Research Article

Interception loss by yerba mate (*Ilex paraguariensis*) in production systems in Southern Brazil[1]

Ezequias Rodrigues dos Santos[2], Leandro Redin Vestena[2], Francisco Belmonte Serrato[3]

ABSTRACT

The partitioning of precipitation into interception, throughfall and stemflow is essential for the hydrological balance in forests, particularly in the Brazilian forest system, regulating the amount of water input and leaf distribution in the ecosystem. This study aimed to present the dynamics of interception loss in yerba mate monoculture, agroforestry and native mixed ombrophilous forest systems, in experimental producing areas in the municipality of Guarapuava, Southern Brazil. The total gross rainfall was 788 mm, distributed in 33 events between July 2019 and March 2020. The throughfall, stemflow and interception loss of rainfall were respectively 78.7, 0.2 and 21.1 % in the native mixed ombrophilous forest; 85.3, 0.1 and 14.6 % in the agroforestry system; and 86.1, 0.3 and 13.6 % in the monoculture system. It was observed that different canopy characteristics influence the variability of rainfall partitioning. The mixed ombrophilous forest showed a higher interception capacity, when compared to the monoculture and agroforestry systems, determined by plant density and meteorological conditions.

KEYWORDS: Agroforestry, ecohydrology, mixed ombrophilous forest.

RESUMO

Perda por interceptação em sistemas de produção de erva-mate (*Ilex paraguariensis*) no Sul do Brasil

A partição da precipitação em interceptação, precipitação interna e escoamento pelo tronco é essencial para o equilíbrio hídrico em florestas, especialmente no sistema florestal brasileiro, regulando a quantidade de entrada de água e a distribuição de folhas no ecossistema. Objetivou-se apresentar a dinâmica de perda por interceptação em sistemas de monocultura, agrofloresta e floresta ombrófila mista nativa de erva-mate, em áreas experimentais de produção no município de Guarapuava, no Sul do Brasil. A chuva total foi de 788 mm, distribuída em 33 eventos entre julho de 2019 e março de 2020. A precipitação interna, escoamento pelo tronco e perda por interceptação da precipitação foram, respectivamente, de 78,7; 0,2; e 21,1 % na floresta ombrófila mista nativa; 85,3; 0,1; e 14,6 % no sistema agroflorestal; e 86,1; 0,3; e 13,6 % no sistema de monocultura. Observou-se que diferentes características de dossel influenciam a variabilidade na partição da precipitação. A floresta ombrófila mista apresentou capacidade de interceptação superior, em comparação aos sistemas de monocultura e agrofloresta, determinada pela densidade de plantas e condições meteorológicas.

PALAVRAS-CHAVE: Agrofloresta, ecohidrologia, floresta ombrófila mista.

INTRODUCTION

The yerba mate (*Ilex paraguariensis*) cultivation plays an important role in the economy of producing countries, due to its economic, social and cultural aspects (Vestena & Santos 2022). Yerba mate belongs to the Aquifoliaceae family and is a native South American tree found mainly in Argentina, Paraguay and the southern states of Brazil (Heck & Mejia 2007, Gawron-Gzella et al. 2021), which extract yerba mate for the domestic market and exportation.

The yerba mate plant presents particular plasticity depending on the type of soil, altitude and temperature, which can affect the leaf composition (Magri et al. 2022). The main production forms is by extractivism, harvesting leaves and branches in a natural environment, as it is an endemic species of the native mixed ombrophilous forest (Atlantic Forest); cultivation in agroforestry system, from planting new seedlings inside the native mixed ombrophilous forest, also called yerba mate densification; and cultivation in monoculture system.

Thus, the interest in research on yerba mate has expanded in recent years, but little is known about the positive and negative impacts of rainwater redistribution by yerba mate, since the vegetation in

[1] Received: Sep. 06, 2023. Accepted: Dec. 18, 2023. Published: Jan. 03, 2024. DOI: 10.1590/1983-40632024v5477226.
[2] Universidade Estadual do Centro-Oeste, Department of Geography, Guarapuava, PR, Brazil.
E-mail/ORCID: ezequiasrses@mail.com/0000-0002-2202-7015; lvestena@unicentro.br/0000-0002-6210-3094.
[3] Universidad de Murcia, Department of Geography, Murcia, Spain. *E-mail/ORCID*: franbel@um.es/0000-0002-1331-1743.

forest environments is an important redistributor of rainwater on ecosystems, and studies on interception loss in annual and perennial crops have been recurrent in recent decades (Antoneli et al. 2021). Interception loss is the amount of rainfall that is intercepted, stored and subsequently evaporated from all parts of the vegetation during or after rainfall (Cui & Jia 2014).

Rainfall partitioning depends on climatic factors and tree characteristics, such as rainfall amount and intensity, wind speed, mean annual temperature and especially the type of vegetation formation: dominant species, density and degree of stratification (Crockford & Richardson 2000). These three fluxes can be altered by various biophysical and anthropogenic factors, and exploring biophysical controls on interception loss and soil water input aids in understanding changes in the soil and water drainage dynamics (Magliano et al. 2019).

Thus, this study aimed to analyze the impacts of yerba mate production systems on the redistribution of rainwater on the soil, providing information that can support a more rational use and management of forests, through the adoption of practices that enable conservation and environmental preservation.

MATERIAL AND METHODS

The study was carried out in a yerba mate growing area in the municipality of Guarapuava, Paraná state, Brazil (between 25º21’53” and 25º23’01”S, 51º17’21” and 51º18’49”W, and altitude of 1,186 m), from July 2019 to march 2020. The climate of the region is Cfb (temperate climate), with cool summers, moderate winters and no dry season, with average annual temperature of 17.5 ºC (Thomaz & Vestena 2003) and average annual rainfall (1991-2021) of 1,872.6 ± 300.7 (IAT 2023). The months with the highest average rainfall were January (216.5 mm) and October (218.6 mm), and the lowest was August (93.7 mm).

The evaluated yerba mate trees (aged from 25 to 28 years old) were located in three areas: monoculture, agroforestry and native mixed ombrophilous forest (Figure 1). The trees in the monoculture and agroforestry areas had an average spacing of 4 m, while, in the native mixed ombrophilous forest, it had an irregular distribution. A total of 8 trees (five *Ilex paraguariensis*, one *Araucaria angustifolia* and two *Campomanesia xanthocarpa*) were used in the experiment.

The yerba mate monoculture system involves the exclusive cultivation of this plant, providing a high production in a specific area, but susceptible to challenges such as pests and diseases (Santos et al. 2022, Santos et al. 2023). On the other hand, the yerba mate agroforestry aims to integrate yerba mate with other plant species, promoting a more sustainable and diversified approach that benefits the soil, biodiversity and ecosystem resilience (Ávila Junior et al. 2016, Urruth et al. 2022). Meanwhile, the mixed ombrophilous forest represents a more natural scenario, where yerba mate coexists with a wide variety of native trees and plants in a balanced ecosystem, favoring biodiversity conservation and the maintenance of ecosystem services (Penteado Junior & Goulart 2017, Vestena & Santos 2022). These approaches reflect on diverse forms of human interaction with yerba mate, ranging from intensive practices to more integrated and sustainable models.

Management practices such as pruning are performed every two years on *Ilex paraguariensis*. Pruning involves cutting the branches and leaves at 10-15 cm above the ground, with the help of electric shears and saws, aiming to acquire a good quality raw material and make the remaining branches form well-structured, productive and healthy canopies (Siles et al. 2010, Penteado Junior & Goulart 2017).

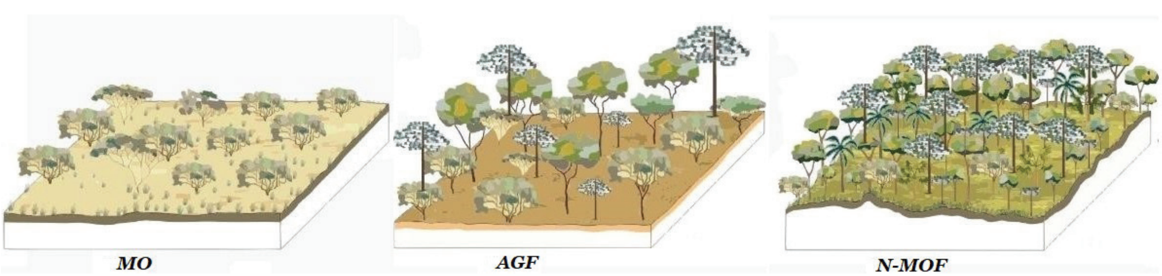

Figure 1. Yerba mate production systems (MO: monoculture; AGF: agroforestry; N-MOF: native mixed ombrophilous forest).

The last prunings performed in the study area took place in August 2018 and March 2020.

Meteorological data for relative humidity, temperature, wind direction and speed, and atmospheric pressure were monitored by an automatic weather station (brand MI-SOL, model WS-2600-1) installed in an open area at 80 m from the monoculture area and at 100 m from the agroforestry and mixed ombrophilous forest, installed at 4 m above the ground. The rainfall events were defined as those with rainfall exceeding 1 mm, also taking into account that each event was characterized by the absence of rain for a minimum period of 24 hours.

The throughfall in monoculture was measured using the same hand-held rain collector model used for rainfall measurement, passing through the vegetation, with the rain gauges distributed in a radial pattern below the yerba mate canopy. In this area, three trees were chosen to represent the crop. In each tree, 18 rain gauges (total of 54 rain gauges) were distributed around the trunk. The internal rainfall value was measured with the same method as the gross rainfall (total volume of gross rainfall multiplied by the collector area). The throughfall for each event was calculated using the throughfall collected from all collectors (Kaushal et al. 2017).

The throughfall under forest cover is highly variable from one point to another, especially at drip sites in areas with overlapping canopies. Llorens et al. (1997) and Rowe et al. (1999) point out that the gutters have a larger catchment area, and because of their rectangular shape, they make it possible to measure throughfall in areas with different canopy overlaps. Thus, differently from the method used to measure the throughfall in the monoculture area, in the agroforestry and mixed ombrophilous forest systems, six gutters (2.00 x 0.13 m) were used, four of which were installed in the agroforestry and two in the mixed ombrophilous forest areas. The throughfall for each event was calculated using the internal rainfall collected from all the gutters in their respective areas (Santos et al. 2023).

The stemflow was collected from eight randomly selected trees using either spiral or collar/funnel-type collectors. The spiral-type collectors were used on trunks larger than 55 cm in diameter and the collar-type collectors on trunks smaller than 55 cm in diameter. The collars were adjusted to the trunk shape and sealed with silicone. The stemflow was diverted from the collars to a collection container with storage capacity of 5-20 L, using ½” diameter PVC hoses (Santos et al. 2023). The corresponding stemflow amount from each selected tree was calculated by dividing the stemflow volume by the crown area. The trees in the experiment were distributed as it follows: three *Ilex paraguariensis* in the monoculture area; two *Ilex paraguariensis*, one *Araucaria angustifolia* and one *Campomanesia xanthocarpa* in the agroforestry area; and one *Campomanesia xanthocarpa* in the mixed ombrophilous forest.

Descriptive statistics were used in the analysis of rainfall partitioning flows (percentage values of interception loss, throughfall and stemflow) at each rainfall event. Linear regression from rainfall to throughfall, stemflow and interception loss was plotted using the rainfall volume data from each area. Analyses of variance followed by the Tukey multiple comparison test at 0.05 were performed to determine significant difference means. The tabulation and statistical analysis were performed using the Microsoft Office and SigmaPlot R 12.0 softwares (Systat Software Inc.).

RESULTS AND DISCUSSION

The gross rainfall over the study period (2019-2020) was 788 mm, with minimum and maximum rainfall of 2.5 mm and 61.1 mm, respectively. The highest rainfall events occurred above 10 mm, thus showing an uneven distribution over the months. According to the accumulated rainfall, 426.3 mm occurred in the spring (54.1 %), 204.5 mm in the summer (26 %) and 157.1 mm in the winter (19.9 %). In the recent study period, the Paraná region experienced a notable disparity in rainfall data, in relation to historical data. The analysis revealed a deficit of 41.6 %, when compared to historical data (1,892.2 mm), a phenomenon mainly attributed to the so-called “veranicos” (period of drought accompanied by intense heat, strong sunshine and low relative humidity) that hit the region during the analyzed period (IAT 2023).

It is also important to note that the study did not cover a full year, what may have influenced the results. Analysis limited to a specific period may not fully reflect the climate variability throughout the year, including important seasonal events that may compensate for the observed shortcomings.

The total throughfall ranged from 78.8 % for the native mixed ombrophilous forest, 86.1 % for monoculture and 85.3 % for agroforestry (Table 1). The mean values increased as the amount of rainfall from the events increased. The interaction in the three yerba mate production systems with rainfall revealed that the mixed ombrophilous forest showed a lower amount of internal rainfall, while, for monoculture, there was an increase.

The stemflow values showed insignificant differences among monoculture (0.3 %), mixed ombrophilous forest (0.2 %) and agroforestry (0.1 %). The three studied areas showed a reduction in stemflow volume as rainfall increased. At certain rainfall volumes, there was a greater trunk runoff production in monoculture than in the other areas. The interception loss was greater in the mixed ombrophilous forest (21.1 % of rainfall) than in the agroforestry (14.6 % of rainfall) and monoculture (13.6 % of rainfall). The values of interception loss were higher in events with a rainfall index of less than 5 mm/event. The three production systems presented this characteristic, thus highlighting that the studied trees have a higher relative interception capacity before the total wetting of leaves and branches.

At a 95 % confidence interval ($p < 0.05$) (Table 2), the hypothesis of equality of the mean interception, throughfall and stemflow occurring in monoculture x native mixed ombrophilous forest was rejected, whereas the hypothesis of equality of the interception and throughfall occurring between agroforestry x native mixed ombrophilous forest and monoculture x agroforestry was not rejected. The results of the present study suggest that yerba mate in monoculture and agroforestry have a little mean difference in interception due to plant density, when compared to the native mixed ombrophilous forest. The yerba mate in agroforestry includes plant thinning, while, in monoculture, the plant density is higher than in the agroforestry and native mixed ombrophilous forest, because the plant has a better development due to the direct incidence of sunlight and the lower competition among species.

Table 2. Simulation by the Tukey test for differences of means.

Variables comparisons	Comparing individual means	p < 0.05
Interception		
MO x N-MOF	24.0	Yes
AGF x N-MOF	18.0	No
MO x AGF	6.0	Yes
Throughfall		
MO x N-MOF	22.5	Yes
AGF x N-MOF	4.5	No
MO x AGF	18.0	No
Stemflow		
MO x N-MOF	39.5	Yes
AGF x N-MOF	20.5	Yes
MO x AGF	19.0	No

MO: monoculture area; AGF: agroforestry area; N-MOF: native mixed ombrophilous forest.

The throughfall, stemflow and interception loss were shown to be positively correlated with gross rainfall (mm). The rainfall values for throughfall ranged from 1.2 to 52.9 mm of the individual rainfall events in the monoculture; from 0.3 to 59.6 mm in the agroforestry; and from 0.2 to 60.8 mm in the mixed ombrophilous forest. Similarly, the stem runoff ranged from 0.0 (0.0015) to 0.9 mm of the individual rainfall events in the monoculture; from 0.0 (0.0001) to 0.1 mm in the agroforestry; and from 0.0 (0.0004) to 0.2 mm in the mixed ombrophilous forest. The interception ranged from -2.6 to 14.9 mm of the individual rainfall events in the monoculture; from -1.4 to 14.9 mm in the agroforestry; and from -3.7 to 16.5 mm in the mixed ombrophilous forest.

The relationships between gross rainfall with throughfall, stemflow and interception loss are presented in Figure 2. The mean throughfall in monoculture events was 20.5 ± 17.3 mm (≈86.1 % of gross rainfall). There was a significant linear relationship between the mean throughfall of the events, which was derived from all 18 collectors and gross rainfall (Figure 2a). For the agroforestry, the average throughfall per event was 20.4 ± 18.3 mm

Table 1. Cumulative measured values of throughfall, stemflow and interception loss from July 2019 to March 2020.

Experimental plot	Throughfall		Stemflow		Interception	
	mm	% GR	mm	% GR	mm	% GR
MO	678.1	86.1	3.1	0.3	106.8	13.6
AGF	672.3	85.3	0.8	0.1	114.9	14.6
N-MOF	619.9	78.7	1.4	0.2	166.6	21.1

MO: monoculture area; AGF: agroforestry area; N-MOF: native mixed ombrophilous forest. The gross rainfall (GR) on the three plots is equal to 788 mm.

(≈85.3 % of gross rainfall). There was a significant linear relationship between mean throughfall and gross rainfall (Figure 2b). Finally, the average throughfall per event in the mixed ombrophilous forest was 29.4 ± 18.5 mm (≈78.7 % of gross rainfall). As with the other production systems, there was a significant linear relationship between throughfall and gross rainfall (Figure 2c).

The interception loss rate gradually decreased in the three study areas until it stabilized. At the beginning of each rainfall event, the interception capacity was higher, but this process decreased as rainfall continued and/or its intensity increased.

This study reveals that the throughfall and stemflow are greater in "disturbed" plants, which suffer the effect of pruning, than in "intact" plants located in areas with little anthropic action. In the field analyses, it was noticed that the yerba mate in monoculture presented a larger width than that in agroforestry, and, consequently, a higher plant density, in relation to the yerba mate in the agroforestry system. However, in the agroforestry, the yerba mate had a greater height. These dasometric characteristics are related to how much insolation each yerba mate tree receives.

In the agroforestry, new yerba mate seedlings are planted in the middle of the mixed ombrophilous forest. This system requires interventions in the vegetation to allow a simultaneous cultivation by cutting and pruning trees, shrubs or vines (Urruth et al. 2022). Another system of yerba mate production is carried out by planting only yerba mate in a given area, a practice of monoculture.

The light influences the appearance of the plant and, in places where light is abundant, the plants are more engaged and have a greater amount of leaves (Troppmair 1995). The monoculture area has a greater insolation reception, for not having other larger vegetation around it, and the plant development is more accelerated, while the yerba mate in agroforestry has larger trees around it, above 10 m, as *Araucaria angustifolia*, *Ocotea porosa*, *Ocotea pulchella* and *Campomanesia xanthocarpa*, partly camouflaging the insolation passage.

The model that compares rainfall with stemflow in the yerba mate monoculture (Figure 2d)

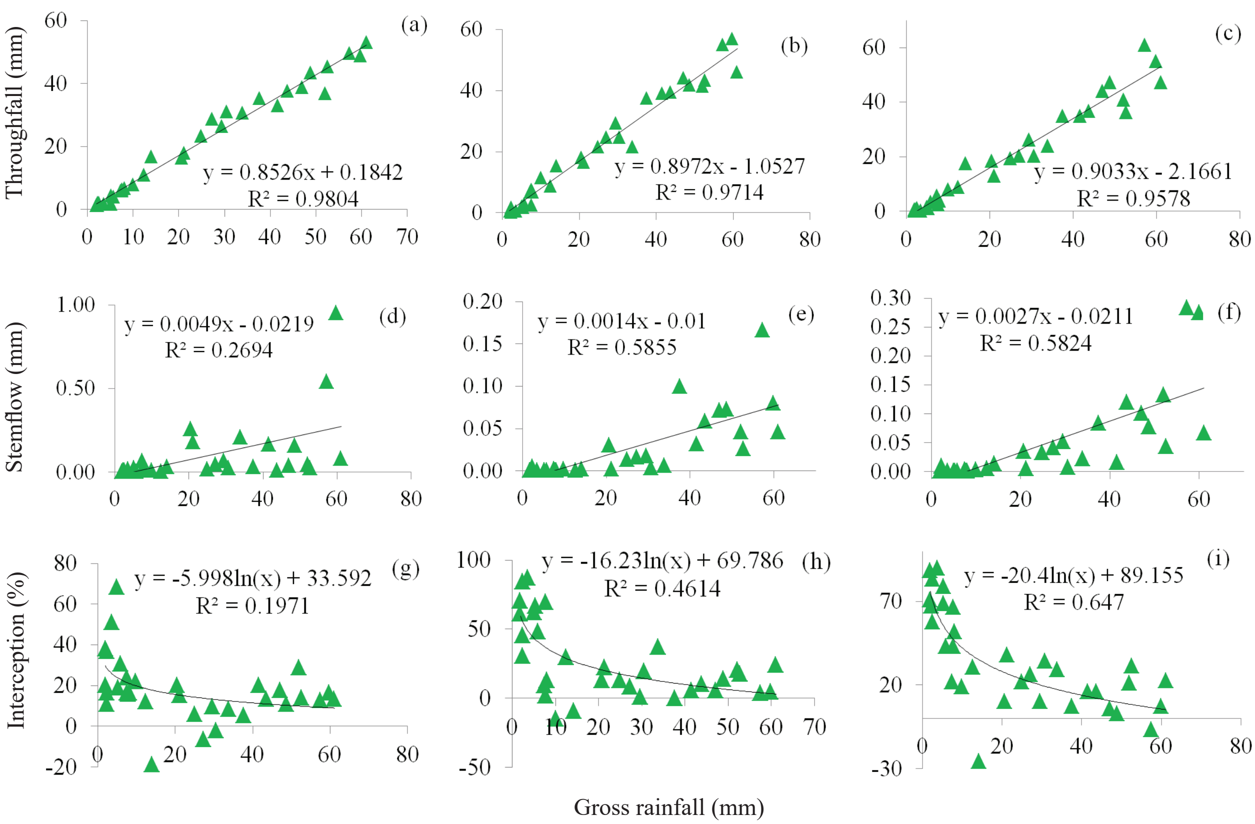

Figure 2. Coefficient of variation of gross rainfall (x axis) for throughfall, stemflow and interception (y axis) in yerba mate in monoculture (a, d and g), agroforestry (b, e and h) and native mixed ombrophilous forest (c, f and i).

explains only 20 % of the variability observed for stemflow. This indicates that there is a significant amount of variability in this phenomenon that is not being captured by the model. For the agroforestry and native mixed ombrophilous forest (Figures 2e and 2f) with yerba mate, the model explains 50 % of the variability for stemflow, in relation to the amount of rainfall. This suggests a significant improvement, when compared to the yerba mate monoculture, but there is still a substantial amount of variability that is not explained by the model.

The model has an insignificant fit to the data, and the amount of rainfall is not contributing significantly to explaining the variations in interception capacity in the monoculture (Figure 2g). The R^2 of 0.4 indicates that 40 % of the variability in the interception capacity is explained by the amount of rainfall in the yerba mate agroforestry (Figure 2h). Although this is a better fit, if compared to monoculture, there is still a considerable amount of variability not explained by the model.

The highest R^2 of 0.6 suggests that 60 % of the variability in the interception capacity is explained by the amount of rainfall in the native mixed ombrophilous forest (Figure 2i). This is the strongest fit among the three growing environments, indicating that the model has a relatively better ability to explain the variations in interception capacity in the forest. However, all three graphs indicate that, as the amount of rainfall increases, the ability of plants or vegetation to intercept this rainfall decreases. This pattern could have important implications for environmental and agricultural management, highlighting the complexity of the interactions between rainfall and interception capacity in different growing environments.

The composition of a lower canopy, mostly formed by cordgrass and the extraction of leaves and twigs, can influence the hydrological cycle, affecting the distribution and interception of rainfall, runoff, infiltration and evapotranspiration (Siles et al. 2010). In a coffee plantation in Costa Rica, these results are also comparable to yerba mate, where the interception loss managed in agroforestry and monoculture resulted in 13 and 15 % of rainfall, respectively (Siles et al. 2010), but with agroforestry achieving lower interception rates.

The difference in stemflow in the three areas was not significant. The differences in stemflow appear when plants with rough barks (change in morphological characteristics of plant species) and old plants have lower stemflow than plants with younger canopies, and they also have greater losses than plant species with smooth bark and broad leaves, because they increase the amount of rainwater reaching the ground, potentiating the stemflow (Chen & Li 2016, Shou et al. 2016, Magliano et al. 2019, Whitworth-Hulse et al. 2020).

Thus, the interception loss in mixed ombrophilous forest is comparatively higher than in monoculture and agroforestry yerba mate production systems, for presenting a diversified and higher density of forest species. In the agroforestry, the forest structure is altered through thinning of leaves and branches and suppression of plants for the cultivation of yerba mate trees with a reduction in forest density.

The results obtained from the data collected in the present study reveal that the volume and spatial pattern of throughfall distribution depend, among other factors, on the storage capacity of the canopy, which, in turn, is determined by the amount of biomass in its structure and the characteristics of rainfall events (rainfall volume, intensity and duration) (Li et al. 2019).

The interception losses in Brazilian forests reach considerable values, especially regarding the high rainfall in these regions, despite the indications of greater losses in temperate forests than in tropical forests (Durocher 1990). In the dry season, the occurrence of greater evaporation is normal, and, besides that, changes in the canopy structure also interfere with the interception process (Chen & Li 2016). A difference that causes the redistribution of rain was observed in the rainfall splitting process in the monoculture and agroforestry yerba mate production systems.

The use of conventional systems for long periods without adopting conservationist practices increases the physical and biological degradation of an environmental system, making it increasingly fragile (Reichert et al. 2022). Yerba mate in a natural environment, when not used for extraction, helps in the hydrological process of the forest, but its use for extraction generates some impacts on the forest which should be better analyzed in further studies.

The agroforestry system is considered one of the most sustainable cropping systems, bringing many ecological benefits, in relation to soil properties, biodiversity and pest control (Ávila Junior et al.

2016). The results of the present study show that the yerba mate in the agroforestry and monoculture systems obtained non-significant results, regarding the interception loss process, being explained by the removal of part of the arboreal vegetation for the plantation of yerba mate.

The benefits of yerba mate cultivation systems in South America are very useful for local farmers. However, in order to combine yield and conservation in Southern Brazil, more efforts must be made to make the system more sustainable.

CONCLUSIONS

1. Rainfall partitioning for yerba mate in monoculture and agroforestry systems is lower, when compared to that of native mixed ombrophilous forest. The rainfall interception, throughfall and stemflow in the investigated yerba mate production systems were, respectively, 21.1, 78.8 and 0.2 % for the native ombrophilous forest; 14.6, 85.3 and 0.1 % for agroforestry; and 13.6, 86.1 and 0.4 % for monoculture;
2. Different canopy characteristics influence the throughfall variability. Rainfall reaches the soil directly through openings in the canopy cover or as dripping, and the concentration of rainwater in rangeland production systems is directed to specific points in the soil when under high rainfall;
3. When cultivated in the agroforestry system, yerba mate presents results of interception loss similar to the monoculture system. This is explained by the management techniques adopted in part of the forest in order to cultivate yerba mate in the agroforestry system.

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