Revista Brasileira de Recursos Hídricos
Brazilian Journal of Water Resources
Versão On-line ISSN 2318-0331
RBRH, Porto Alegre, v. 28, e20, 2023
Scientific/Technical Article

https://doi.org/10.1590/2318-0331.282320220111

Modeling vegetation interception under natural rainfall in yerba mate production systems

Modelagem da interceptação vegetal sob chuva natural em sistemas de produção de erva-mate

Ezequias Rodrigues dos Santos[1], Leandro Redin Vestena[1] & Jacques Carvalho Ribeiro Filho[2]

[1]Universidade Estadual do Centro-Oeste, Guarapuava, PR, Brasil
[2]Universidade Federal do Ceará, Fortaleza, CE, Brasil
E-mails: ezequiasrses@gmail.com (ERS), lvestena@unicentro.br (LRV), jacquesfilho1@hotmail.com (JCRF)

Received: November 12, 2022 - Revised: April 26, 2023 - Accepted: May 21, 2023

ABSTRACT

Interception loss plays an important role in rainfall partitioning, retaining significant amounts of water that would be directed to the soil. In this work, the objective was to measure interception by vegetation and evaluate the Rutter and Gash models to estimate the interception in different yerba mate production systems. The study was conducted the period from July/2019 to March/2020 in the municipality of Guarapuava, southern Brazil. The total rainfall, stemflow, and the throughfall were monitored in each rainfall event. Rutter and Gash interception models were applied. The interception losses estimated by Rutter and Gash models were considered satisfactory but, in general, underestimated. In the yerba mate monoculture system, an average interception loss of 15.6% was recorded, in the yerba mate agroforest, 21.4%, and, in the native Mixed Ombrophilous Forest, 16.2%. Rutter's model presented estimates close to the measured rainfall interception estimate for the yerba mate monoculture system and Gash's model for the agroforestry system and the native Ombrophilous Mixed Forest.

Keywords: Throughfall; Stemflow; Rutter model; Gash model.

RESUMO

A perda de intercepções desempenha um papel importante na divisão da chuva, retendo quantidades significativas de água que seriam direcionadas para o solo. Neste trabalho, o objetivo foi medir a intercepção por vegetação e avaliar os modelos Rutter e Gash para estimar a intercepção em diferentes sistemas de produção de erva-mate. O estudo foi realizado no período de Julho/2019 a Março/2020 no município de Guarapuava, sul do Brasil. Foram monitoradas a chuva total, o escoamento pelo tronco e a precipitação interna em cada evento pluviométrico. Foram aplicados modelos de intercepção de Rutter e Gash. Os resultados da perda por intercepção estimados pelos modelos Rutter e Gash foram considerados satisfatórios e, em geral, subestimaram a perda por intercepção. No sistema de monocultura de erva-mate, foi registrada uma perda média de intercepção de 15,6%, na agrofloresta de erva-mate, 21,4%, e na Floresta Ombrófila Mista nativa, 16,2%. O modelo de Rutter apresentou estimativas próximos da estimativa de interceptação pluviométrica medida para o sistema de monocultura de erva-mate e o modelo de Gash para o sistema agroflorestal e a Floresta Ombrófila Mista nativa.

Palavras-chave: Precipitação interna; Escoamento pelo tronco; Modelo de Rutter; Modelo de Gash.

INTRODUCTION

The rainfall interception by the canopy is an important component of hydrological cycles, and trees play an significant role in the water cycle, returning a large amount of water to the atmosphere through evapotranspiration (Linhoss & Siegert, 2020; Wei et al., 2022).

Interception studies in annual and perennial crops have often been expanded in recent years, while few studies have been conducted in different Ilex paraguariensis producing systems (Antoneli et al., 2021). However, Santos et al. (2022) found that interception loss in yerba mate in monoculture system represented an average of 13% of total rainfall.

Yerba mate (Ilex paraguariensis) is a shade-tolerant tree found in southern Brazil, Argentina, Paraguay, and Uruguay (Ávila Júnior et al., 2016; Vestena & Santos, 2022) and is cultivated in both consortium and monoculture systems. In addition, when properly managed in consortium with forest (agroforestry), it can contribute to the conservation of tree species, soil and water conservation, and the generation of ecosystem services (Vestena & Santos, 2022). Thus, measurement and modeling are essential for understanding water balances and formulating scientific management strategies in different ecosystems (Návar, 2017; Wang et al., 2022). And quantifying and modeling interception loss in Ilex paraguariensis under different production systems is important to improve our understanding of the effect of yerba mate planting on regional water balances and to formulate reasonable strategies for managing water resources in the southern region of Brazil.

In this study, we measured rainfall, throughfall, stemflow and interception loss during the period 07/2019 to 03/2020 in three production systems of Ilex paraguariensis in the municipality of Guarapuava, southern region of Brazil. We modeled interception loss using the Rutter and Gash model in monoculture and agroforestry of Ilex paraguariensis and in the Native Mixed Ombrophylous Forest (Native MOF). The objective of this study was: (1) to quantify the interception loss for different yerba mate production systems and (2) to evaluate the efficiency of Rutter and Gash models in determining interception loss in different yerba mate cultivation and production systems.

MATERIAL AND METHODS

Study area

The experimental area is located in the municipality of Guarapuava, southern Brazil (Figure 1) on a private property (31 ha) with a monoculture yerba mate production system (6 ha), an agroforestry system (6 ha) and a native Mixed Ombrophilous Forest (19 ha).

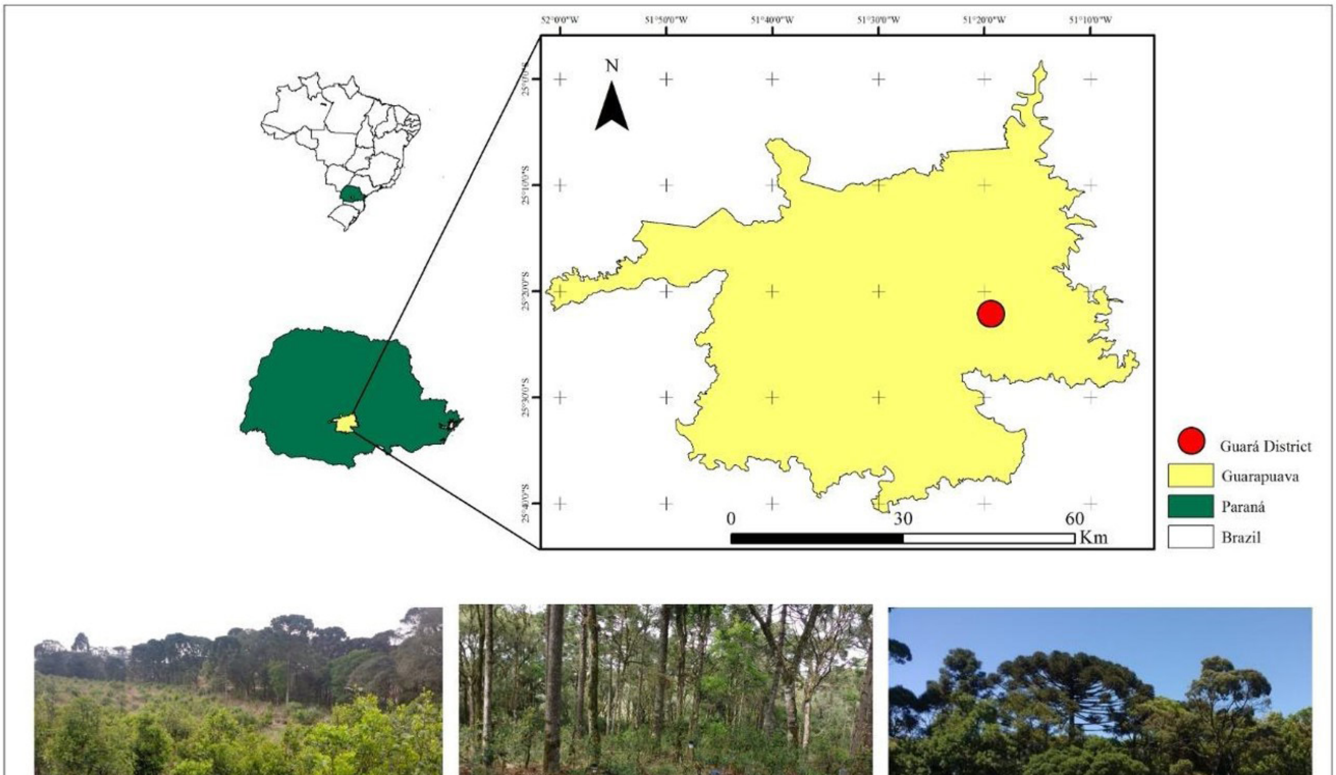

Figure 1. Location map of the study site in the District of Guará, Paraná, in the municipality of Guarapuava, in the south of Brazil. The abbreviation MO represents yerba mate in monoculture system; AGF yerba mate in agroforestry system, and N-FOM represents Mixed Native Ombrophylous Forest.

The average elevation in the experimental area is 1,080 meters above sea level, located between coordinates 25°21'53" and 25°23'01" South Latitude and 51°17'21" and 51°18'49" West Longitude. The average annual rainfall (1991-2020) in the area is 1,892.2 mm (Instituto das Águas do Paraná, 2023), and the climate is Cfb (temperate climate) according to the Köppen classification (Figure 2). The average annual temperature is 17.0°C, with cool summers, moderate winters, and no dry season (Thomaz & Vestena, 2003).

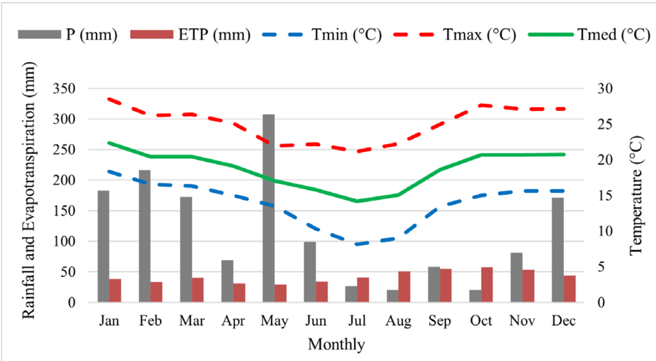

Figure 2. Monthly distribution of precipitation, evapotranspiration, and temperature in Guarapuava, Paraná, Brazil.
Note: P – rainfall; ETP – evapotranspiration; Tmin – minimum temperature; Tmax – maximum temperature; Tmed – mean temperature.

Soil and vegetation

The Guarapuava region predominant soils are classified as Red-Yellow Latosols with low cation exchange capacity, deep, acidic, and with low base saturation (V < 50%). It presents low levels of natural fertility requiring the use of fertilizers for good productivity (Empresa Brasileira de Pesquisa Agropecuária, 2018; Santos et al., 2022).

The experimental plot is mostly occupied by yerba mate (*Ilex paraguariensis*). In the experimental area of the monoculture system, the yerba mate is planted at an average distance of 4 m x 4 m, with ages ranging from 25 to 28 years. The soil surrounding the yerba mate in the monoculture system is covered by grazed natural vegetation (grasses, herbaceous plants, and shrubs), such as barba-de-bode grass (*Aristida pallens*), rabo-de-burro (*Andropogon sp.*), vassourinha (*Miconia candolleana* and others), caninha grass (*Andropogon icanus*), and capim flexa (*Tristachya chrysothrix*) (Santos et al., 2022).

The yerba mate agroforestry system is characterized by the removal of the lower stratum to provide a greater incidence of sunlight, essential for the yerba mate development. The understory is formed by forage species and by extensively managed weeds, providing a layer of litter. The average spacing between the yerba mate plants in the agroforestry system is also 4 m x 4 m. In the experimental area (40m X 45m), 214 yerba mate trees (*Ilex paraguariensis*); five imbuia (*Ocotea porosa*); three canelas (*Ocotea pulchella*); fifteen araucárias (*Araucaria angustifolia*), two samambaia-açu (*Dicksonia sellowiana*), and one gabirobeira (*Campomanesia xanthocarpa*) were encountered.

In the Native MOF, there is a diversity of species distributed in three levels: the first lower extract formed by herbaceous plants and grasses, such as *Hydrocotyle exigua* (Urb.) *Malme* and *Achyrocline satureioides* (Lam.) DC.; The second extract is formed by shrubs such as Yerba Mate (*Ilex paraguariensis*) and *Mollinedia schottiana* (Spreng). Finally, the third extract is formed by trees such as Araucária (*Araucaria angustifolia*), gabirobeira (*Campomanesia xanthocarpa*), imbuia (*Ocotea porosa*), and canela (*Ocotea pulchella*). In this area, there is the presence of species such as *Merostachys skvortzovii* SEND (taquara-lixa), *Dicksonia sellowiana* (samambaia-açu), and Lianas (cipó) (Instituto Brasileiro de Geografia e Estatística, 2012).

Meteorological data

Daily meteorological data were collected during the period from July/2019 to March/2020 by a weather station installed in an open area at the edge of the experimental area at a height of two meters above the ground surface. The station monitored total rainfall (0.2 mm resolution), air temperature, relative humidity, solar radiation, wind speed and direction continuously at five-minute intervals. The weather station was installed 80 m away from the monoculture system and 100 m away from the yerba mate in consortium and Native MOF.

Throughfall and stemflow

The throughfall in the monoculture area was measured using 54 rain gauges distributed around three yerba mate trees, 18 rain gauges in each yerba mate tree (Figure 3a). In the agroforestry system and the Native MOF, six 2.00 m X 0.13 m gutters were used, four of these installed in the agroforest and two in the forest.

The stemflow was collected from eight randomly selected trees using either spiral or collar/funnel type collectors from flexible PVC hoses. The spiral-type collectors were used on trunks larger than 55 cm in diameter, and the collar-type collectors were used on trunks smaller than 55 cm in diameter (Figure 3b). The collars were adjusted to the trunk shape and sealed with silicone. The stemflow was diverted from the collars into a collection containers with a storage capacity of 5 to 20 L. The corresponding stemflow amount from each selected tree was calculated by dividing the stemflow volume by the crown area. Stemflow was monitored on three *Ilex paraguariensis* in the monoculture area; two *Ilex paraguariensis*, one *Araucaria angustifolia*, and one *Campomanesia xanthocarpa* in the agroforestry area; and finally, one *Campomanesia xanthocarpa* in the Native MOF.

Rainfall events in which the observed throughfall was greater than the total rainfall were excluded because they generated negative interception.

Modeling interception loss

The models of Rutter et al. (1971) and Gash (1979) were used to predict interception losses in different yerba mate production systems. The following section describes the interception models, their equations, and the methodology for calibrating the data.

Figure 3. Materials used to measure throughfall and stemflow in this study. (a) Monoculture system; (b) Agroforestry system; and (c) Native Mixed Ombrophilous Forest.

The Rutter model was run at hourly time-scale and the results were aggregated at daily time-scale to be comparable with the Gash model results, which are simulated at daily event scale.

The potential evapotranspiration in the experimental area was estimated using the modified Penman method (Doorenbos & Pruitt, 1977), from temperature, relative humidity, incident solar radiation, and wind speed data monitored at the Simepar weather station.

$$E_P = F\left[W \cdot Rad_n + (1-W)\cdot f(u)\cdot(e_a - e_d)\right] \quad (1)$$

The modified Penman method results in daily averages of potential evapotranspiration. Here, E_P is the potential evapotranspiration (mm/d^{-1}); F is the correction factor for the region in question; W is the weighting factor related to temperature and altitude; Rad_n is the net radiation expressed as equivalent evaporation (mm/d^{-1}); $f(u)$ is the wind-related function; e_a is the water vapor pressure in saturated air (mbar); and e_d is the water vapor pressure in the actual condition (mbar) (Sá et al., 2015).

Rutter model

Rutter's model is based on the estimation of throughfall, stemflow, and interception losses based on the amount of water in the canopy, including the timing of rainfall, evaporation, drainage, and changes in canopy storage, where evaporation from the wet canopy constitutes the interception loss (Rutter et al., 1971; Eliades et al., 2022). The main disadvantage of Rutter's model is that it requires hourly meteorological data that are often not available.

Rutter's model uses equations that describe canopy water balance (Equation 2), trunk water balance (Equation 3), canopy drainage rate (Equation 4), canopy evaporation (Equation 5), stemflow (Equation 6), and trunk evaporation (Equation 7) (Linhoss & Siegert, 2020).

$$(1 - p - p_t)\int R\,dt = \int D\,dt + \int E\,dt \quad (2)$$

$$p_t \int R\,dt = Sf + \int E_t\,dt + \Delta C_t \quad (3)$$

$$D_C = \begin{cases} D_S \exp[b(C-S)] C \geq S \\ 0 \quad\quad C < S \end{cases} \quad (4)$$

$$E_C = \begin{cases} E_P \dfrac{c}{S} & C < S \\ E_P & C \geq S \end{cases} \quad (5)$$

$$Sf = \begin{cases} C_t - S_t & C_t \geq S_t \\ 0 & C_t < S_t \end{cases} \quad (6)$$

$$E_t = \begin{cases} \in E_P \dfrac{c}{s} & C_t < S_t \\ \in E_P & c_t \geq S_t \end{cases} \quad (7)$$

Where R is the average rainfall rate, S is the maximum canopy storage capacity, S_t is the maximum stem storage capacity, p is the free throughfall coefficient, p_t is the stemflow coefficient, C is the actual canopy storage capacity, C_t is trunk storage, E_P is the potential evaporation, E_C is the canopy evaporation, E_t is stem evaporation, ∈ describes stem evaporation as a proportion of evaporation from the saturated canopy, D_S is the rate at which water drips from the canopy when the canopy storage capacity has been reached, b is a drainage parameter, and I is interception (Linhoss & Siegert, 2020).

Gash model

Gash's model (1979) makes an analysis of rainfall from the capacity of vegetation to be saturated with considering the potencial evaporation during the rainfall event (Equations 8 and 9). The model was conceptually based on Rutter's model but replaced the numerical approach of that model with analysis by discrete storm events separated by intervals long enough for the canopy and stems to dry completely, making it simpler to apply, i.e., 1) the canopy wetting phase, (2) the canopy saturation phase, and (3) the canopy drying phase (Linhoss & Siegert, 2020).

$$\sum_{j=1}^{n+m} I_j = n\left(1-p-p_t\right)P'_G + (\bar{E}/\bar{R}) \quad (8)$$
$$\sum_{j=1}^{n}\left(P_{Gj}-P'_G\right)+\left(1-p-p_t\right)\sum_{j=1}^{m}P_{Gj}+qS_t+p_t\sum_{j=1}^{m+n-q}P_{Gj}$$

$$P'_G = (-\bar{R}S/\bar{E})In\left\{1-(\bar{E}/\bar{R})\left(1-p-p_t\right)^{1}\right\} \quad (9)$$

The p, p_t, S, and S_t parameters of this model are equal to Rutter's model. Ē is the average evaporation rate during post-saturation rainfall, R̄ is the average intensity of post-saturation rainfall, P_{GJ} is the amount of rainfall in a given rainfall event, and P'_G is the amount of rainfall required to reach canopy saturation. In this model, n is the number of storms that saturate the canopy, m is the number of storms insufficient to saturate the canopy, q is the number of storms with stemflow.

Calibration and validation

Model calibration is a phase that ensures improved results based on realistic, physically-based parameter values and can be used to identify flaws in the way systems that are perceived and modeled (Linhoss & Siegert, 2020). For modeling the interception process, the parameters required by the Rutter et al. (1975) and Gash (1979) models were estimated by applying existing equations (Ribeiro Filho et al., 2019). In each area (Table 1), the storage capacity (S) and the free throughfall coefficient (*p*) were applied according to the method of Leyton et al. (1967) and Rutter et al. (1971), respectively. The stemflow parameters and the proportion of rain that runs off the branches and trunks were deduced using a regression calculation methodology between stemflow versus rainfall. The parameter *b* was obtained from the methodology proposed by Schellekens et al. (1999), and the parameter Ds from the value given by Lloyd & Marques (1988).

The calibration and validation of Rutter and Gash models were determined by means of linear regression. In order to calculate the model estimate error, the Nash & Sutcliffe (1970) coefficient was also used for the data set measured in the field and estimated by the models. This coefficient can range from -1 to 1, and the performance of a model is considered adequate and good if the NSE value exceeds 0.75, and it is considered acceptable if the NSE value is in the range between 0.36-0.75 (Ribeiro Filho et al., 2019).

The Percent Bias (Pbias) calculation was also used to identify the overall over or underestimation settings of the sample. The ideal value of Pbias is 0 (zero). Positive values indicate an underestimation, and negative values indicate an overestimation. The ranges of values used for satisfactory or unsatisfactory judgment of the models are NSE ≥0.5 and Pbias ≤±25% (Moriasi et al., 2007).

RESULTS AND DISCUSSION

In the years 2019 and 2020, the total annual rainfall was below the average of the historical series (1,892.2 mm), 1,401.6 (-25.9%) and 1,338.3 mm (-29.3%), respectively. The monthly rainfall during the study period was lower than the monthly average of the historical serie. The lower average rainfall volume in the period was due to the formation of "veranicos" because of longer than usual dry spells (Sistema de Tecnologia e Monitoramento Ambiental do Paraná, 2020).

Interception loss in the different yerba mate production systems ranged from 15.2 to 21.4% of total rainfall (Table 2). The interception patterns recorded are associated with variations in canopy cover and rainfall characteristics. Thus, our results are within the interception pattern in tropical forests, where the vegetation characteristic is dense, but the interception loss depends on the intensity and amount of rainfall.

Table 1. Parameter values of Rutter and Gash models.

	Rutter/Gash			
	S	***p* (mm)**	**b**	**Ds (mm/min^{-1})**
Yerba mate monoculture	1.1552	0.8521	5.25	0.0014
Yerba mate agroforestry	2.4511	0.8991	5.25	0.0014
Native MOF	3.0065	0.876	5.25	0.0014

S – water retained in the canopy; *p* – free throughfall; b – empirical parameter; Ds – drainage when the canopy is saturated.

Table 2. Summary of data measured in the different yerba mate production systems.

Yerba Mate Production System	Number of events considered in the modeling	Gross rainfall (mm)	Throughfall (mm) (%)	Stemflow (mm) (%)	Interception loss (mm) (%)
Monoculture	30	716.2	601.2 (83.9)	3.0 (0.4)	112 (15.6)
Agroforestry	31	716.7	608.0 (84.8)	0.7 (0.1)	153.6 (21.4)
Native MOF	30	726.5	562.0 (77.4)	1.1 (0.2)	117.8 (16.2)

The values measured in the different production systems corroborate the results obtained in araucaria forest environments, similar to the native MOF environment developed by Calux & Thomaz (2013), who obtained interception loss values ranging from 14 to 26% of the total rainfall. In the native MOF, the interception loss is higher than the ones found in monoculture and agroforestry systems due to the denser vegetation and greater diversity of plant species.

Rutter and Gash's estimates

In the three yerba mate production systems, both Rutter and Gash models tended to underestimate interception (Figure 4). The monoculture yerba mate showed the lowest underestimation, on the order of -1.3% and -3.1% for Rutter and Gash, respectively. In the agroforestry system, the estimate was on the order of -6.3% and 5.7%, for Rutter e Gash, respectively. The forest area presents greater tree volume and the underestimation tends to increase since the area of native MOF presents estimation of -9.3% and 8.0% for Rutter and Gash models, respectively.

A study conducted by Ribeiro Filho et al. (2019) in Brejo de Altitude of the northeastern Atlantic forest showed underestimation with data above 19%, being considered acceptable differences (<25%). Interception in the different yerba mate production systems also showed similar characteristics, the highest rates of rainfall interception were found in the events that had lower rainfall rates, and interception rate decreased until it stabilized as the rain continued. The relative interception losses estimated by the models, as observed in the field, were greater in rainfall events with low intensity, long duration, and discontinuous rainfall than in events with high intensity and short duration.

The total interception of the study was underestimated by both models. In comparing the application of the Gash and Rutter models, it can be seen that the results presented satisfactory for an interception estimate (Figure 5). The interception loss measured at each event was on average greater (112 ± 0.64 mm) than obtained by the Rutter (102.4 ± 0.58 mm) and the Gash (89.8 ± 0.34 mm) models for the monoculture area. In yerba mate agroforestry the same pattern occurred, the interception loss measured at each event was on average greater (117.8 ± 0.65 mm) than obtained by the Rutter (72.3 ± 0.37 mm) and the Gash (76.6 ± 0.32 mm) models. As in the previous area, the interception loss measured at each event was on average greater (153.6 ± 0.69 mm) than obtained by the Rutter (87.1 ± 0.43 mm) and the Gash (95.9 ± 0.33 mm) models.

The interception loss measured at each event showed greater rate in values in both yerba mate production systems than that estimated by Rutter and Gash models (Figure 6). Both models showed limitations in estimating extreme interception loss values (outliers). In this sense, Vieira & Palmier (2006) had already pointed out that, although studies in tropical forests indicated the models as adequate, it was not known whether the description of the phenomenon considers well the extreme events present in tropical climate regions.

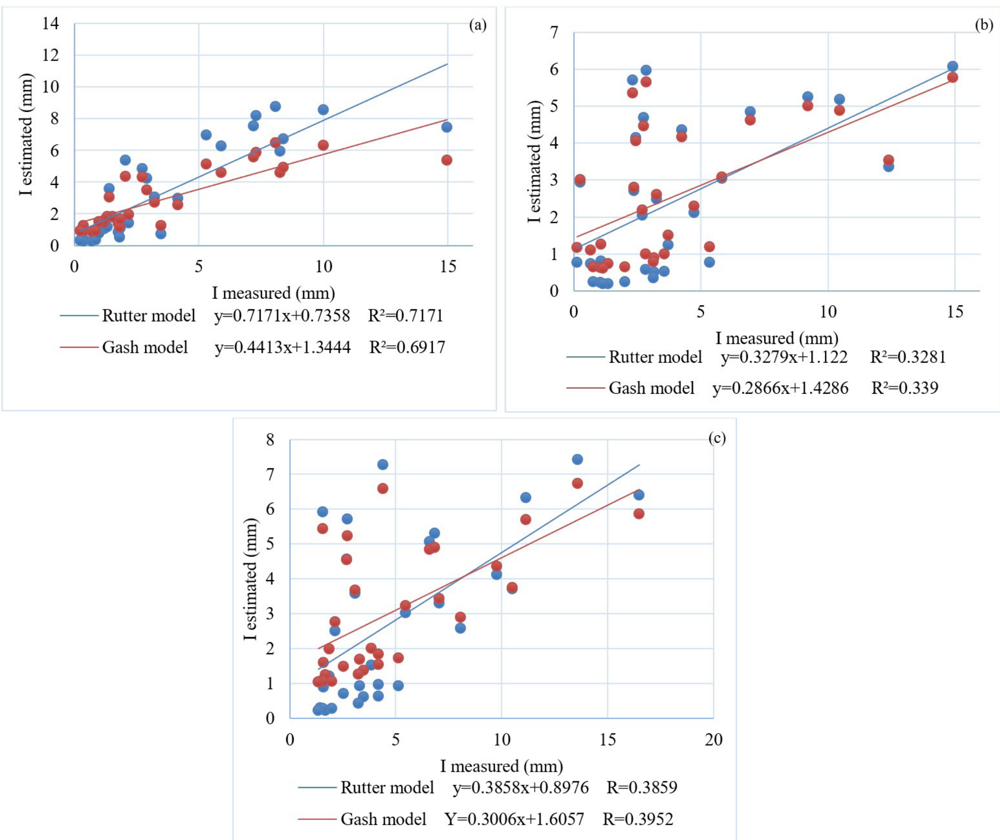

Figure 4. Relationship between measured interception and modeled interception. (a) Yerba mate monoculture; (b) Yerba mate agroforestry; and (c) Native mixed ombrophilous forest.

Table 3. NSE and Pbias values in the performance analysis of Rutter and Gash models.

	Monoculture yerba mate	Agroforestry yerba mate	Native MOF
NASH (Rutter)	0.99	0.84	0.80
NASH (Gash)	0.96	0.87	0.85
Pbias (Rutter)	8.57	38.6	43.3
Pbias (Gash)	19.8	3.33	37.5

NSE – Nash-Sutcliffe efficiency; Pbias – percent bias.

Table 4. Comparison among the Rutter and Gash total interception estimations to difference vegetation formations.

Models	Vegetation types	Interception (%)			Source
		Measured	Estimated	Difference	
Rutter	Northeastern Atlantic Forest	38.4	14.5	23.9	Ribeiro Filho et al. (2019)
Gash	Northeastern Atlantic Forest	38.4	14.9	23.5	Ribeiro Filho et al. (2019)
Gash	Coniferous Forest (*Dayekou*)	24.2	20.8	3.4	Cui & Jia (2014)
Gash	Coniferous Forest (*Pailugou*)	37.5	32.4	5.1	Cui & Jia (2014)
Rutter	Semi-deciduous Mesophilous Forest	23.0	19.0	4.0	Vieira & Palmier (2006)
Gash	Semi-deciduous Mesophilous Forest	23.0	20.0	3.0	Vieira & Palmier (2006)
Gash	Rainforest	10.2	9.8	0.4	Jackson (2000)
Rutter	Monoculture yerba mate	15.6	14.3	1.3	This study
Gash	Monoculture yerba mate	15.6	12.5	3.1	This study
Rutter	Agroforestry yerba mate	16.2	9.9	6.3	This study
Gash	Agroforestry yerba mate	16.2	10.5	5.7	This study
Rutter	Mixed ombrophilous forest	21.4	12.1	9.3	This study
Gash	Mixed ombrophilous forest	21.4	13.4	8.0	This study

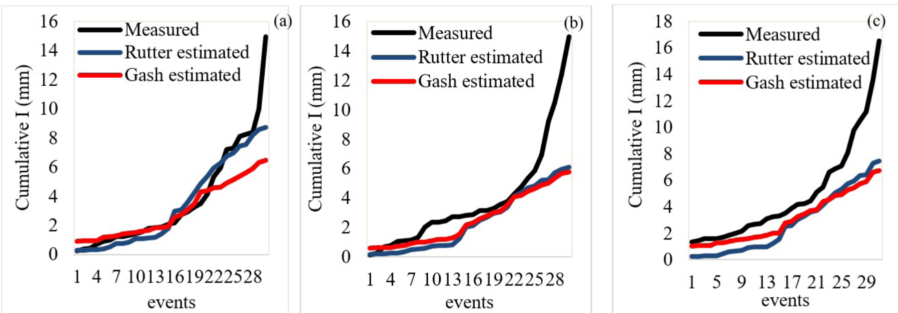

Figure 5. Comparison of observed and calculated losses by Rutter and Gash model. (a) Yerba mate monoculture; (b) Yerba mate agroforestry; and (c) Native mixed ombrophilous forest.

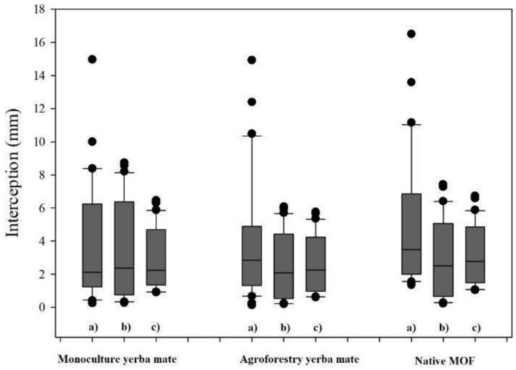

Figure 6. BoxPlot of interception (mm) occurring in the production systems. Note: a) is the monitored interception, b) is the Rutter estimates, and c) is the Gash estimates.

Gash's model produced better interception estimates in a study by Jackson (2000) in a Kenya Forest, which resulted in an underestimate of only 0.4%. Our results show a result closer to that obtained in a Coniferous Forest in China (Cui & Jia, 2014), which showed an underestimate of 3.4 and 5.1%.

The results obtained by both models were considered satisfactory when evaluated by the NSE and Pbias coefficients (NSE≥0.5 and Pbias≤±25%) (Table 3).

The results showed that the Rutter and Gash models underestimated the interception loss in the three yerba mate production systems. In analyzing the performance of the models, in general, an underestimation of interception loss values of 19% by the Rutter model and 21% by the Gash model was observed, differences considered acceptable. Návar (2017) investigated the interception estimated by the models in a temperate forest in Mexico and also concluded that the models can be used to satisfactorily estimate interception in that environment.

Rutter's model resulted in higher underestimates, except in the yerba mate monoculture. The model showed underestimates on the order of 6.3 and 9.3% for the agroforestry system of yerba mate and native MOF, respectively (Table 4).

The change in vegetation cover and meteorological conditions can generate underestimates in the interception process. Rainfall partitioning in periods when vegetation is leafless a priori tends to underestimate fluxes due to the changes it causes in the canopy and leads to a misleading conclusion about the dynamics of rainfall partitioning (Muzylo et al., 2011).

Interception loss in light rainfall events tends to be somewhat underestimated due to the wind acting on the forest, which can change the path of raindrops during throughfall, thus increasing interception loss (Cui & Jia, 2014). Differences in rainfall characteristics and other meteorological factors may therefore have led to the differences in interception loss in each system analyzed. Other characteristics to be considered are the different structures and vegetation cover that have an effect on the total interception differences.

More field experiments and a longer time of data collection are needed to better understand the characteristics of interception loss and the effects of interception loss on regional water balances in yerba mate production systems.

CONCLUSIONS

The average total interception loss measured during the study period was 112 ± 3.5 mm (15.6%), 102.4 ± 3.0 mm (14.3%), and 89.8 ± 1.9 mm (12.5%) for the yerba mate monoculture system, yerba mate agroforest, and the native MOF, respectively.

Rutter and Gash's model, simulated on a daily scale, satisfactorily predicted interception losses in the different yerba mate production systems.The best estimates was obtained with Rutter's model (only 1.3% underestimation of the total measured for the study period) in the yerba mate monoculture system. In the agroforestry system and native MOF, the best estimates were obtained with the Gash model, with only 5.7% and 8.0% of underestimation, respectively.

This study concludes that, although the models underestimated the interception loss values in yerba mate monoculture systems, agroforestry with yerba mate densification, and native MOF, they presented satisfactory and acceptable values. On the one hand, Rutter's model showed better interception estimation results in the yerba mate monoculture system. On the other hand, Gash's model showed better results in the yerba mate agroforestry and native MOF systems. This comparative study is particularly useful to guide decisions for choosing future applications of the models.

More field experiments should be conducted in southern Brazil to quantify and model the dynamics of interception loss in Ilex paraguariensis at different tree densities, climatic zones, and management practices using the Rutter and Gash model.

ACKNOWLEDGEMENTS

The authors thank CAPES and CNPq for the scholarships granted and the Schier family for the support in the access to the study areas.

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Authors contributions

Ezequias Rodrigues dos Santos: Participated in the field data collection, data analysis, and article writing.

Leandro Redin Vestena: Participated in the data analysis and revision of the article.

Jacques Carvalho Ribeiro Filho: Participated in the data analysis and revision of the article.

Editor-in-Chief: Adilson Pinheiro
Associated Editor: Fernando Mainardi Fan