greater variability than throughfall, when compared relatively to gross precipitation. These results are in line with the literature, which reports that stemflow is a highly variable component not only from event to event (LEVIA JR; FROST, 2003), but also from tree to tree, possibly due to the different degrees of stem roughness, canopy arrangement and other morphological changes resulting from plant development (STOGSDILL et al., 1989; FAN et al., 2014). Intraspecific variations can also occur in the generation of stemflow, such as the reduction in volumes as age increases (LEVIA; FROST, 2003).

For all the events analyzed, stemflow resulted in an average of 6.8%, 9.7% and 12.7% of gross precipitation, for E1, E2 and E3, respectively.

RA'EGA
O ESPAÇO GEOGRÁFICO EM ANÁLISE
https://revistas.ufpr.br/raega
ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.60, n.1, p. 92 – 112, 8/2024
http://dx.doi.org/10.5380/raega.v60i0.96238

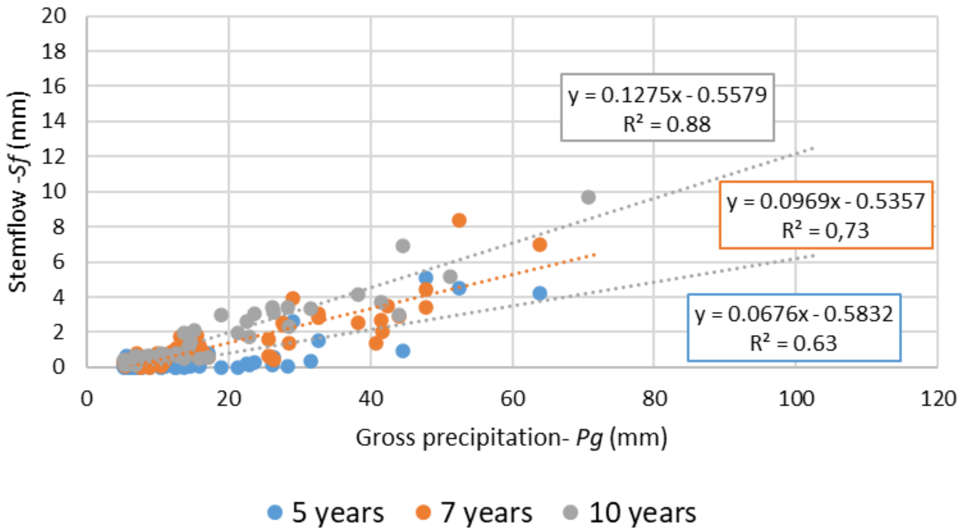
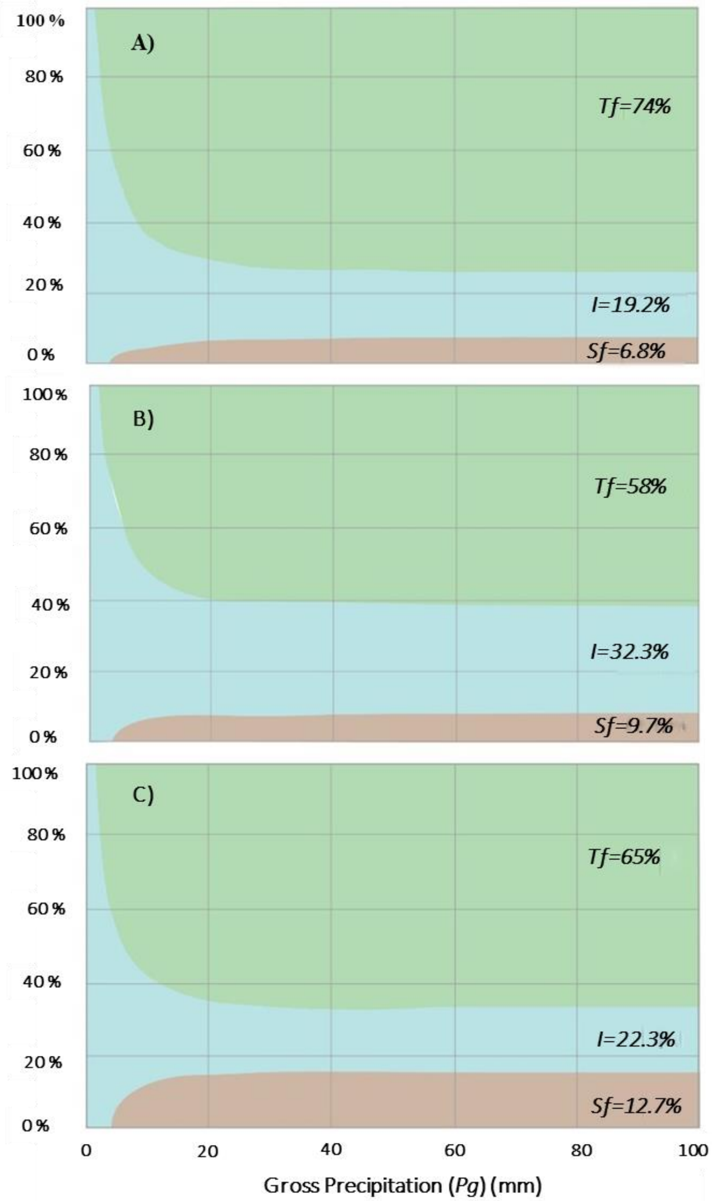


Figure 7 - Relationship between gross precipitation (*Pg*) and stemflow (*Sf*). Authors' production (2024).

There is variability in the interception components between the monitored events, which is more pronounced for the results of stemflow in relation to gross precipitation, with coefficients of determination of 0.63, 0.73 and 0.88. For throughfall, the variability is lower in relation to gross precipitation, with coefficients of determination of 0.90, 0.93 and 0.98, considering the set of events and the three sites monitored.

Based on the results obtained, Figure 8 shows the conceptual behavior of the components of the interception process in relation to gross precipitation for the three experiments evaluated. The lines drawn on the diagram were obtained from the general trend of the points sampled in each of the experiments. Analysis of the events based on temporal discretization (10-minute intervals) indicated precipitation values similar to those indicated in the literature for the complete saturation of the canopy and consequent start of the throughfall component (approximately 2.7 mm) as well as for the start of stemflow (approximately 5 mm).

RA'EGA
O ESPAÇO GEOGRÁFICO EM ANÁLISE
https://revistas.ufpr.br/raega
ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.60, n.1, p. 92 – 112, 8/2024
http://dx.doi.org/10.5380/raega.v60i0.96238



A) E1, B) E2 and C) E3. *Tf* - throughfall, *Sf* - stemflow and *I* - interception
Figure 8 - Conceptual behavior of the interception process components in the three evaluated experiments: A) E1 - 5 years, B) E2 - 7 years, C) E3 - 10 years. Authors' production (2024).

As can be seen in figure 8, there is a tendency for the relative retention capacity of precipitation by the canopy to decrease as the volume of precipitation increases (HORTON, 1919; HOOVER, 1953; DAVID; GASH, 2009; GAVAZZI et al., 2016). On the other hand, the behavior of throughfall and stemflow manifests itself inversely, with the increase in these values throughout the precipitation event; for each stage of plantation development, the proportion of the components of the process changes, which indicates greater or lesser ease of precipitation passing through the canopy.

RA'EGA O ESPAÇO GEOGRÁFICO EM ANÁLISE
https://revistas.ufpr.br/raega
ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.60, n.1, p. 92 – 112, 8/2024
http://dx.doi.org/10.5380/raega.v60i0.96238

When comparing the data from the experiments with the average observed in the literature (Table 4), the throughfall rates measured in this study were higher than in previous studies. When compared to the research carried out in the same study area, but occupied by 30-year-old pine stands, carried out by Santos (2009), the throughfall rates were close for the five and ten-year-old stands. According to the studies listed by Giglio and Kobiyama (2013), throughfall values for pine plantations can vary between 71.2% and 90.4% of gross. This may be due to the different precipitation regimes, planting conditions, management and environmental characteristics of each study area.

Table 4 - Summary of intercept component values obtained from the literature (described in Table 1).

	Tf (%)	Sf (%)	I (%)
Mean	76.8	4.9	20.6
Stand. dev.	8.7	6.0	11.0
C.v. (%)	11	123	53

Tf = throughfall, Sf = stemflow, I = Interception, Stand. dev. = standard deviation and C.v.= Coefficient of variation. Authors' production (2024).

Figure 9 shows the relationship between throughfall and vegetation age. There is a considerable dispersion in the throughfall values for the data collected from the literature (R^2 = 0.654). The data obtained in this study showed lower throughfall than the values obtained in the literature. However, the sampled values vary little in relation to age when compared to the general data.

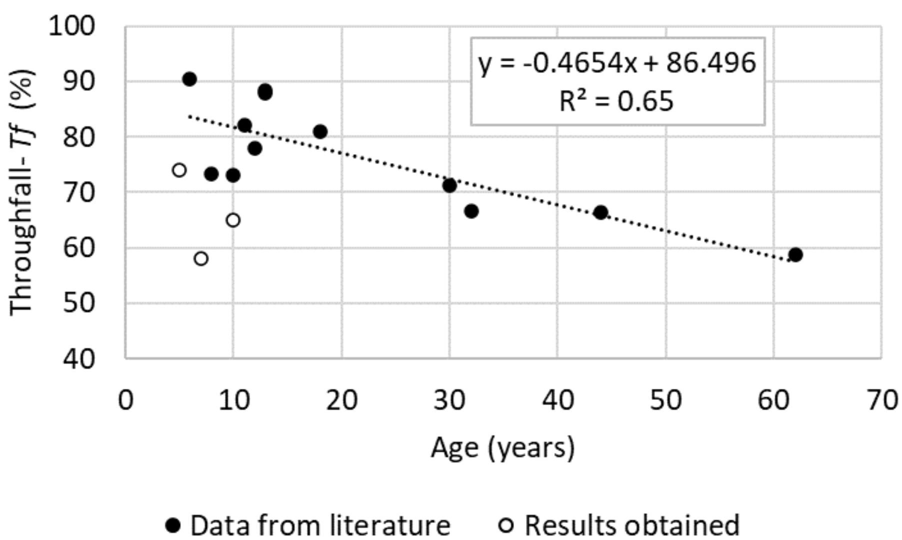


Figure 9 - Relationship between the proportion of throughfall (*Tf*) over gross precipitation (*Pg*) and the age of the vegetation, based on data obtained from the literature (shown in Table 1) and measured data. Authors' production (2024).

Evaluating the data obtained in this research in conjunction with that reported in the literature (Figure 10) clearly shows that there is a decrease in stemflow as the pine develops. This reduction can be explained by the need for a greater volume of precipitation for saturation and stemflow in older pine forests. Although there

ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.60, n.1, p. 92 – 112, 8/2024
http://dx.doi.org/10.5380/raega.v60i0.96238

is a general downward trend with age, there is great variability in stemflow values, especially in younger plantations, and the results obtained in this study are part of this context.

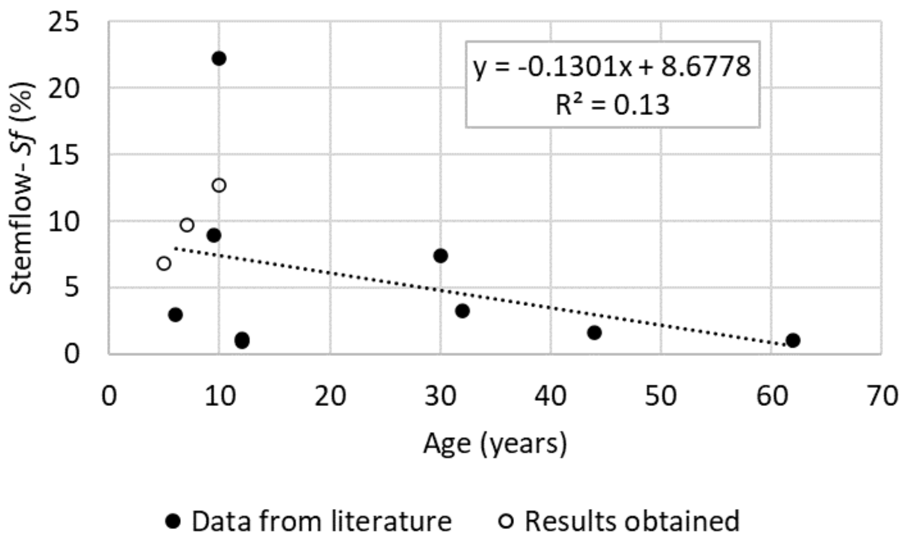


Figure 10 - Relationship between the percentage of stemflow (*Sf*) in relation to age from data obtained from the literature (described in Table 1) and measured data. Authors' production (2024).

IV. Conclusions

This study evaluated the effects of the development of *Pinus taeda* L. tree stands on the interception process through hydrological monitoring. The interception components were measured in 54 events that took place between September 2017 and January 2019, in a *Pinus taeda* L. stand with ages of five, seven and ten years, in the municipality of Rio Negrinho-SC.

During the period, the average throughfall rates (*Tf*) measured were 74%, 58% and 65% and the stemflow rates (*Sf*) were 6.8%, 9.7% and 12.7%, in relation to gross precipitation, for ages 5, 7, 10 with densities 1333 (ha $^{-1}$), 1100 (ha $^{-1}$) and 1666 (ha $^{-1}$) respectively.

The results for throughfall (*Tf*) indicated that, in homogeneous *Pinus taeda* L. stands, age partially explains the hydrological dynamics of the canopy, which also responds to the spacing patterns of the stands and consequent alteration of the environmental characteristics that condition their development. Significantly high values were found for stem runoff (*Sf*) compared to the literature and directly related to the age of the plantation.

In general, the monitoring results obtained in this study are consistent with those published in previous studies, indicating great variability in the interception components, especially in younger plantations.

ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.60, n.1, p. 92 – 112, 8/2024
http://dx.doi.org/10.5380/raega.v60i0.96238

In relation to gross precipitation, greater variability was observed in stemflow (coefficients of determination of 0.63, 0.73 and 0.88) than in throughfall (coefficients of determination of 0.90, 0.93 and 0.98), considering the set of events and the three sites monitored.

Analysis of the temporal discretization of the events indicated precipitation values similar to those indicated in the literature for the complete saturation of the canopy and consequent start of the throughfall component (approximately 2.7 mm), as well as for the start of stemflow (approximately 5 mm).

V. References

BRAGA, S. M.; SANTOS, I.; FERNANDES, C. V. S.; KOBIYAMA, M. Desenvolvimento de um sistema automático de baixo custo para medição indireta da interceptação. Anais. XVIII Simpósio Brasileiro de Recursos Hídricos, 2009.

BREUER, L.; ECKHARDT, K.; FREDE, H. G. Plant parameter values for models in temperate climates. Ecological Modelling, v.169, 2003, p. 237–293.

CALUX, J.; THOMAZ, E. L. Interceptação e precipitação interna: comparação entre Floresta Ombrófila Mista e *Pinus* elliottii var. elliottii. Geoambiente, v. 19, 2012, p. 24-39.

FAN, J.; OESTERGAARD, K. T.; GUYOT, A.; LOCKINGTON, D. A. Measuring and modeling rainfall interception losses by a native Banksia woodland and an exotic pine plantation in subtropical coastal Australia. Jornal of Hydrology, v. 515, 2014, p. 156-165.

GASH, J. H. C.; WRIGHT, I. R.; LLOYD, C. R. Comparative estimates of interception loss from three coniferous forests in Great Britain. Journal of Hydrology, v. 48, 1980, p. 89-105.

GAVAZZI, M. J.; SUN, G.; MCNULTY, S. G.; TREASURE, E. A.; WIGHTMAN, M. G. Canopy rainfall interception measured over ten years in a coastal plain loblolly pine (*Pinus taeda* l.) Plantation. American Society of Agricultural and Biological Engineers, v.59 (2), 2016, p. 601-610.

GIGLIO, J. N.; KOBIYAMA, M. Interceptação da chuva: Uma revisão com ênfase no monitoramento em florestas brasileiras. Revista Brasileira de Recursos Hídricos, v.18 (2), 2013, p. 297-317.

HELVEY, J. D. Interception by Eastern White Pine. Water Resources Research, v. 3 (3), 1967, p. 723-729.

HOOVER M. D. Interception of rainfall in a young loblolly pine plantation. U.S. Department of Agriculture- Forest Service. Piedmont Research Center, n. 21, 1953

HORTON, R. E. Rainfall interception. Monthly Weather Review, v. 47 (9). 1919, p. 604-623.

IBA. Relatório 2017. Industria Brasileira de Árvores. Available at: http://iba.org/images/shared/Biblioteca/IBA_RelatorioAnual2017.pdf

KLEIN, R. M. Mapa Fitogeográfico do Estado de Santa Catarina. Flora Ilustrada Catarinense, V Parte. 1978.

LEVIA JR. D. F.; FROST, E. E. A review and evaluation of stemflow literature in the hydrologic and biogeochemical cycles of forested and agricultural ecosystems. Journal of Hydrology, Amsterdam, v.274, 2003, p.1—29.

LIMA, R.; INOUE, M. T; FIGUEIREDO FILHO, A.; et al. Efeito do espaçamento no desenvolvimento volumétrico de *Pinus taeda* L. Floresta e Ambiente, v. 20(2), 2013, p. 223-230.

ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.60, n.1, p. 92 – 112, 8/2024
http://dx.doi.org/10.5380/raega.v60i0.96238

LIMA, W. P. Estudos de alguns aspectos quantitativos e qualitativos do balanço em plantações de eucaliptos e *pinus*. 1975. 111f. Tese (Doutorado em Ciência Florestal). Escola Superior de Agricultura "Luiz de Queiroz", Piracicaba, 1976.

LIMA, W. P.; NICOIELO, N. Precipitação efetiva e interceptação em florestas de pinheiros tropicais e em reserva de cerradão. IPEF, n.24, 1983, p.43-46.

PINHEIRO, A.; ROSA, A. S. Comportamento hidrológico em bacias com floresta nativa e implantada no município de Caçador, SC. Revista Brasileira de Recursos Hídricos, v.15 (4), 2010.

PREFEITURA MUNICIPAL DE RIO NEGRINHO. Informações gerais. Available at: <http://www.rionegrinho.sc.gov.br/caracteristicas.htm>. Accessed on: 04 de novembro de 2017.

RUTTER, A. J.; KERSHAW, K. A.; ROBINS, P. C.; MORTON, A. J. A predictive model of rainfall interception in forests, I. Derivation of the model from observations in a plantation of Corsican Pine. Agricultural Meteorology, v. 9, 1971, p.367–384.

SÁ, J. H. M.; CHAFFE, P. L. B.; OLIVEIRA, D. Y. Análise comparativa dos modelos de Gash e de Rutter para a estimativa da interceptação por Floresta Ombrófila Mista. Revista Brasileira de Recursos Hídricos, v. 20 (4), 2015, p. 1008 – 1018.

SANQUETTA, C. R; MOURA, A. L; BORSATO, R.; et al. Efeito do espaçamento de plantio em reflorestamentos II. *Pinus taeda* l. em Jaguariaíva-PR Revista Acadêmica: ciências agrárias e ambientais, v.1, n.1, 2003, p. 55-61.

SANTOS, I. Monitoramento e modelagem de processos hidrogeomorfológicos: mecanismos de geração de escoamento e conectividade hidrológica. 167 f. Tese (Doutorado em Geografia). Departamento de Geografia, Universidade Federal de Santa Catarina. Florianópolis, 2009.

SHINZATO, E. T.; et al. Escoamento pelo tronco em diferentes povoamentos florestais na Floresta Nacional de Ipanema em Iperó, Brasil. Scientia Florestalis, v. 39, n. 92, 2011, p. 395-402.

SILVA, L. C.; BORTOLUZZI, C. A. (Org). Texto explicativo para o mapa geológico do Estado de Santa Catarina. Florianópolis: 11º Distrito do Departamento Nacional de Produtos Minerais, Coordenadoria de Recursos Minerais da Secretaria da Ciência Tecnológica, Minas e Energia, 1987.

STOGSDILL, W. R.; WITTWER, R. F.; HENNESSEY, S. T.; DOUGHERTY, P. M. Relationship between throughfall and stand density in a *Pinus* taeda plantation. Forest Ecology and Management, n. 29, 1989, p. 105-113.

SWANK, W. T.; GOEBEL, N. B.; HELVEY, J. D. Interception loss in loblolly pine stands of the South Carolina Piedmont. Journal of Soil and Water Conservation, n. 27, 1972, p. 160-164.

TSIKO, C. T.; MAKURIRA, H.; GERRITS, A. M. J.; SAVENIJE, H. H. G. Measuring forest floor and canopy interception in a savannah ecosystem. Physics and Chemistry of the Earth, v.47–48, 2012, p.122–127.

TUCCI, C. E. M.; CLARKE, R. T. Impacto das Mudanças da Cobertura Vegetal no Escoamento: Revisão. Revista Brasileira de Recursos Hídricos, v. 2, n.1, 1997.

VALENTE, F.; DAVID, J. S.; GASH, J. H. C. Modelling interception loss for two sparse eucalypt and pine forests in central Portugal using reformulated Rutter and Gash analytical models. Journal of Hydrology, v.190, 1997, p.141–162.

WISHMEIER, W. H.; SMITH, D. D. Rainfall energy and its relationship to soil loss. Transactions American Geophysical Union, v.39, 1958, p.285-291.

RA'EGA
O ESPAÇO GEOGRÁFICO EM ANÁLISE
https://revistas.ufpr.br/raega
ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.60, n.1, p. 92 – 112, 8/2024
http://dx.doi.org/10.5380/raega.v60i0.96238

O ESPAÇO GEOGRÁFICO EM ANÁLISE
https://revistas.ufpr.br/raega
ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.60, n.1, p. 92 – 112, 8/2024
http://dx.doi.org/10.5380/raega.v60i0.96238