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ISSN eletrônico 2177-2738
RA'EGA, Curitiba, PR, V.55, p. 78-92, 12/2022
DOI: http://dx.doi.org/10.5380/raega.v55i0.81030

The role of yerba mate (*Ilex paraguariensis*) in the redistribution of rainfall by interception

O papel da erva-mate (*Ilex paraguariensis*) na redistribuição da água da chuva por interceptação

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DOI: http://dx.doi.org/10.5380/raega.v55i0.81030

Abstract

Vegetation cover plays an essential role in the vertical and horizontal distribution of rainwater. As rainwater passes through the canopy, it can be divided into interception loss, throughfall, and stemflow. In the areas where yerba mate is cultivated, interception loss influences the variability of water reaching the soil, surface runoff, and nutrient cycling. The objective of this study was to evaluate throughfall, stemflow, and interception in yerba mate (*Ilex paraguariensis*). The study was conducted in the Guará District, municipality of Guarapuava, south-central region of Paraná, Brazil. Measurements were conducted from July 2019 to March 2020. Average rainfall interception, throughfall, and stemflow for yerba mate accounted for 13.6%, 86.1%, and 0.3% of precipitation, respectively. Throughfall and stemflow increased with precipitation. The interception rate showed variation according to rainfall characteristics: volume, duration, and intensity. The structure, shape, and density of yerba mate leaves and branches result in uneven distribution of the water that reaches the soil by directing the flow to specific points. The results indicate that yerba mate caused changes in water circulation and distribution.

Keywords: Ecohydrology, throughfall, stemflow, precipitation partitioning.

Resumo

A cobertura vegetal desempenha um papel importante na distribuição vertical e horizontal da água da chuva. Na passagem da chuva pela copa das árvores a água pode ser dividida em perda por interceptação, precipitação interna e escoamento pelo tronco. Nas áreas de cultivo de erva-mate a perda por interceptação influencia na variabilidade de água que chega ao solo, no escoamento superficial e no ciclo de nutrientes. O presente estudo teve como objetivo avaliar a precipitação interna, o escoamento pelo tronco e a interceptação em erva-mate (*Ilex paraguariensis*). A pesquisa foi realizada no Distrito do Guará, município de Guarapuava, região centro-sul do estado do Paraná, Brasil. As mensurações foram conduzidas entre julho de 2019 a março de 2020. A média de interceptação, de precipitação interna e escoamento pelo tronco da chuva na erva-mate foram de

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13.6%, 86.1 e 0.3% da precipitação, respectivamente. A precipitação interna e o escoamento pelo tronco aumentaram com a precipitação. A taxa de interceptação apresentou variação de acordo com as características da chuva: volume, duração e intensidade. A estrutura, forma e densidade de folhas e galhos da erva-mate condicionam uma distribuição desigual da água que chega no solo por meio do direcionamento do fluxo para determinados pontos. Os resultados indicaram que a erva-mate ocasiona mudanças na circulação e distribuição da água.

Palavras-chave: Ecohidrologia, precipitação interna, escoamento pelo tronco, partição da precipitação.

I. Introduction

Trees play an essential role in rainfall redistribution and variability. Rainfall partitioning by vegetation implies the redistribution of rainfall as water passes through the canopy, regulated by throughfall (Tf), stemflow (Sf), and interception loss (I), thus playing an essential role in the terrestrial water balance on both the local scale and the catchment scale (LLORENS; DOMINGO, 2007). Tf is the part of precipitation (P) that comes into contact with the canopy, being drawn and drained freely by branches and trunks until it reaches the ground (LEVIA *et al.,* 2017). Sf is the part of precipitation drained only by the base of tree trunks (SADEGHI *et al.,* 2020). Interception loss is the part of rainfall intercepted by vegetation and which evaporates.

Studies on forest interception have gained visibility in recent decades. It is a process that affects the water cycle and other aspects of the physical environment, such as the spatial variability of moisture and physical and chemical properties of the soil (BELMONTE-SERRATO; ROMERO-DIAZ; 1999a; MATEOS; SCHNABEL, 2013). For all these reasons, gaining more in-depth knowledge about the interception process becomes an essential component that impacts watershed climates and hydrology.

In Brazil, the Mixed Ombrophilous Forest (MOF) is part of the Atlantic Forest and is of great importance for forest hydrology. An endemic species of this forest with significant economic and cultural value is *Ilex paraguariensis*, popularly known as yerba mate. Originally, yerba mate was once one of the main raw materials exported from Brazil (DANIEL, 2009). Among the agricultural alternatives, yerba mate cultivation is an important economic activity that generates employment and income, especially for small and medium-sized rural producers in Southern Brazil (RODIGHERI; MOSELE, 2000).

The exploitation of native and cultivated yerba mate forms one of the most important agroforestry systems in the southern region of Brazil, where the species is found. Yerba mate can be exploited in its native

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form (in forests, in pastures, or together with agricultural crops) and cultivated alone, in monoculture systems, with simultaneous or sequential cultivation of yerba mate (RODIGHERI; MOSELE, 2000).

Concerning the MOF, the possibilities and limitations of the management of yerba mate, a tree species native to the Araucaria Forest and of significant cultural and economic importance for the conservation of native forest remnants, have been discussed from a socio-environmental conservation perspective (MARQUES *et al.,* 2017).

This perspective led to the approval in Brazil of Federal Bill of Law No. 5650/2016, sanctioned in 2019 as Law No. 13791/2019. This law allows the planting and harvesting of yerba mate (*Ilex Paraguariensis*) in Permanent Preservation Areas (PPAs) located on small properties and rural landholdings, provided that it is of social interest and public utility, upon prior authorization to be obtained from the state environmental agency. Thus, the new law enables the introduction and management of new yerba mate seedlings in PPAs, areas hitherto destined for environmental preservation and restricted use (BRASIL, 2019).

Studies on precipitation partitioning in different forest species in Brazil are few and essentially conducted in forest formations with a diversity of plant species (MEDEIROS, 2005). In addition, studies on interception loss in crops are scarce. Standing out among these studies, Castilho (2000) and Fernandes *et al.* (2017) analyze interception loss in sugarcane. They found interception loss of 39.5% and 24%, respectively. In their study, Siles *et al*. (2010) analyzed interception loss in coffee plantations in monoculture (MC) and Agroforestry (AFS) systems. The results showed interception loss of 11.4% in AFS and 9.4% for MC.

Kaushal *et al.* (2017) analyzed the interception process in *Morus Alba* dealt with by the practice/treatment of "looping" canopy management. During the experiment, throughfall accounted for 80.8% of precipitation while stemflow accounted for 10%, decreasing the percentage of rainfall through stemflow as rainfall volume increases. The average interception in *Morus Alba* was 9.2%.

Limin *et al.* (2015) investigated the effect of the canopy in a clove (*Syzygium aromaticum*) plantation during the rainy season in the Saba River Basin, Bali, Indonesia. Comparison between the results of measuring internal precipitation and stem runoff concluded that the canopy in managed clove plantations intercepts more rainwater than the canopy in natural forests. The results showed that throughfall, stemflow, and interception were 62.86%, 0.98%, and 36.16%, respectively.

Therefore, this study aims to address the lack of research on precipitation partitioning in yerba mate (*Ilex paraguariensis*) plantations in the MOF. The study investigates the effect of the canopy of yerba mate trees on interception, throughfall, and stemflow in these trees. The results of this research should be considered for the

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development of land use management concerning yerba mate plantations, either in monoculture systems or in association with the MOF in areas of conservation or environmental preservation.

II. Materials and Methods

Site study

Yerba mate (*Ilex paraguariensis St.Hil.*) belongs to the MOF *Aquifoliaceae* family and is native to Southern Brazil, also found in Argentina and Paraguay (Figure 1). Moreover, it is used as raw material for extraction. In Brazil, 587 municipalities produce yerba mate on approximately 180,000 properties, generating more than 700,000 jobs (IBGE, 2018). According to IBGE data (2018) the state of Paraná is the largest national producer of yerba mate, followed by the state of Rio Grande do Sul, Santa Catarina, and Mato Grosso do Sul.

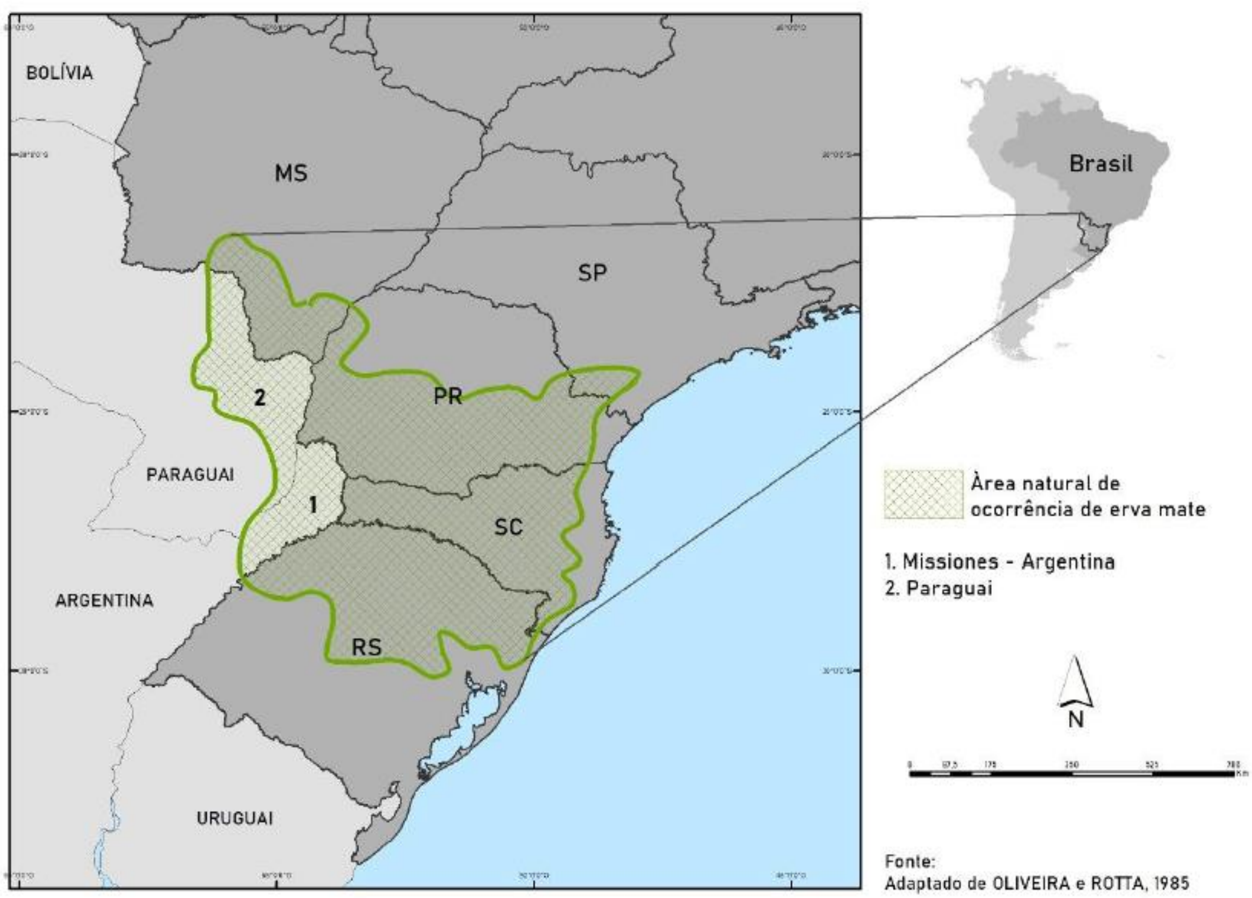

Figure 1 – Area of natural occurrence of yerba mate.
Source: Prepared by the authors (2021)

For this study, a representative area of the yerba mate production system (monoculture) measuring six hectares was chosen for the experiment located in the District of Guará, municipality of Guarapuava, State of

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Paraná, in the southern region of Brazil (Figure 2), owned by the "Erva-mate 81" company. The average altitude in the experimental area is 1,186 meters. The climate in the region is temperate without a dry season, with cool summers and moderate winters, with an average annual temperature of 16° to 17.5°C and average annual rainfall of 1,961 mm (THOMAZ; VESTENA, 2003). The predominant soil in the area is dystrophic brown latosol.

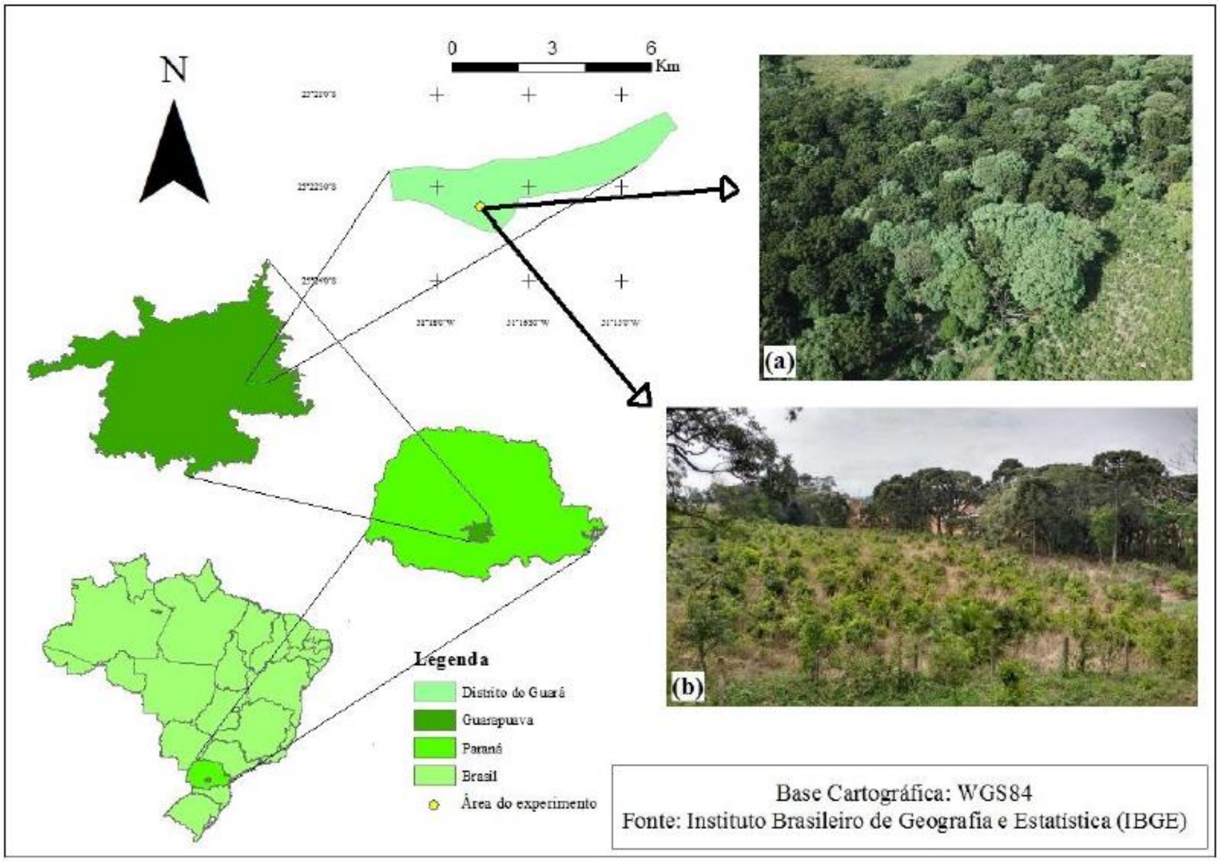

Figure 2- Location of the experimental area, in the District of Guará, Municipality of Guarapuava, Paraná, Brazil. (a) Yerba mate in an Agroforestry system (b) Yerba mate in a monoculture system.
Source: Prepared by the authors (2021)

The soil surrounding the yerba mate in the monoculture system is covered by cut natural vegetation (grasses, herbaceous plants, and shrubs), such *as barba-de-bode* (*Aristida pallens*), rabo-de-burro (*Andropogon sp.),* vassourinha (*Miconia candolenna* and others), *capim caninha* (*Andropogon icanus*), and capim flecha (*Trystachia chrysothirx*). The yerba mate monoculture system experimental area has yerba mate trees planted at an average distance of 4 m x 4 m. The most recent pruning took place in August 2018 and March 2020.

The average heights of yerba mate trees in the monoculture system studied vary from 2.36 to 3.10 m, and their crown area varies from 3.42 to 5.39 m². The trunk circumferences of the yerba mate trees range from 24.50 to 55.50 cm, even though the trees have the same age. The shape of the trunk may vary between the base, close to the ground, and the first branch of the crown, due to the way pruning is done. In general, yerba

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mate trees have branches that appear starting from 10 to 44 cm from the ground on the main trunk. However, it is not uncommon to find these trees with branches emerging close to the ground.

Methodological procedures

Throughfall, stemflow, and interception were measured from July 2019 to March 2020 on three randomly chosen, representative yerba mate trees growing in the sunlit planted area aged between 25 and 28 years, having last been pruned in August 2018 (yerba mate pruning occurs every two years).

Precipitation was measured using three rain gauges and a pluviograph installed in an open area, close to the grasslands, 1.5 m above the ground. Precipitation was measured per event (rain gauges) and every five minutes (pluviograph) to monitor the precipitation amount and intensity.

Fifty-four rain gauges were used to measure internal rainfall. Eighteen rain gauges were distributed around the trunk of each yerba mate tree, located at the height of 40 cm from the ground in a radial form below the canopy.

Throughfall, stemflow, and interception were measured in 33 rainfall events. Precipitation and throughfall were obtained using equation (1):

$$P \; or \; Tf = V/A \tag{1}$$

where: P is precipitation, Tf is throughfall, V is water volume, and A is the collector catchment area.

Yerba mate stemflow volume was collected using collar collectors. The collars or funnels were made from 5L bottles. First, each bottle was cut in half to fit into the tree trunk. Then the top or bottom was cut across and fitted in an apparently circular area near the base of the tree trunk. The contact area between the tree and the funnel was sealed with silicone. The flow of water draining from the trunk was directed from the collars to a container with a storage capacity of 5 to 20 L, with the aid of ½" diameter PVC (Poly Vinyl Chloride) hoses.

The volume of water drained through the trunk was obtained using equation (2).

$$\mathrm{S}f = \frac{V_{Sf}}{A_c} \tag{2}$$

where: Sf is stemflow, V_{Sf} is volume of water collected from the trunk, and A_c is the crown area.

Estimated interception loss was given by equation (3).

$$I = P - (Tf + Sf) \tag{3}$$

where: I is interception loss, P is precipitation, Tf is throughfall, and Sf is stemflow.

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The correlation between precipitation and throughfall, stemflow or interception was tested by regression analysis. Statistical analyses were performed with the aid of SigmaPlot R 14.0 software. When analyzing throughfall, stemflow, and interception in the studied species, normality of distribution was verified using analysis of variance (one-way ANOVA).

III. RESULTS AND DISCUSSION

Precipitation measured between 07/2019 and 03/2020 was 788 mm. This was lower than the historical average for the site in this period of the year, which is 1,471 mm (Figure 3), i.e. 53.5% below the normal volume. According to the Paraná System of Technology and Environmental Monitoring (SIMEPAR) this was due to "Indian summers", which caused longer than usual periods of drought.

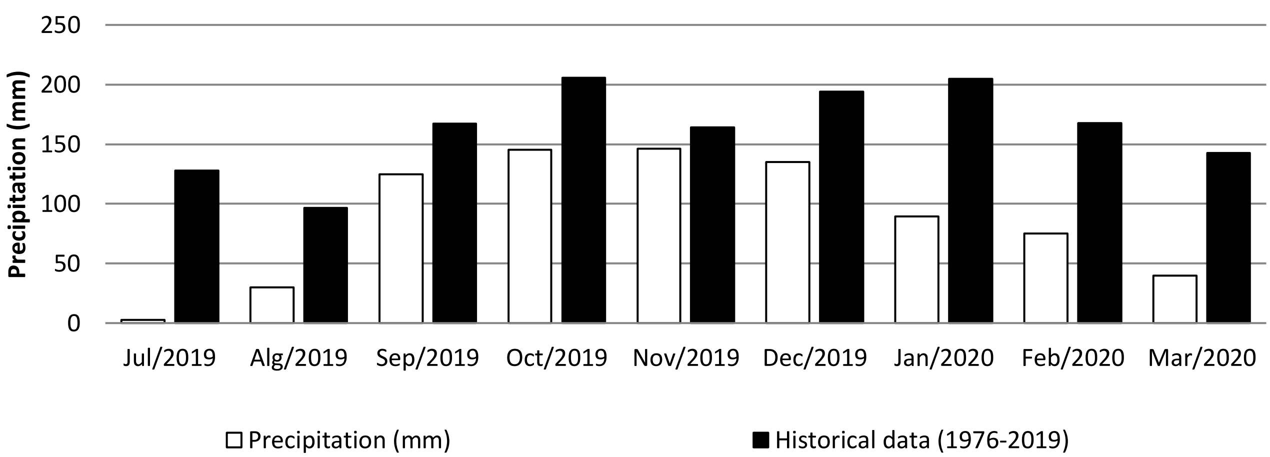

Figure 3- Monitored monthly precipitation
Note: Monitoring started on 07/30/2019; the last day of monitoring was 03/19/2020.

Average throughfall accounted for 86.1% precipitation. On the other hand, stemflow accounted for 0.3% and interception accounted for 13.6% precipitation (Figure 4).

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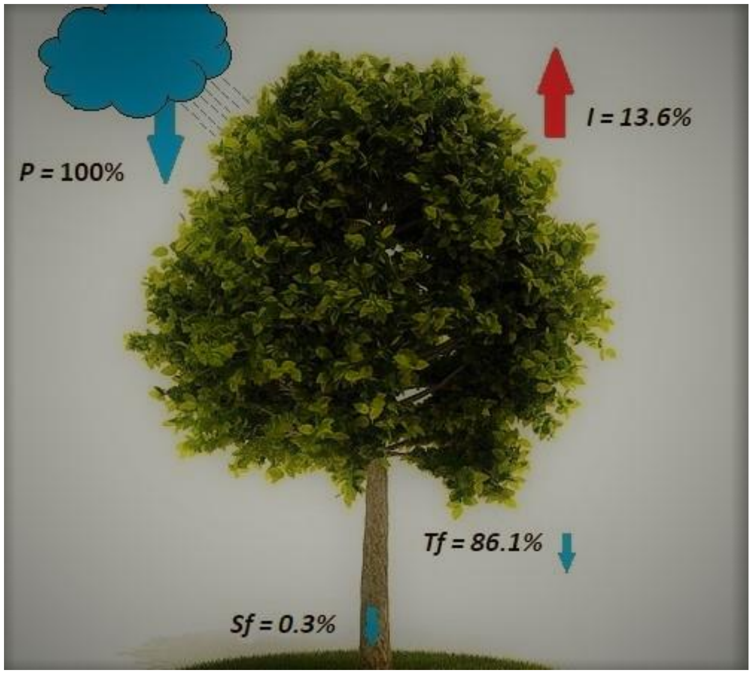

Figure 4. Representative image of precipitation partitioning in yerba mate.
Source: Prepared by the authors (2021)

Precipitation showed a higher positive correlation index with throughfall (R^2 = 0.98) than with stemflow (R^2 = 0.26) (Figure 5a and 5b). The data also show that as precipitation volume increases, throughfall and stemflow also increase. On the other hand, the relationship between precipitation and interception (Figure 5c) showed a correlation index R^2 of 0.19, indicating that over time interception capacity decreases exponentially, pointing to the influence of other factors such as rainfall intensity and duration and wind speed and direction.

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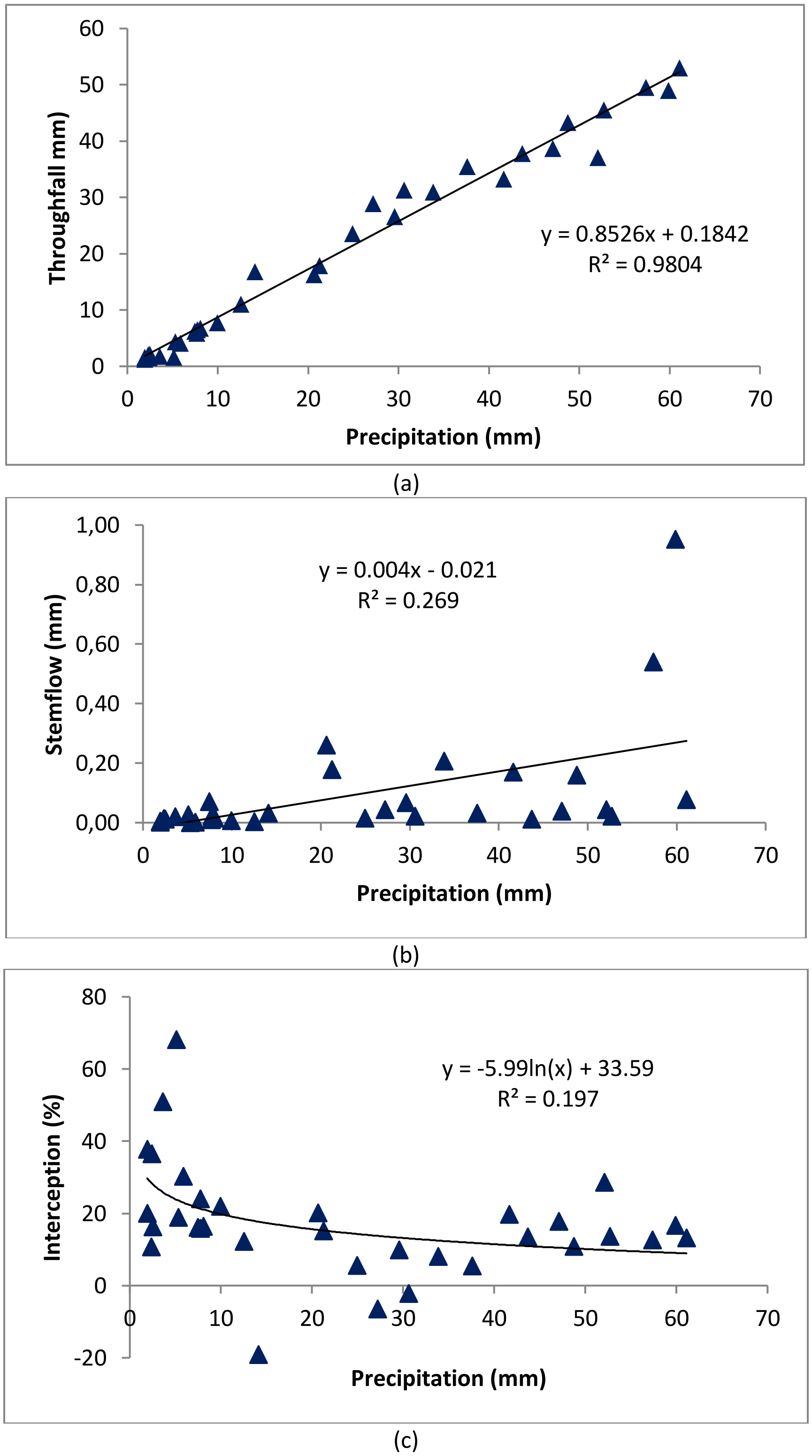

Figure 5- Relationship of precipitation to throughfall, stemflow, and interception in yerba mate in rainfall events.

Throughfall in the herbaceous forests varied from 1.2 to 52.9 mm and stemflow varied from 0.9 to 0.0 mm. The highest relative volumes of throughfall occurred at precipitation higher than 10 mm and the lowest at

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lower precipitation. In contrast, the lowest stemflows occurred when precipitation was less than 20 mm, specifically in the 10-20 mm class (Table 1, Figure 6). It is also noteworthy that the highest yerba mate interception rate was 36.9%, occurring in the average rainfall class of 2.5-5 mm. In contrast, the lowest interception rate was measured in the 10-20 mm rainfall class (-4.3%), i.e., internal precipitation was higher than precipitation itself.

Table 1- Precipitation (P), throughfall (Tf), stemflow (Sf), and interception (I) in the yerba mate monoculture system

		P	Tf		Sf		I	
CLASS (mm)	**Frequency**	**(mm)**	**(mm)**	**(%)**	**(mm)**	**(%)**	**(mm)**	**(%)**
< 2.5	4	8.5	6.3	73.4	0.0	0.4	2.2	26.2
2.5 - 5	2	6.1	3.8	62.6	0.0	0.5	2.2	36.9
5 - 10	8	57.1	42.9	75.1	0.2	0.3	14.1	24.6
10 - 20	2	26.6	27.7	104.2	0.0	0.1	-1.2	-4.3
20 - 30	5	123.5	113	91.5	0.6	0.5	10	8.1
30 - 40	3	102	97.6	95.7	0.3	0.3	4.2	4.1
40 - 50	4	181.1	152.9	84.4	0.4	0.2	27.9	15.4
> 50	5	283.1	233.9	82.6	1.6	0.6	47.5	16.8

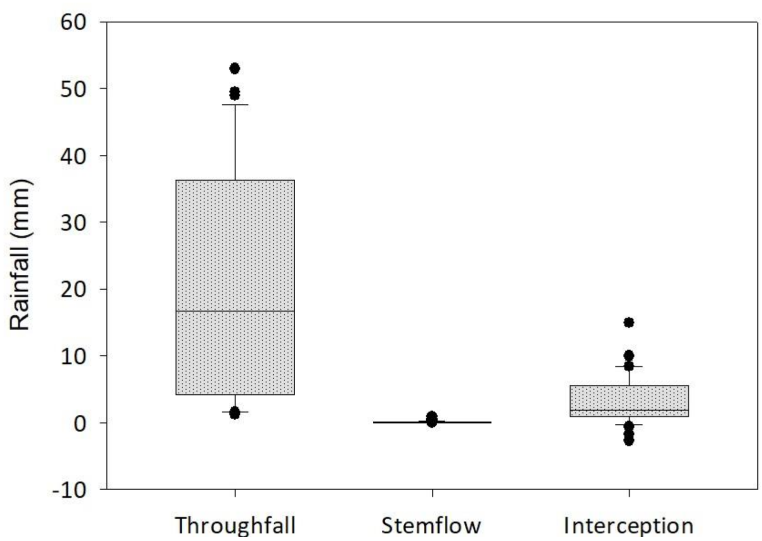

Figure 6- Box-plot of throughfall, stemflow, and interception in the yerba mate monoculture system.

Measurements of a larger volume of mean throughfall than precipitation volume have also been recorded by Lloyd *et al.* (1988) and Crockford and Richardson (2000), as a result of wind speed and rainfall intensity and the structure of the canopy leading to a direction of flow through the leaves to specific points after they have soaked through. According to Calabuig (2013), events that present negative precipitation are known

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as "hidden precipitation", which, in a large number of cases, are of great importance due to the amounts of water collected under the forest cover.

The precipitation partitioning data for yerba mate can be compared to distribution that occurs in tropical and subtropical forests. According to Bruijnzeel (1990), 75% to 96% of rainfall in tropical forests is throughfall, between 1% and 2% is stemflow, and between 4.5% and 24% is intercepted by the canopy. Interception patterns are associated with variations in canopy cover and rainfall characteristics (CROCKFORD; RICHARDSON, 2000). For Giglio and Kobiyama (2013), in Brazilian forests, such as the Atlantic Forest, 8.4% to 20.6% of rainfall is intercepted, whereas in the Amazonian forest interception corresponds to 7.2% to 22.6%.

The interception rate varies temporally in the yerba mate areas due to management practices (Table 2). Kaushal *et al*. (2017) comment that pruning changes the architecture of trees, thus significantly impacting tree biomass and rainfall partitioning. In general, pruning is performed every two years on yerba mate, when the leaves and part of the branches are removed for cultivation and or regrowth.

The average minimum amount of rainfall required for throughfall and stemflow initiation was 1.9 mm. That is, rainfall amounts less than 1.9 mm are totally intercepted by yerba mate.

Table 2- Descriptive statistics of rainfall data by event (mm)

	Mean	**Median**	**Minimum**	**Maximum**	**SD**	**SE**
Throughfall	20.50	16.70	1.10	52.90	12.30	3.00
Stemflow	0.09	0.02	0.00	0.90	0.10	0.03
Interception	3.20	1.80	-2.60	14.90	3.70	0.60

Note: SD = standard deviation and SE = standard error.

The proportion of interception loss concerning precipitation was close to the value found by Scheer (2008) for secondary mixed ombrophilous forest (13% and 16%). Thomaz and Antoneli (2015) analyzed interception of rainfall in a secondary ombrophilous forest fragment interspersed with mixed farming areas (*faxinal* in Portuguese), resulting in interception loss of 10.5%. For Thomaz and Antoneli (2015), the average interception recorded was lower than other Brazilian forests, mainly due to the internal characteristics of the forest, such as change in structure of the middle and lower strata and reduction in the entry of undergrowth.

Different yerba mate management systems cause different impacts on the local microclimate. According to Vieira *et al.* (2003), a difference in average daily air temperature was found between the agroforestry and monoculture systems, with a variation of around 0.5°C. Regarding relative humidity, the maximum difference obtained between the different systems was 1% in winter and 26% in summer. These results show that the extreme values of temperature and humidity were higher in yerba mate cultivated in an agroforestry system as

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a consequence of changes in leaf area and phytomass existing between the plants submitted to the different forms of treatment within the agroforestry system and monoculture system (VIEIRA *et al*., 2003).

Interspecific morphological characteristics of the canopy played an essential role in the interception in yerba mate in a monoculture system. Tomilson (1983) presents 23 models to represent tree architecture. *Ilex paraguariensis* best fits the Attim tree architectural model (Figure 7). This model is determined by irregular growth of branches with thick trunks and broad leaves, with branching occurring either continuously or diffusely.

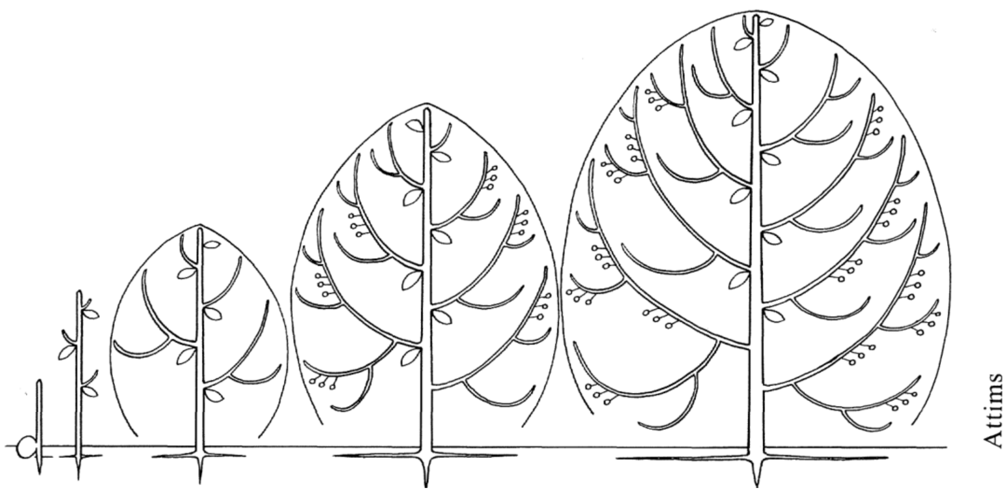

Figure 7- Attims architecture model of tree growth.
Source: Halle *et al.,* (1978).

The leaves of the yerba mate tree act as water collectors due to their shape, and water flows over the leaves generating drops with a diameter possibly larger than natural rainfall drops (THOMAZ; ANTONELI, 2008). Thus, for Ferreira *et al.* (2013), when yerba mate trees are planted alone, they have a lower level of soil protection, but when they are planted together with other MOF forest species this helps to restore ecosystem dynamics and balance.

IV. Conclusion

The partitioning of precipitation into interception, throughfall, and stemflow by vegetation affects the amount and spatial heterogeneity of water in the soil and the dynamics and regulation of hydrological processes. The presence of yerba mate causes alterations in the partitioning of precipitation into interception, throughfall, and stemflow, and consequently affects the dynamics and regulation of hydrological processes.

The study results show that the average interception loss, throughfall, and stemflow in yerba mate accounted for 13.6%, 86.1%, and 0.3% of precipitation, respectively. Stemflow volume is directly related to

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rainfall volume. However, the greater the volume of rainfall, the lower the percentage of stemflow. This reveals that the greater the amount of rainfall, the lower the average percentages of interception. The tendency for interception to increase as rainfall decreases occurs until the < 10 mm class is reached. However, this behavior reverses when considering increased precipitation.

Our results help to understand the key role of the yerba mate canopy that affects the amount of water entering the soil. These results also indicate that yerba mate management practices can produce high evapotranspiration rates, which may increase the risk of lower soil moisture, and indicate that yerba mate found in a monoculture system may have low percentage soil protection, although as a raw material for consumption, it has a high potential for growth and extraction.

Acknowledgments

The authors thank the "Erva-mate 81" company, especially Mr. José Schier and Mr. Marcelo Schier for their support in accessing the experimental area. The first author also thanks the Coordination for the Improvement of Higher Education Personnel/Ministry of Education for his scholarship.

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