ISSN 2359-6562 (ONLINE) 2359-6562 (CD-ROM)

RAINFALL PARTITIONING IN DEGRADED AND PRESERVED AMAZON FOREST ECOTONE

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ABSTRACT: Understanding hydrological processes in tropical forests is crucial for conserving biodiversity and maintaining ecosystem functions. This study evaluated rainfall partitioning—throughfall, stemflow, effective precipitation, and interception—in an Amazon rainforest-savannah ecotone by monitoring four plots with varying conservation statuses. Measurements were taken from 48 trees across degraded and preserved areas over five months. Results showed that throughfall and effective precipitation accounted for over 90% of total precipitation (923.30 mm), while interception represented approximately 7.75%, and stemflow less than 0.5%. Significant differences were observed between degraded and preserved plots in most parameters except stemflow, highlighting vegetation's role in soil protection against erosion. These findings contribute to a better understanding of water redistribution in tropical forest ecotones and emphasize the importance of forest conservation for maintaining hydrological balance and ecosystem integrity in the Amazon region.

Keywords: stemflow; throughfall, rainforest, Amazon forest

PARTIÇÃO DA CHUVA EM ECÓTONO DE FLORESTA AMAZÔNICA DEGRADADA E PRESERVADA

RESUMO: Compreender os processos hidrológicos em florestas tropicais é crucial para a conservação da biodiversidade e manutenção das funções do ecossistema. Este estudo avaliou a partição da precipitação - precipitação, escoamento pelo tronco, precipitação efetiva e interceptação - em um ecótono de floresta amazônica-savana, monitorando quatro parcelas com diferentes status de conservação. As medições foram feitas em 48 árvores em áreas degradadas e preservadas ao longo de cinco meses. Os resultados mostraram que a precipitação e a precipitação efetiva foram responsáveis por mais de 90% da precipitação total (923,30 mm), enquanto a interceptação representou aproximadamente 7,75% e o escoamento pelo tronco inferior a 0,5%. Foram observadas diferenças significativas entre parcelas degradadas e preservadas na maioria dos parâmetros, exceto no escoamento pelo tronco, destacando o papel da vegetação na proteção do solo contra a erosão. Esses achados contribuem para uma melhor compreensão da redistribuição hídrica em ecótonos de florestas tropicais e enfatizam a importância da conservação florestal para a manutenção do equilíbrio hidrológico e da integridade do ecossistema na região amazônica.

Keywords: escoamento pelo tronco; de queda total, de floresta tropical, de floresta amazônica

1 INTRODUCTION

The reduction in native vegetation cover and intensified land use in river basins have led to the deterioration of natural resources (Lorenzon; Dias; Garcia, 2013). Changes in the soil cover make these basins vulnerable, for affecting the soil properties and influencing the

Recebido em 19/05/2025 e aprovado para publicação em 14/10/2025
DOI: http://dx.doi.org/10.17224/EnergAgric.2025v40p1-13

qualitative and quantitative aspects of fluvial water and the balance of the hydrological cycle (Balbinot *et al.*, 2008). It is assumed that changes in the water, solar energy, carbon and nutrient cycles, resulting from land use changes in the Amazon region, can have climatic and environmental consequences at different scales (Laurance *et al.*, 2018; Nobre, 2014; Betts *et al.*, 2004).

The rainforest plays an important role in energy and water distribution on the surface, influencing processes of canopy interception (Linhoss; Siegert, 2016; Ribeiro Filho *et al.*, 2019), stemflow (Carlyle-Moses *et al.*, 2018; Tonello *et al.*, 2014; Bessi; Tonello; Dias, 2018) and surface runoff. In the context of the forest hydrological cycle, the first partitioning of rainfall consists of the canopy interception, of which one fraction evaporates directly and another runs off down the tree trunks into the forest floor (Junqueira Júnior, 2016; Sari; Paiva; Paiva, 2016).

Part of the incident precipitation crosses the canopy directly, called throughfall (Oliveira Júnior; Dias, 2005; Lorenzon, Dias, Tonello, 2015). The balance of this system makes it possible to maintain a constant tributary flow to rivers and lakes, with the necessary quality to warrant the maintenance of the aquatic biota and multiple uses.

For an effective conservation of tropical biodiversity, the components of the hydrological cycle in the forest context must be well understood. Even though the Amazon region is recognized as a highly diverse biome, little is known about its hydrological cycle (Nobre *et al.*, 2004), which is fundamental for the local, regional and global climate regulation, by pumping water into the atmosphere and maintaining ecosystems through water infiltration into the soil.

In this sense, the objective of this study was to evaluate the hydrological behavior of a upland rain forest to savannah ecotone forest of a native rainforest fragment in the Amazon region.

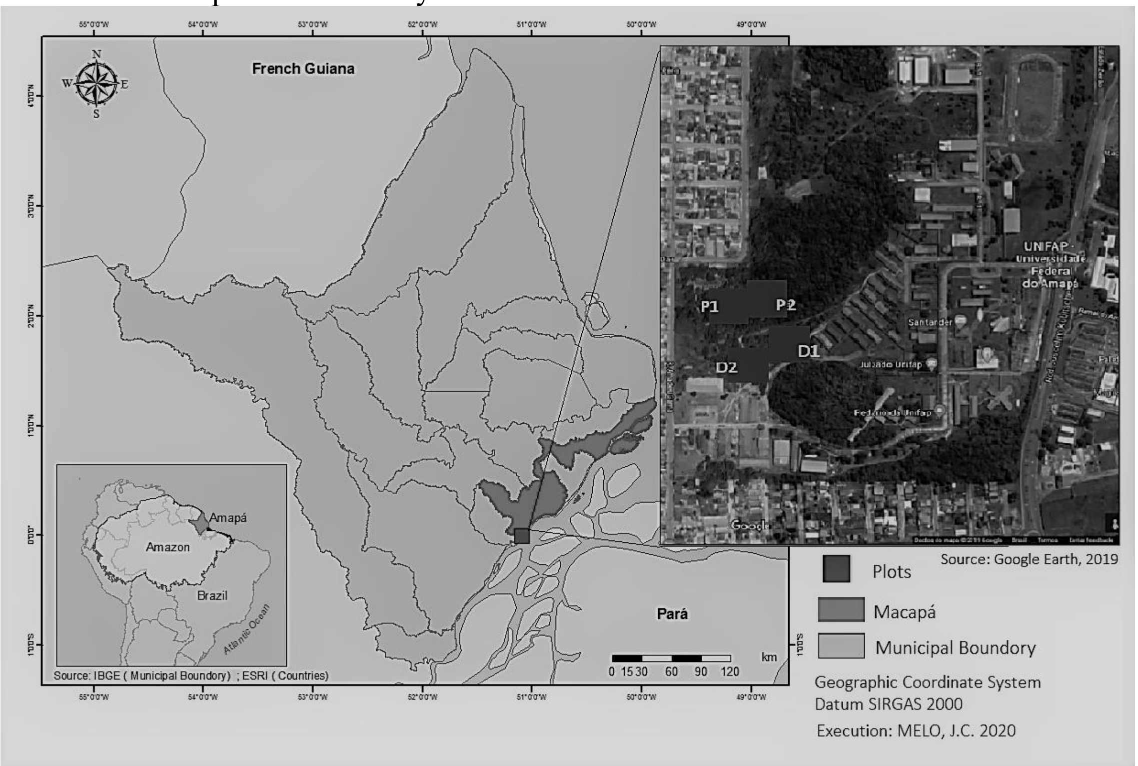
2 MATERIALS AND METHODS

The study was carried out in two Terra Firma rainforest fragments of the Federal University of Amapá, Campus Marco Zero, in the municipality of Macapá - AP, Rodovia Juscelino Kubitschek, Km 2, Jardim Marco Zero. The plot location in the study area is shown in Figure 1. The region is a savannah-rainforest ecotone, with relatively young vegetation in regeneration. The absolute tree density per area is 20757.4 trees (Estigarribia *et al.*, 2014) in all rainforest fragments on the university campus, with a mean tree height from 3.44 to 6.46 m.

Amapá has a super-humid equatorial climate, with little temperature variation. In the coastal region of Macapá, the mean annual rainfall is 3,250 mm, with least rainfall between July and November (Drummond, 2004).

Four plots were outlined, two with a higher vegetation density and two more degraded fragments, to represent distinct study conditions. The plots D1 (69, 28m^2) and D2 (60.41 m^2) are part of the forest edge, and therefore degraded. In these plots, seven and eight trees, respectively, were selected for monitoring. Plots P1 (82.96 m^2) and P2 (58.43 m^2) are located in the interior of the preserved forest fragment, where 16 trees per plot were monitored.

Figure 1. Location of plots in the study area



Fonte: The authors (2020)

To determine the total precipitation, a rainfall gauge was installed, close to plot D1, without interference of vegetation, to avoid any influence on rainwater collection (Figure 2a). The total precipitation was calculated by the Equation 1:

$$P = 10\left(\frac{V}{A}\right) \quad (1)$$

where P is the precipitation; V the collected volume and A the catchment area (cm²)

To determine throughfall, 13 internal rain gauges were randomly installed under the tree canopy, three in each of the plots D1, D2 and P1 and four in plot P2. They consisted of PVC tubes (circumference 0.15 cm), superimposed onto funnels to which plastic hoses and collecting containers were attached, and fixed to a wooden pole driven into the ground (Figure 2b). The throughfall was calculated by the Equation 2:

$$Pi = 10\left(\frac{V}{B}\right) \quad (2)$$

where Pi is the throughfall; V the volume (mm) and B the rain gauge area (cm²)

To quantify the stemflow, expansive foam was adhered to the tree trunks, with a circumference at breast height (CBH) of > 15 cm, with collars shape, with a circumferential cut at the top and a hole at the bottom, to which a plastic hose was connected (Figure 2c). A container was installed at the end of each hose to collect the drained volume.

Pe is defined as the sum of the stemflow (Fst) plus the throughfall (Pi) in the respective plots of each forest fragment.

$$Pe = ThF + Fst \quad (3)$$

where Pe is the effective precipitation; ThF the throughfall and Fst the stemflow.

Rainwater interception represents all water retained by the leaves, branches, trunks and rain gauges, and is computed by subtracting the effective from the total precipitation:

$$I = P - Pe \quad (4)$$

where I is the intercept, P the total precipitation and Pe the effective precipitation.

The data were collected between November 2019 and March 2020. After each significant rainfall event, the runoff volume collected from each tree was measured in a graduated plastic cylinder. Similarly, the water volume collected in the rain gauges was determined. Figure 2 shows the equipment.

Figure 2. (a) rain gauge; (b) throughfall gauge; (c) stemflow

Fonte: The authors (2020)

Analysis of variance (ANOVA) was performed with the plot means, followed by the Tukey test (p = 0.05), to identify differences between the plot values. Statistical tests were performed using software Excel and Past.

3 RESULTS AND DISCUSSION

During the measurements, a P of 923.30 mm was recorded. It worth mentioning that the monitoring lasted 5 months and was interrupted in March 2020 by the COVID 19 Pandemic. Consequently, the hydrological cycle was not completely sampled, since the rainy period in Macapá lasts 7 months (December - July), with a total annual precipitation that can exceed 2000 mm. According to data of the Brazilian institute of meteorology (INMET) from the automatic weather station of Macapá (0°03’50.20”N; 51°08’87.63”), the total rainfall until May 2020 was 1614.40 mm.

The variability in rainfall distribution in the Amazon region is wide. According to Limberger and Silva (2016), the main influence on rain variability in the Amazon basin is the El Niño - Southern Oscillation (Enso) phenomenon, causing drier periods in a hot phase and wetter periods in a cold one. The Atlantic also plays an important role in the rainfall variability, in particular by regulating the moisture fluxes to the Amazon basin. Other studies in the Amazon/Macapá region clearly show this variability, e.g., an annual total rainfall of 1,153.4 mm recorded by Oliveira *et al.* (2008), versus 2,913 mm reported by Ferreira, Luizão and Dallarosa (2005).

A mean ThF of 847.70 mm was measured, corresponding to 91.81% of the total precipitation (P). In rainforests of the Amazon region, Giglio and Kobiyama (2013) recorded ThF values between 38 and 98.2%. Lower values in preserved upland rainforests in Central Amazonia were reported by Ferreira, Luizão and Dallarosa (2005), varying between

74% and 87%. Other authors such as Franken *et al.* (1982) recorded 77.7% and Oliveira *et al.* (2008) 76.8%. Slightly higher values were measured by Ubarana (1996), with 86.3% in the environmental protection area of Vale do Rio Doce, in southeastern Pará, and 87% in the nature reserve of Jarú, in northeastern Rondônia.

The ThF values were highest in D1 and D2, with a mean of 881.12 mm, and 823.83 mm in P1 and P2. The difference is only 6.2%, but highlights the importance of the rainforest in protecting the soil against erosion.

These differences can be attributed to the presence of more clearings, since plots D1 and D2 are areas with lower tree density and less developed trees (canopy, height, DBH), located in forest edges. The distance between the trees facilitated the channeling of a high water flow into the throughfall gauges, since this spacing reduces rainwater interception by the canopy. On the other hand, Konishi *et al.* (2006) suggested that the incompleteness of the canopy is not the only factor that influences this process, but that the spatial distribution of throughfall is regulated by mechanisms at different scales, which vary according to the size of the tree canopies or clearings in the vegetation.

Recorded separately, the ThF in the plots D1, D2, P1 and P2 was 908.48; 862.88; 781.31; 855.73 mm, or expressed in percentage of P: 98.39; 93.45 84.62 and 92.68%. Interestingly, the values of plots 2 and 4, in spite of the differences in tree density and regeneration stage, did not vary much. This result may have been influenced by the possible occurrence of points where throughfall flux may be higher, under preferential drip points, as also highlighted by Gasparoto *et al.* (2014).

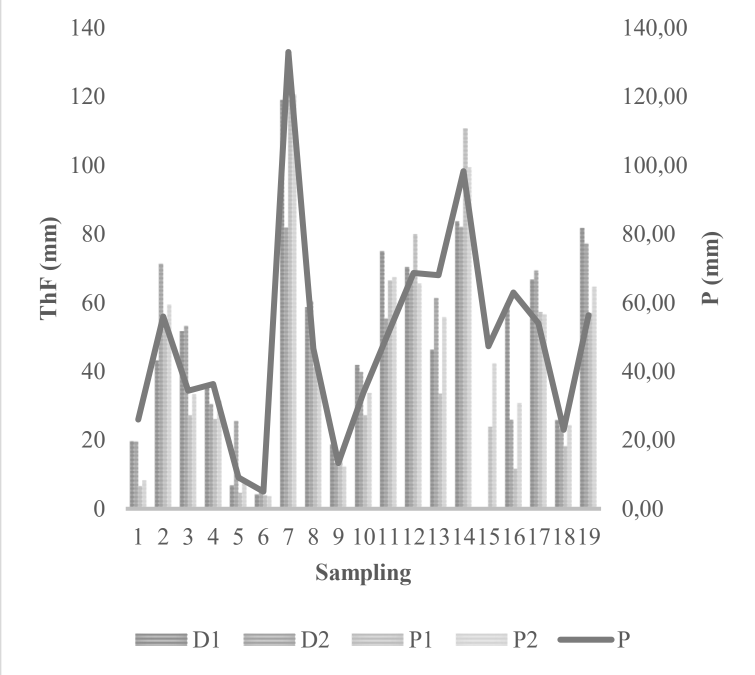
Plot D1 was the most degraded, containing a smaller number of less developed trees. Thus, ThF was almost equal to P, reaching 908.48 mm, i.e., 98.39% of the fallen rain. Aside from being degraded, this area is in regeneration, since the trees growing in this area are relatively young. The statistical analysis indicated significant differences between plots D1 and P2 ($p > 0.05$), which suggests that the stage of rainforest regeneration (based on the number of trees, tree development) may influence the capacity of rainfall interception, since these are the most antagonistic plots (less and more preserved, respectively). In the study period, P and ThF followed similar trends (Figure 3), confirmed by correlation analysis of the throughfall (ThF) and total precipitation (P) (Figure 4).

The different determinant factors for these results are mainly the sampling method, number of gauges, canopy structure, as well as the rainfall variability characteristics (Giglio; Kobiyama, 2013; Sari, Paiva, Paiva, 2016).

The mean volume of Fst was 3.96 mm, corresponding to 0.43% of P. in the Amazon rainforest (upland rainforests) in Rondônia, Germer, Elsenbeer and Moraes (2006) found a stemflow rate of 7.8 % in relation to total precipitation (P). It is noteworthy that the high incidence of palm trees (*Orbignya phalerata*) contributed to the high value in that study, which is a rather different condition from our experiment, where no palm trees were registered. In an Atlantic Forest fragment, Lorenzon, Dias and Tonello (2015) found the highest Fst values on *Euterpe edulis* trunks, indicating that the presence of trees with these characteristics contributes to raise rainwater capture. Although low, the mean total stemflow volume was in line with values reported in other studies in the Amazon, as those of Melo, Sá and Moller (2005) with 0.28% and of Ubarana (1996) with 0.20%. According to Tucci (2001), this fraction can correspond to 1 to 15% of the total precipitation.

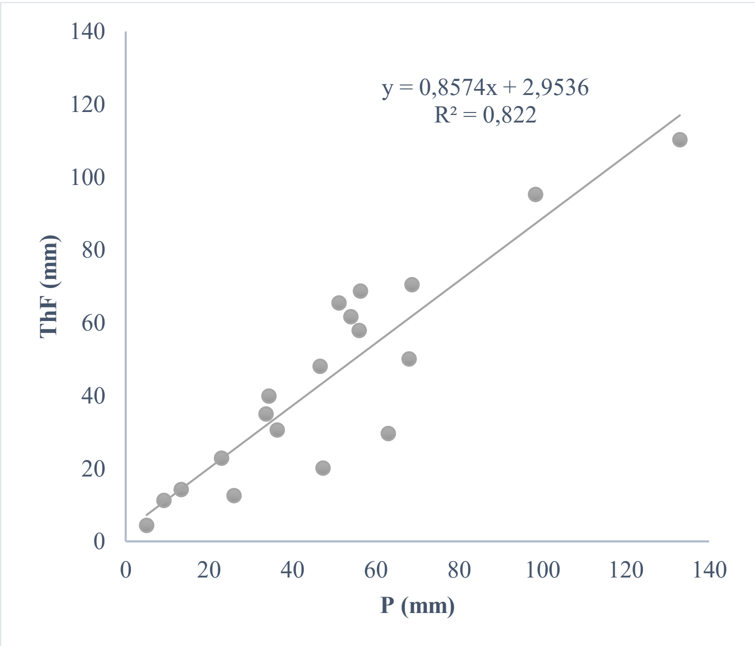
In a data compilation of the Amazon biome, Giglio and Kobiyama (2013) found that in Amazon rainforests, Fst can vary between 0.30 and 41% of the total rainfall. They claim that this wide range of values is due to the heterogeneity of vegetation and characteristics of the rainfall events, but also to factors such as the diversity of measurement methods, study scales and monitoring periods. However, the same authors point out that a quarter of the studies carried out in this biome did not include Fst in their evaluations, indicating that this flow is often overlooked by researchers. According to Carlyle-Moses *et al.* (2018), although reports on the hydrological and biogeochemical importance of stemflow are readily available, recent literature reviews suggest that the hydrologic scientific community may have underrated the significance of stemflow.

Figure 3. Distribution of throughfall (ThF) and relationship with total rainfall (P), in degraded (D1 and D2) and preserved (P1 and P2) environments in the Amazon region in bar chart format



Fonte: The authors (2020)

Figure 4. Distribution of throughfall (ThF) and relationship with total rainfall (P), in degraded (D1 and D2) and preserved (P1 and P2) environments in the Amazon region in correlation format



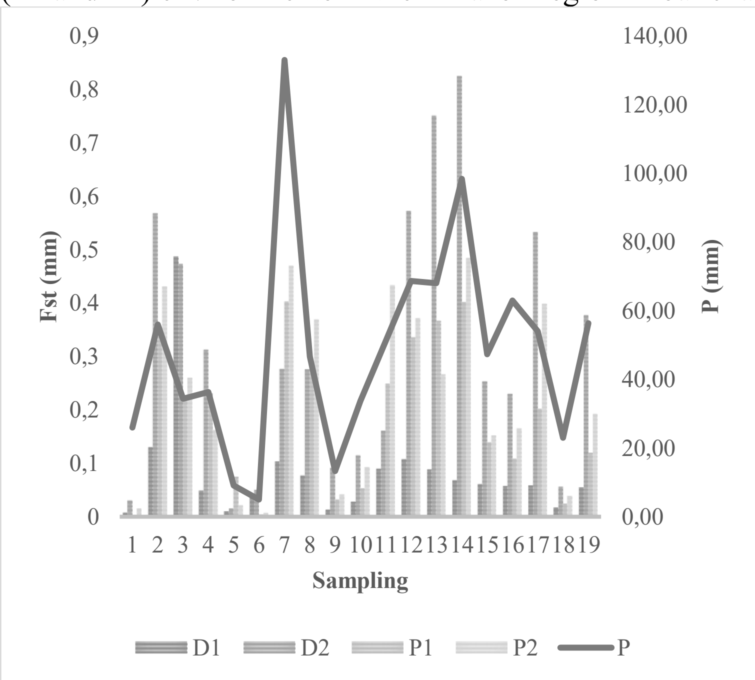
Fonte: The authors (2020)

The high ratio ($r^2 = 0.82$) is noteworthy, which shows that this variable is highly influenced by the rainfall characteristics. Similar values were reported by Ferreira, Luizão and Dallarosa (2005) in preserved upland rainforests in Central Amazonia, varying between 0.81 and 0.94. In Atlantic Forest fragments, Sari, Paiva, Paiva (2016) found higher correlation values, with indices between 0.93 and 0.99.

The largest Fst volume was captured on plot D2 (5.96mm, i.e., 0.65% of P), followed by P2 and P1 (with 4.36mm and 3.60mm, i.e., 0.48% and 0.36% of P, respectively). The lowest Fst was measured in plot D1 (1.54 mm, i.e., 0.17% of P). The statistical analysis showed no significant differences between any plots. According to Lorenzon, Dias and Tonello (2015), the canopy quality did not influence the stemflow in an Atlantic Forest formation, and found widely varied values between species. This may explain the pattern observedd in this study, since the highest stemflow volume was recorded in a plot with inferior preservation characteristics than those of P1 and P2. The above authors reinforced the need to understand the mechanisms of rainwater interception by forest species and to identify the most promising for environmental preservation and recovery.

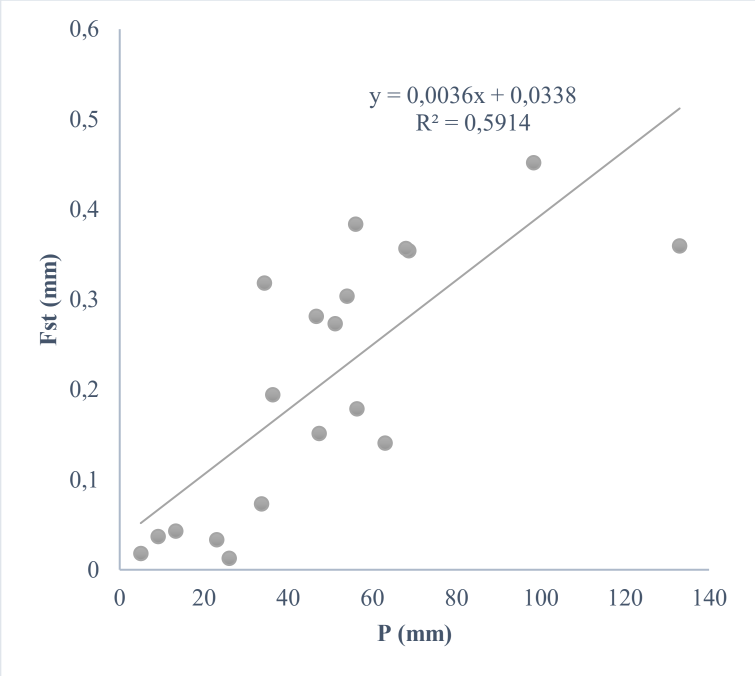
In a way, Fst seems to be influenced by P (Figure 5), which was confirmed through linear regression analysis ($r^2 = 0.59$) (Figure 6). A similar value was found by Shinzato *et al.* (2011), in an Atlantic forest fragment ($r^2 = 0.64$). These values indicate that stemflow cannot be explained by precipitation alone, suggesting that there are other determining factors of runoff patterns. The influence of other factors in this process was explained by Levia Junior and Frost (2003), as for example of rain intensity (not evaluated in this study), influence of wind, seasonality and morphological and age variations between species.

Figure 5. Distribution of Stemflow (Fst) and Total precipitation (P), in degraded (D1 and D2) and preserved (P1 and P2) environments in the Amazon region in bar chart format



Fonte: The authors (2020)

Figure 6. Relationship of Stemflow (Fst) and Total precipitation (P), in degraded (D1 and D2) and preserved (P1 and P2) environments in the Amazon region in correlation format



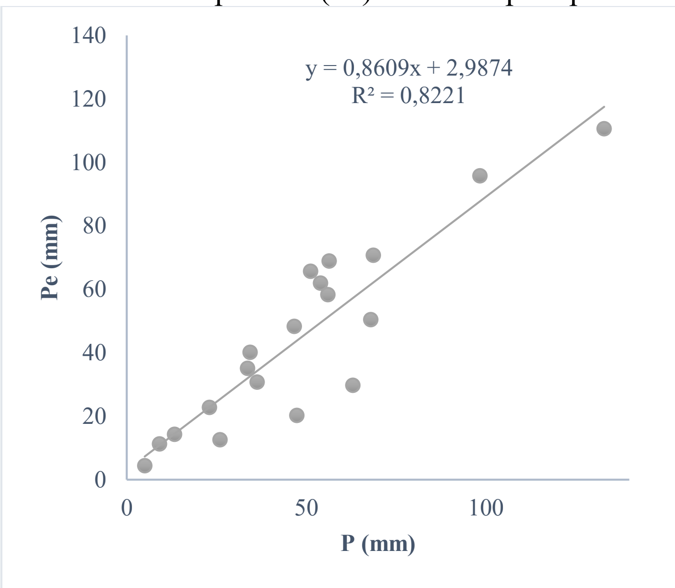
Fonte: The authors (2020)

The sum of the Fst and Pi volumes represents the effective precipitation (Pe), which is the rainwater fraction of the total precipitation that actually reaches the forest floor. In this study, Pe was 851.66 mm, 92.24% of P, in agreement with Franken *et al.* (1982) and Ubarana (1996), who found between 78.0% and 97.6%, respectively, in areas of the Amazon region. Considering each plot separately Pe did not differ significantly (784 mm (85%) in P1; 868 mm (94%) in D2; 860 mm (93%) in P2). The highest effective precipitation was recorded in D1 (910 mm, i.e., 98% of P), and differed statistically from P2. For the relationship between Pe and P, r^2 of 0.82 was calculated (Figure 7), this values had been expected, since Pi, highly correlated with P, represents most of this hydrological fraction.

A mean I of 71.63 mm was recorded, corresponding to 7.75% of P. This fraction represents the amount of rainwater retained on the upper part of the canopy, from where it evaporated (Carlyle-Moses, 2004). In conventional studies to determine the interception by tropical rainforests, Czikowsky and Fitzjarrald (2009) found data between 8% and 40% of the total annual precipitation. Higher values (12.9 - 25.8%) in relation to this study were observed by Ferreira, Luizão and Dallarosa (2005) in the Amazon rainforest, and an interception of 16.5% by Cuartas *et al.* (2007), in the central Amazon rainforest.

The total I in the plots was 13.28 mm (1.43%) in plot D1, 54.44 mm (5.89%) in D2, 138.37 mm (14.98%) in P1 and 63.19 mm (6.84%) in P2, and the difference between D1 and plots P1 and P2 was significant.

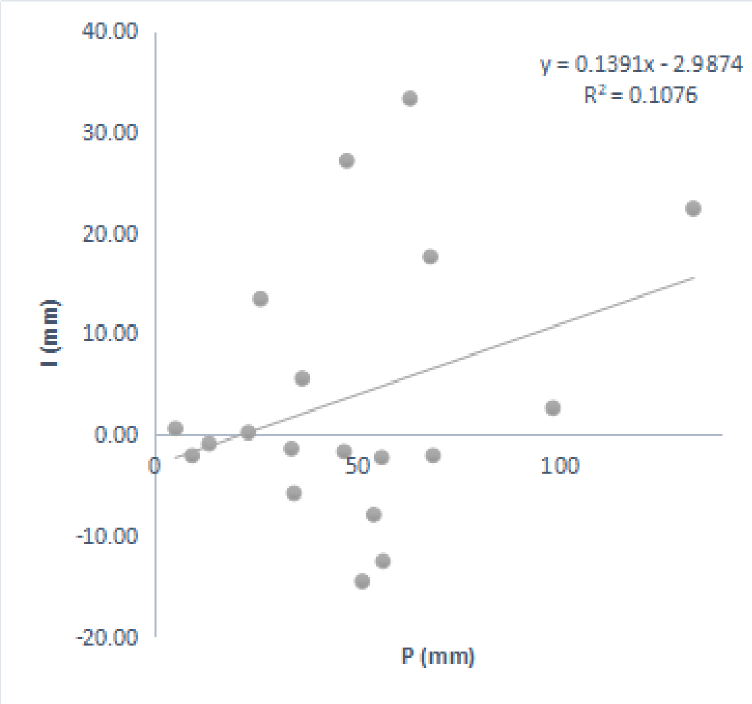
Figure 7. Relationship of Effective Precipitation (Pe) and Total precipitation (P) in correlation format



Fonte: The authors (2020)

Interception was weakly correlated with P ($r^2 = 0.11$) (Figure 8). In an earlier study, Kuraji *et al.* (2001) measured the monthly volumes of total rainfall, throughfall and stemflow on conifers, in two consecutive hydrological years. These authors observed that the loss percentage by interception was higher in the year with more rain events and lower total precipitated volume, so that interception may be better correlated with the number of rainfall events than with the proper rainfall volume. It is worth emphasizing that negative I values were observed because of events in which the effective exceeded the total precipitation (P), as also observed by Sari, Paiva, Paiva (2016) and Dunkerley (2010), attributed to the existence of dripoints and openings in the canopy due to the heterogeneity of tropical forests, opening preferential pathways for throughfall due to its interaction with the tree leaves and branches. The weak correlation between I and P may also have been a result of these peculiarities.

Figure 8. Effective Precipitation (Pe) and Total precipitation (P)



Fonte: The authors (2020)

4 CONCLUSIONS

The results for the monitored hydrological components are in line with the studies carried out in the same biome. Statistically, the most antagonistic plots in terms of conservation status (P2 and D1) differed significantly, except for the parameter stemflow (Fst), indicating that vegetation may influence hydrological processes relevant to forest soil conditions.

Total precipitation (P) was well correlated with the analyzed variables, except the data of interception. The heterogeneity of tropical forests and variability of rainfall characteristics may explain this pattern.

The hydrological processes responsible for rainwater redistribution in the rainforest (interception, throughfall, stemflow and effective precipitation) are influenced by the climate, rainfall characteristics and vegetation. The understanding of the mechanisms involved in these processes in tropical forests is still limited and underscores the relevance of the results presented in this paper.

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