



Interaction of precipitation with tree canopy increases nutrient input

ARTICLES doi:10.4136/ambi-agua.2761

Received: 20 Jun. 2021; Accepted: 04 Oct. 2021

Gian Carlos Poletto¹; Dione Richer Momolli^{1*}; Mauro Valdir Schumacher¹;
Aline Aparecida Ludvichak¹; Kristiana Fiorentin dos Santos²; Márcio Viera¹;
Clayton Alcarde Alvares³; James Stahl⁴

¹Universidade Federal de Santa Maria (UFSM), Avenida Roraima, n° 1000, CEP: 97105-900, Santa Maria, RS, Brazil. E-mail: gianpoletto@gmail.com, mauro.schumacher@ufsm.br, aline_lud@yahoo.com.br, marcio.viera@ufsm.br

²Departamento de Engenharia Florestal. Universidade Regional de Blumenau (FURB), Rua São Paulo, n° 3250, CEP: 89030-000, Blumenau, SC, Brazil. E-mail: kristianaflorentin@gmail.com

³Suzano SA, Estrada Limeira, n° 391, CEP: 13465-970, Limeira, SP, Brazil. E-mail: calcarde@suzano.com.br

⁴Klabin S.A., Unidade de Monte Alegre, Avenida Brasil, n° 26, CEP: 84275-000, Telêmaco Borba, PR, Brazil. E-mail: jstahl@klabin.com.br

*Corresponding author. E-mail: dionemomolli@gmail.com

ABSTRACT

Given that atmospheric deposition is the first source of nutrient input into forest ecosystems, and that the precipitation partition serves as a nutritional source mainly when there is an interaction with the forest canopy, the objective of the present study was to quantify the nutrients input into rainfall, throughfall and stemflow in *Eucalyptus urophylla* stands with partial exclusion (E) and without exclusion (WE) of throughfall. The experiment was conducted in the northeast of the state of Paraná-Brazil, in the municipality of Telêmaco Borba. The partial precipitation exclusion system (E) is formed by a system of gutters that conduct 30% of throughfall out of the experiment. The nutrient input in rainfall was 55.7 kg ha⁻¹ yr⁻¹, while the sum of throughfall and stemflow was 64.1 kg ha⁻¹ yr⁻¹ in treatment (WE) and 39.8 kg ha⁻¹ yr⁻¹ in treatment (E). Interaction with the canopy of the trees enriched the rainfall with nutrients, mainly the elements potassium and chlorine, due to leaching of the vegetal tissues. The reduction of the water treatment system in partial exclusion of precipitation (E) reduced representative nutrient input. Although stemflow represents on average only 2.6% of the water volume, it is responsible for 6.7% of the amount of nutrients in relation to precipitation. Therefore, stemflow cannot be neglected in the balance of nutrient cycling. With a rotation of 7 years, the application of significant amounts of fertilizers can be avoided, considering the inputs of 449 and 277 kg ha⁻¹year⁻¹.

Keywords: nutrient cycling, stemflow, throughfall.

Interação da precipitação com o dossel florestal aumenta o aporte de nutrientes

RESUMO

Sabendo que a deposição atmosférica é a primeira fonte de entrada de nutrientes nos ecossistemas florestais e que a partição de precipitação serve como fonte nutricional principalmente quando há interação com o dossel florestal, o objetivo do presente estudo foi



This is an Open Access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

quantificar o aporte de nutrientes na precipitação incidente, precipitação interna e escoamento pelo tronco em um povoamento de *Eucalyptus urophylla* com exclusão parcial (E) e sem exclusão parcial (WE) da precipitação interna. O experimento está localizado no nordeste do estado do Paraná-Brasil, no município de Telêmaco Borba. O sistema de exclusão parcial de precipitação (E) é formado por um sistema de calhas que conduzem 30% da precipitação interna para fora do experimento. O aporte de nutrientes pela precipitação incidente foi de $55.7 \text{ kg ha}^{-1} \text{ ano}^{-1}$, enquanto que a soma dos mesmos na precipitação interna e escoamento pelo tronco foram de $39.8 \text{ kg ha}^{-1} \text{ ano}^{-1}$ no tratamento com exclusão (E) e de $64.1 \text{ kg ha}^{-1} \text{ ano}^{-1}$ no tratamento sem exclusão (WE). A interação com o dossel florestal enriquece com nutrientes especialmente com os elementos potássio e cloro devido a lixiviação dos tecidos vegetais. A redução do regime hídrico no tratamento com exclusão parcial da precipitação (E) reduziu de forma representativa a entrada de nutrientes. Embora o escoamento pelo tronco represente em média apenas 2.6% do volume de água, ele é responsável por 6.7% da quantidade de nutrientes em relação à precipitação. Portanto, o mesmo não pode ser negligenciado no balanço da ciclagem de nutrientes. Com uma rotação de 7 anos a aplicação de importantes quantidades de fertilizantes podem ser evitados considerando as entradas de 449 e $277 \text{ kg ha}^{-1} \text{ ano}^{-1}$.

Palavras-chave: ciclagem de nutrientes, escoamento pelo tronco, precipitação interna.

1. INTRODUCTION

The forestry sector has occupied a prominent position in the Brazilian economy. Planted forests occupy 9.0 million hectares of the country and the genus *Eucalyptus* represents 77% of this area. Even with the large area occupied, the industrial forest plantations cover about 0.92% of the Brazilian territory. Paper and cellulose commodities occupy the second place in the list of products most exported by Brazil (IBÁ, 2020).

Extensive areas occupied by forest plantations are able to modify the hydrological balance (Ferraz *et al.* 2019). The partition of the rainfall in the area covered by vegetation is very dynamic. During precipitation, a portion of the water is intercepted by the canopy and immediately evaporated into the atmosphere (Llorens and Domingo, 2007). Part of the precipitation crosses the canopy and drips into the stand; this is called “throughfall” (Navar, 2011). A portion of the throughfall flows from the leaves to the branches and trunk, reaching the base of the tree; this portion is called “stemflow” (Zhang *et al.*, 2016; Johnson and Lehmann, 2006). The knowledge of the partition of precipitation is important in studies of modeling the water balance of a watershed; however, many studies have considered a generic value for the index of canopy interception (Chaffe *et al.*, 2010).

Many studies show the importance of the partition of precipitation in the biogeochemical cycle of nutrients (Staelens *et al.*, 2006; Fan *et al.*, 2015). Some studies also point out that the productivity and stability of a forest ecosystem is determined by the cycling of nutrients (Likens 2013). According to Viera and Schumacher (2010), part of the input of nutrients into an ecosystem occurs through precipitation that carries dust particles from the atmosphere to the ground. In addition, when interacting with the canopy of the trees, precipitation leaches the different tissues of the plant, increasing the nutritional contribution (Schrumpf *et al.*, 2006; Bhat *et al.*, 2011; Levia *et al.*, 2011). Thus, precipitation is responsible for providing information regarding environmental quality (Zhou *et al.*, 2019). In addition, soils from areas of low natural fertility, the entry of nutrients by precipitation may be the only nutritional source (Dawoe *et al.*, 2018; Lu *et al.*, 2017).

The chemical composition of throughfall and stemflow is influenced by the interaction of water with the forest canopy, distance from the sea and anthropogenic activities (Andre *et al.*, 2008; Navar *et al.*, 2009; Tiwari *et al.*, 2016). In general, these pathways provide an important

nutritional source for tree roots, especially with cation enrichment (Zhang *et al.*, 2013; Su *et al.*, 2019). Although the stemflow represents a small portion of the volume of water that reaches the forest soil, this solution is responsible for accelerating the redistribution of nutrients and changing the physico-chemical properties in the root region (Swaffer *et al.*, 2014; Momolli *et al.* 2019b)

Climate change has caused great variation in the rainfall regime (Allan and Soden, 2008), in addition, the water regime in southern Brazil is determined by atmospheric-oceanic phenomena. When equatorial waters in the Pacific Ocean cool, the phenomenon of “La Niña” occurs, which is responsible for the significant decrease in rainfall in this region. As a consequence, there is a loss of productivity of several crops, including those of *Eucalyptus* plantations. This study evaluates nutrient input into rainfall, throughfall and stemflow in a *Eucalyptus* stand with and without partial exclusion of throughfall.

2. MATERIALS AND METHODS

2.1. Characterization of the experimental area

The experimental area is located in the northeast region of the state of Paraná, in the municipality of Telêmaco Borba, under the geographic coordinates 24°13'41.0” S and 50°31'40.0” W. The climate classification is Cfb (temperate climate), with an average annual temperature of 18.8°C and an average annual precipitation of 1646 mm, according to the Köppen classification (Alvares *et al.*, 2014). According to Flores *et al.* (2016) the species *E. urophylla* is classified as having low climatic aptitude for the study region.

Figure 1 shows meteorological data for the period from July 2017 to June 2018, obtained from the meteorological station located at the company Klabin SA in Telêmaco Borba – PR – Brazil at 880 m altitude, 24°12'40.6” S and 50°33'29.2” W. The distance between the experimental area and the weather station is approximately 3.4 km in a straight line.

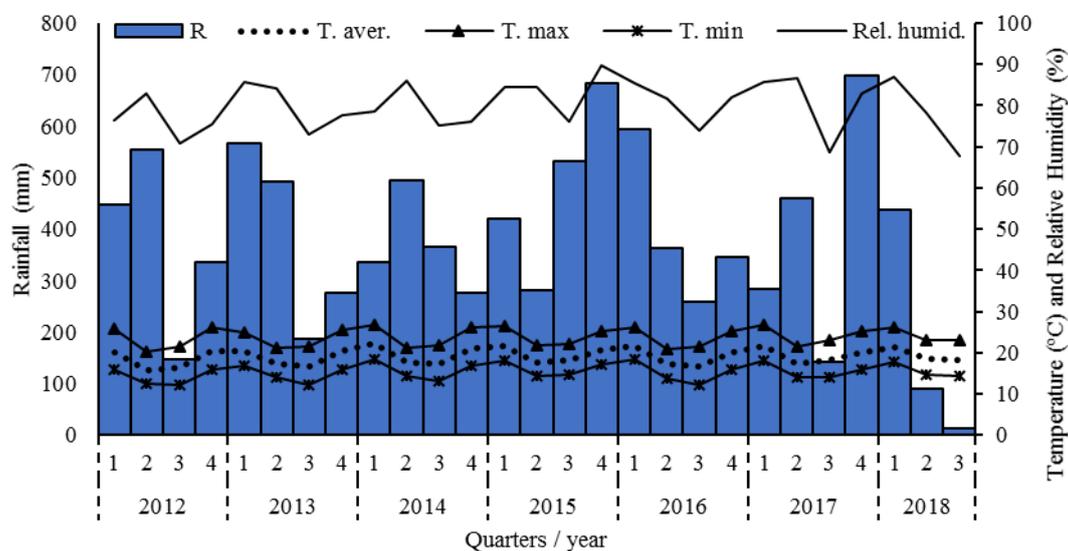


Figure 1. Weather data for the municipality of Telêmaco Borba, PR during the study period.

In March 2017, dendrometric characterization was performed, measuring the height and diameter at breast height (DBH) of all trees. The mean DBH and the total height in the Exclusion (E) treatment were 16.8 cm and 28.6 m, respectively. For the Without Exclusion (WE) treatment, the mean DBH was 17.3 cm and the total height 28.3 m. The volume per hectare in the E and WE treatment was 346 and 365 m³ ha⁻¹, respectively. The leaf area index was 2.95 and 2.82 for treating exclusion (E) and without exclusion (WE), respectively.

2.2. Experimental design

The study belongs to the TECHS project (Tolerance of Eucalyptus Clones to Hydric, Thermal and Biotic Stresses). The experiment was carried out in a completely randomized design, with 720 m² plots of eight lines with ten plants each in spacing of 3 m x 3 m (1,111 trees ha⁻¹). For the hybrid *E. urophylla* x *E. sp.* two treatments of the water regime were defined: one receiving 100% of the throughfall (WE) and the other receiving only 70% of the throughfall (E). For the treatment (E) that received 70% of the precipitation, a system of partial exclusion of the throughfall was used with plastic gutters that prevented the precipitation reaching the ground. A schematic representation of the precipitation exclusion treatment (E) can be seen in Figure 2. This technique is based on the coverage between the planting lines covering 216 m² of the area of each treatment, being the equivalent to 30% of the plot area (Binkley *et al.*, 2017).

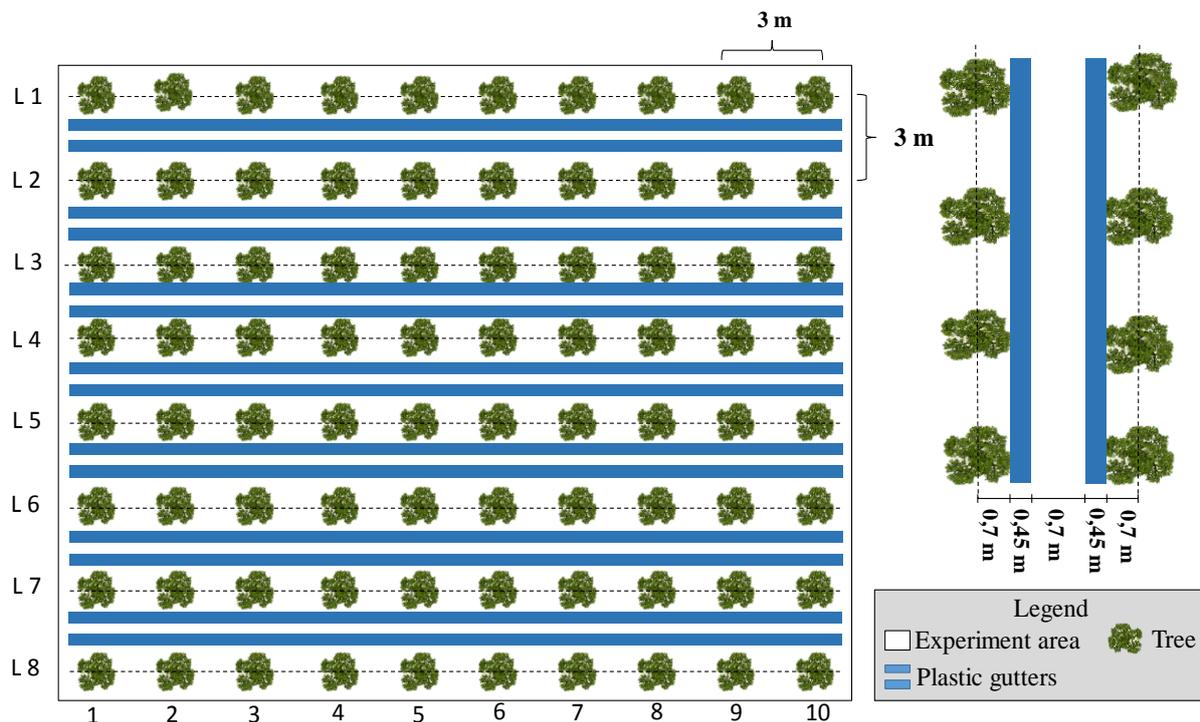


Figure 2. Representative scheme of the partial precipitation exclusion treatment (E), with dimensions and spacing.

The monitoring of the partition of precipitation under the two rainfall regimes occurred from July 2017 to June 2018. Sampling was started when the stand was 66 months old. For the (E) treatment, a partial exclusion system of throughfall was used, installed when the stand was one year old.

2.3. Measurement of rainfall, throughfall and stemflow

To quantify the rainfall (R), three collectors with a 20 cm catchment diameter were installed in an area adjacent to the eucalyptus stand at a height of 1.5 m above ground level. Straps with steel wires were placed in order to prevent birds from using the collectors as perches.

For the evaluation of throughfall (Tf), nine collectors per treatment were installed, with a collection diameter of 20 cm and height of 1 m from ground level, systematically distributed along the line, between the lines and diagonally between four trees. Collections were started at 66 months of age.

The stemflow quantification (Sf) occurred with the installation of nine sets formed by a plastic hose with a diameter of one inch and a reservoir for water storage. The hose was cut longitudinally and then it was installed in a spiral shape on the tree trunk. This configuration allowed the water to drain through the trunk and be stored in the reservoir.

Bi-weekly, the values of rainfall (R), throughfall (Tf) and stemflow (Sf) were measured. To obtain the values of precipitation and throughfall in millimeters, the following Equation 1 was used:

$$R = V/a \quad (1)$$

Where:

R = rainfall (mm);

V = volume collected (L);

a = collector area (m²).

The values of stemflow were obtained using the following Equation 2, used by Preuhsler *et al.* (2006):

$$Sf = \left(\frac{V}{g}\right) * \left(\frac{G}{A}\right) \quad (2)$$

Where:

Sf = stemflow (mm);

V = volume collected (L);

g = basal area of the tree (m²);

G = basal area of the plot (m²);

A = plot area (m²).

For the canopy interception calculation, the Equation 3 was used:

$$I = \frac{R-(Tf+Sf)}{R} * 100 \quad (3)$$

Where:

I = canopy interception (%);

R = rainfall (mm);

Tf = throughfall (mm);

Sf = stemflow (mm).

The rainfall and throughfall collectors were composed of plastic bottles with a capacity of 2 liters, and the collections were carried out every 15 days. The throughfall collectors were arranged on the line, between the lines and diagonally between four trees. The stemflow samples were also collected for chemical analysis every 15 days.

2.4. Statistics and Data Analysis

The rainfall, throughfall and stemflow samples were sent to the Forest Ecology Laboratory where the pH was determined. For this variable, the electrode (Methohm 827 pH LAB) was used, and filtered with a 0.45 µm pore filter. According to the methodology proposed by the

American Public Health Association (APHA *et al.*, 1998), NO_2^- , NO_3^- , PO_4^{3-} , SO_4^{2-} , Cl^- , K^+ , Ca^{2+} and Mg^{2+} ions were analyzed, with a pre-treatment with simple filtration followed by ion chromatography. The amount of nutrient input is given by multiplying the concentrations of ions (mg L^{-1}) by the volume (liters).

The Tukey average test was performed at 5% probability of error for ion concentrations between precipitation, throughfall and stemflow. In order to verify the dilution effect, Pearson's correlations were applied between the volumes of rainfall partitions and the concentrations of ions. All statistical analyses were performed using SPSS 18.0 (SPSS Inc., Chicago, IL, USA).

3. RESULTS AND DISCUSSION

3.1. Rainfall partitioning

During the monitored period, the quantified precipitation was 1627 mm. The month of December 2017 had the highest volume of R 371 mm, while the months of July 2017 and April 2018 registered the lowest volumes (0.00 and 21 mm) (Figure 3).

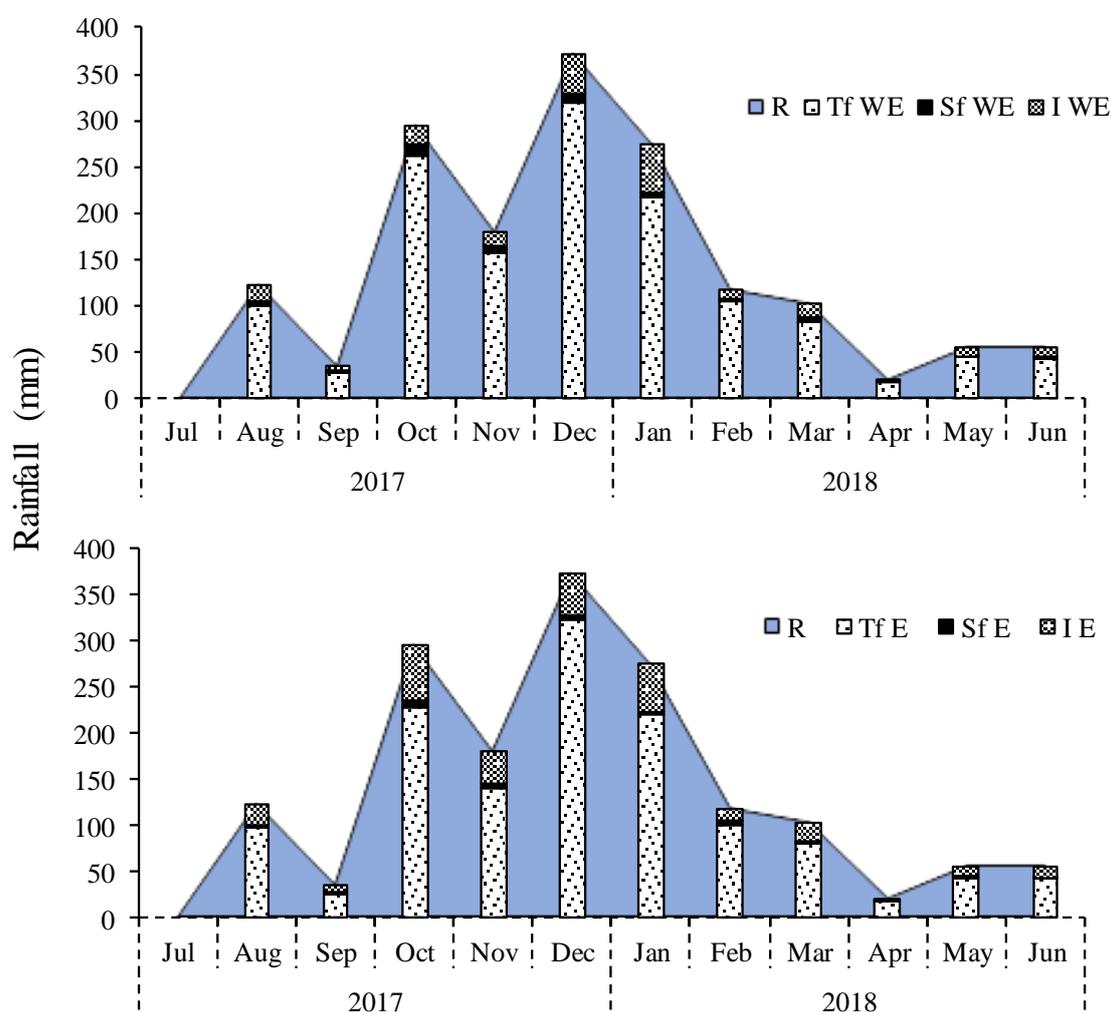


Figure 3. Temporal variation of the partition of pluviometric precipitation.

Regarding throughfall, the WE treatment showed 1379 mm, equivalent to 84.8% of the precipitation. In contrast, the E treatment showed a lower value (1311 mm), corresponding to 80.6% of the precipitation. The volume collected for the Sf WE treatment was 48.40 mm, representing 2.9% of the rainfall. For the Sf E treatment, 37 mm was accumulated, corresponding to 2.3% of the rainfall. In the canopy interception, the lowest observed value was

200 mm (12.3%) for WE treatment, while in treatment E the value was 280 mm (17.2%) (Poletto *et al.*, 2021).

3.2. Chemical composition of rainfall, throughfall and stemflow

In the evaluated period (Figure 3), the average pH value of rainfall was 6.17. The throughfall for the E and WE treatment of the throughfall was 5.94 and 5.96, respectively. Stemflow provided an average of 4.92 and 4.55 for the E and WE treatment of throughfall (Figure 4).

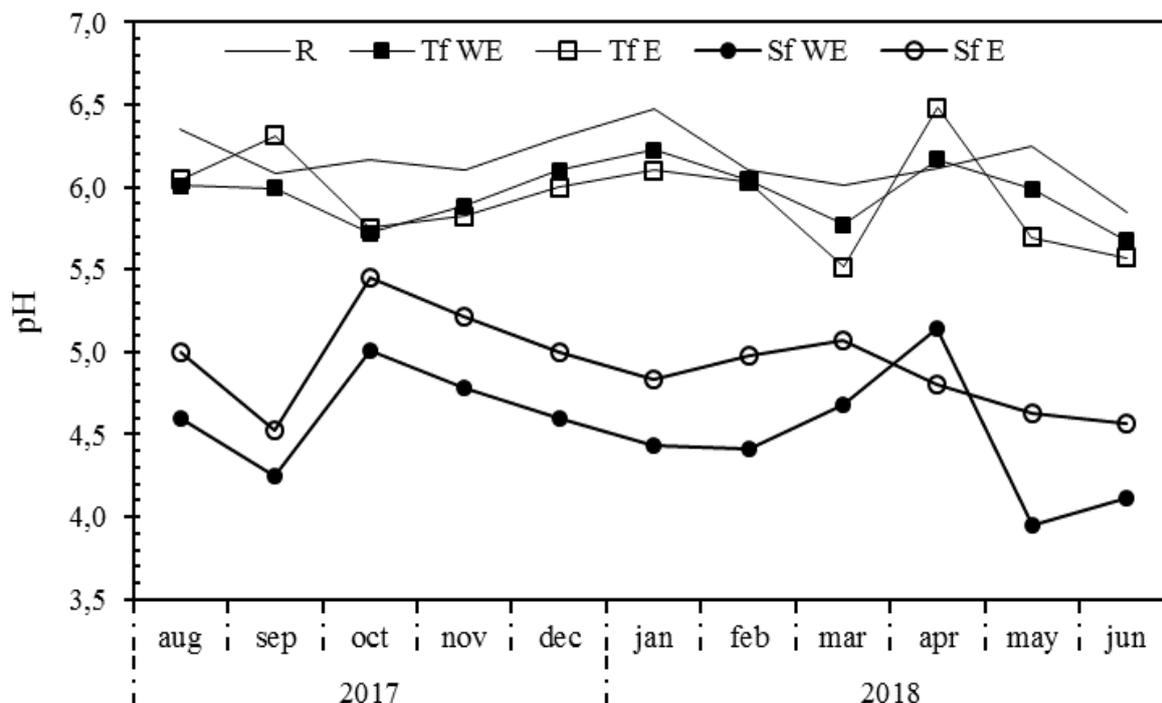


Figure 4. Average pH values of rainfall, throughfall and stemflow in the hybrid *Eucalyptus urophylla* x *E. sp.*

Momolli (2019b) found mean pH values of 4.57 for rainfall, 4.64 for throughfall and 5.54 for stemflow evaluation in a 7 to 8-year-old *Eucalyptus dunnii* stand in Alegrete, RS. Assessing the same species, from 4 to 5 years old, Dick *et al.* (2018) also found an increase in pH as precipitation interacts with the canopy. The pH was 4.3 in rainfall, 5.0 in the throughfall and 5.3 in the stemflow, respectively.

The ion concentration is variable as it interacts with the forest canopy. The SO_4^{2-} and Ca^{2+} ions showed higher levels of rainfall, differing statistically from other rainfall partitions. Inverse behavior was observed with respect to Cl^- , Na^+ , N-NH_4^+ , K^+ , Mg^{2+} ions that registered the greatest increases, especially in Stemflow and Throughfall. The ions N-NO_2^- and P-PO_4^{3-} showed no statistically significant difference. The mean test of the ions analyzed for each partition of the precipitation in the two water regimes can be verified in Table 1.

It is observed that the concentration of nutrients is influenced by the water regime, that is, during the months of higher rainfall, the ion concentrations are reduced while during the months of lower precipitation, the concentrations increase considerably. In the present study, the highest concentrations were recorded in the months of September, April and May, coinciding with the lowest rainfall. Other studies report the same behavior as in the case of Su *et al.* (2019) who monitored the chemical variation of rainwater in the different partitions in a mixed evergreen and deciduous broadleaved forest in Central China.

Table 1. Chemical characteristics of water in precipitation, throughfall and stemflow during the monitoring period.

Ion	Concentration (mg L ⁻¹)		
	Precipitation	Throughfall	Stemflow
	Without exclusion		
*Cl ⁻	0.55 ± 0.09 ^a	1.97 ± 0.55 ^b	3.86 ± 0.73 ^c
N-NO ₂ ⁻	0.04 ± 0.00 ^a	0.04 ± 0.00 ^a	n.d
N-NO ₃ ⁻	0.12 ± 0.03 ^a	0.16 ± 0.04 ^a	0.15 ± 0.04 ^a
P-PO ₄ ³⁻	0.06 ± 0.00 ^a	0.07 ± 0.00 ^a	0.08 ± 0.00 ^a
*SO ₄ ²⁻	0.15 ± 0.02 ^b	0.15 ± 0.02 ^b	0.08 ± 0.01 ^a
*Na ⁺	0.78 ± 0.36 ^a	0.78 ± 0.25 ^a	1.69 ± 0.29 ^b
*N-NH ₄ ⁺	0.13 ± 0.05 ^a	0.16 ± 0.03 ^a	0.27 ± 0.03 ^b
*K ⁺	0.94 ± 0.43 ^a	2.51 ± 0.69 ^b	5.42 ± 0.83 ^c
*Mg ²⁺	0.30 ± 0.12 ^a	0.32 ± 0.08 ^a	1.23 ± 0.18 ^b
*Ca ²⁺	2.44 ± 0.57 ^b	0.99 ± 0.20 ^a	1.69 ± 0.33 ^b
	Exclusion		
*Cl ⁻	0.55 ± 0.09 ^a	1.49 ± 0.35 ^b	4.19 ± 0.93 ^c
N-NO ₂ ⁻	0.04 ± 0.00 ^a	0.04 ± 0.01 ^a	0.06 ± 0.00 ^a
*N-NO ₃ ⁻	0.12 ± 0.03 ^a	0.17 ± 0.05 ^{ab}	0.24 ± 0.09 ^b
P-PO ₄ ³⁻	0.06 ± 0.00 ^a	0.05 ± 0.00 ^a	0.05 ± 0.00 ^a
*SO ₄ ²⁻	0.15 ± 0.02 ^b	0.14 ± 0.02 ^b	0.08 ± 0.01 ^a
*Na ⁺	0.78 ± 0.36 ^a	0.75 ± 0.22 ^a	1.83 ± 0.33 ^b
*N-NH ₄ ⁺	0.13 ± 0.05 ^{ab}	0.09 ± 0.02 ^a	0.19 ± 0.06 ^b
*K ⁺	0.94 ± 0.43 ^a	2.71 ± 0.53 ^b	6.27 ± 0.96 ^c
*Mg ²⁺	0.30 ± 0.12 ^a	0.36 ± 0.09 ^a	1.45 ± 0.23 ^b
*Ca ²⁺	2.44 ± 0.57 ^c	0.79 ± 0.18 ^a	1.66 ± 0.33 ^b

(*) Different letters in the same row indicate statistical differences at $p < 0.05$.

The verification of the ion dilution effect as a function of the precipitated rainfall volume

is verified with the Pearson correlation test presented in Table 2. Mostly, a negative correlation was observed for more than 90% of the ions in the different precipitation partitions. In addition, there were strong significant correlations to a <1% error probability for K^+ , Ca^{2+} and Mg^{2+} ions and for many throughfall ions.

Table 2. Pearson's correlation between ion concentration and measured water volume.

Ion	Measured volume				
	R	Tf WE	Tf E	Sf WE	Sf E
Cl^-	-0.31	-0.70**	-0.62*	-0.51*	-0.48
NO_2^-	0.56*	1.00**	0.24	-	-
NO_3^-	-0.38	-0.15	-0.22	-0.37	-0.53*
PO_4^{3-}	0.05	-0.90**	-	0.35	1.00**
SO_4^{2-}	-0.54*	-0.46	-0.29	-0.05	0.06
Na^+	-0.36	-0.41	-0.53*	-0.55*	-0.40
NH_4^+	-0.51*	-0.20	0.28	-0.49	-0.35
K^+	-0.41	-0.78**	-0.67*	-0.64*	-0.72**
Mg^{2+}	-0.62*	-0.64*	-0.51*	-0.61*	-0.76**
Ca^{2+}	-0.43	-0.72**	-0.53*	-0.73**	-0.76**

** . Correlation is significant at the 0.01 level (2-tailed).

* . Correlation is significant at the 0.05 level (2-tailed).

Figure 5 shows in detail the variation in ion concentration over the monitored period for the different partitions of rainfall. As can be seen, for most ions there are two months of prominence: September and May.

The order of the ion contents in rainfall was: $Ca^{2+} > K^+ > Na^+ > Cl^- > Mg^{2+} > SO_4^{2-} > N-NH_4^+ > N-NO_3^- > P-PO_4^{3-} > N-NO_2^-$. In the throughfall for the WE treatment, it was: $K^+ > Cl^- > Ca^{2+} > Na^+ > Mg^{2+} > N-NO_3^- > N-NH_4^+ > SO_4^{2-} > P-PO_4^{3-} > N-NO_2^-$. In the throughfall for the E treatment, it was: $K^+ > Cl^- > Ca^{2+} > Na^+ > Mg^{2+} > N-NO_3^- > SO_4^{2-} > N-NH_4^+ > P-PO_4^{3-} > N-NO_2^-$.

For stemflow, the ion concentration was $K^+ > Cl^- > Na^+ > Ca^{2+} > Mg^{2+} > N-NH_4^+ > N-NO_3^- > SO_4^{2-} > P-PO_4^{3-} > N-NO_2^-$ for the treatment without exclusion and $K^+ > Cl^- > Na^+ > Ca^{2+} > Mg^{2+} > N-NO_3^- > N-NH_4^+ > SO_4^{2-} > N-NO_2^- > P-PO_4^{3-}$ for treatment with partial removal of throughfall.

Our results clearly show an increase in the contents of certain nutrients as the rainwater interacts with the forest canopy. Balieiro *et al.* (2007), evaluating a *Eucalyptus* stand in Seropédica, RJ found concentrations ($mg L^{-1}$) of 0.82; 0.20; 3.52; 0.62; 0.39 and 1.44 for $N-NH_4^+$, P, K^+ , Ca^{2+} , Mg^{2+} and Na^+ , respectively. For throughfall, the concentrations of 1.38; 0.33; 14.83; 0.94; 0.96 and 3.78 $mg L^{-1}$, for $N-NH_4^+$, P, K^+ , Ca^{2+} , Mg^{2+} and Na^+ , respectively. In stemflow, the concentrations were as follows: 2.28; 0.40; 14.17; 0.75; 1.42 and 2.73 for $N-NH_4^+$, P, K^+ , Ca^{2+} , Mg^{2+} and Na^+ , respectively.

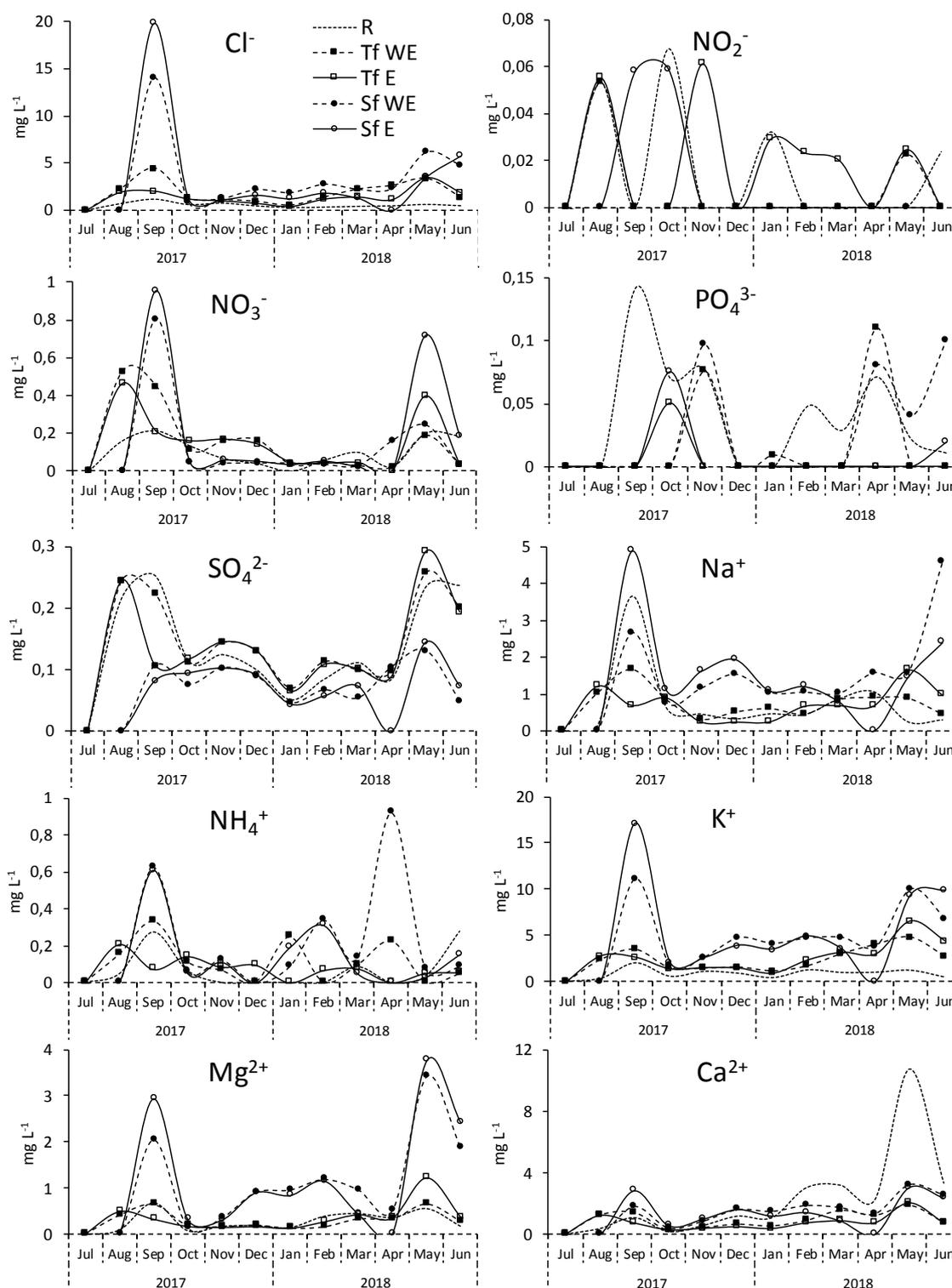


Figure 5. Monthly variation in ion concentration in different precipitation partitions.

3.3. Nutrient input

The rainfall had a total nutrient input of $55.69 \text{ kg ha}^{-1} \text{ yr}^{-1}$. For throughfall, the contribution was 60.20 kg ha^{-1} and 36.27 kg ha^{-1} for TfWE and TfE, respectively. The significant reduction in the amount of nutrients in treatment E refers to the fact that these nutrients are being carried out of the stand due to the system of excluding water from rainfall. For stemflow, the contribution was greater, with 3.96 kg ha^{-1} in the SfWE and 3.36 in the SfE (Figure 6).

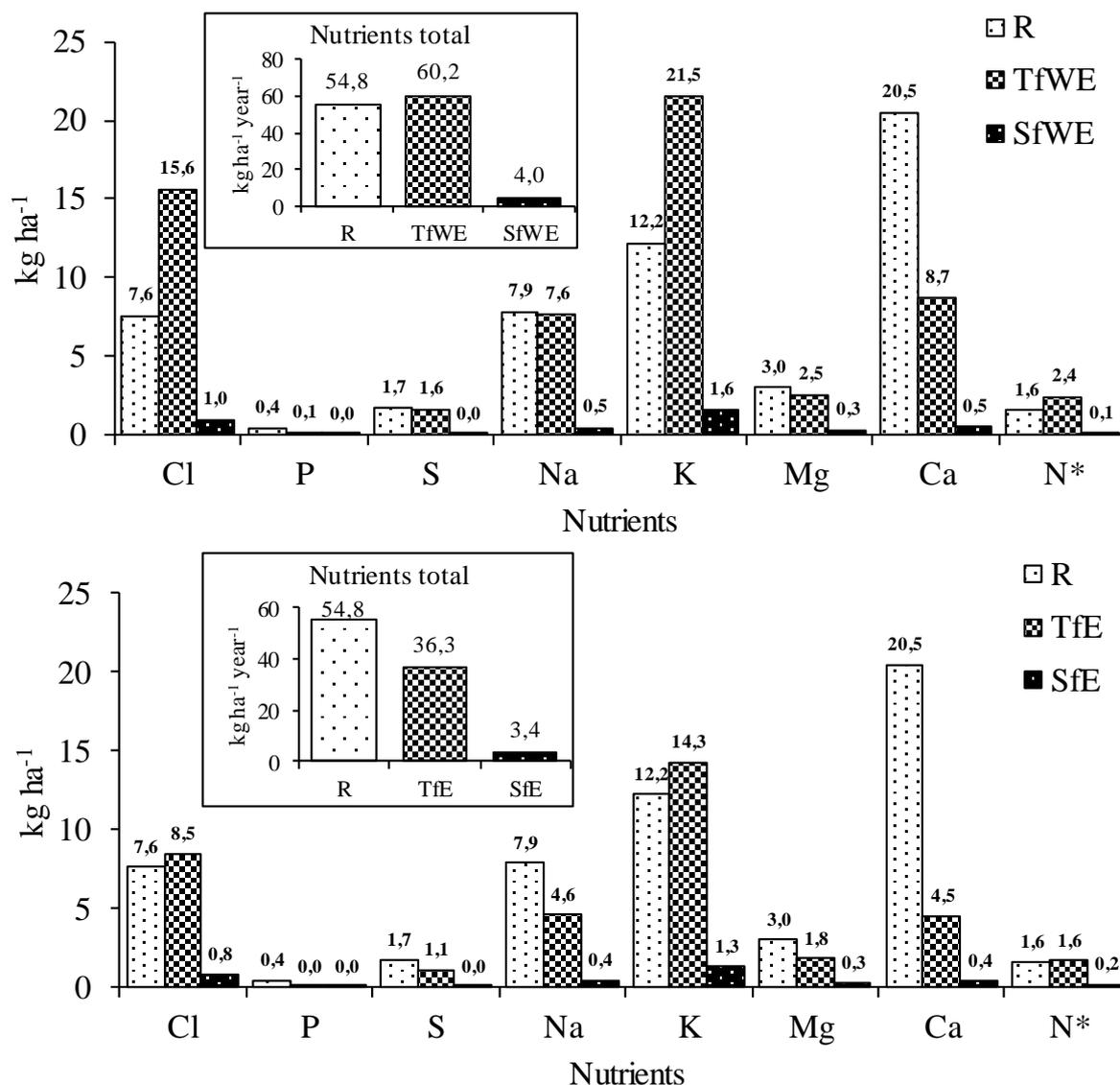


Figure 6. Annual amount of nutrients ($\text{kg ha}^{-1} \text{ yr}^{-1}$) incorporated into the system by rainfall (R), throughfall (Tf) and stemflow (Sf) in a stand of the hybrid *Eucalyptus urophylla* x *E. sp.*
*N total = $\text{NO}_2^- + \text{NO}_3^- + \text{NH}_4^+$.

The flow of nutrients in rainfall had the following distribution order: $\text{Ca} > \text{K} > \text{Na} > \text{Cl} > \text{Mg} > \text{S} > \text{N} > \text{P}$. In Tf WE, the order was as follows: $\text{K} > \text{Cl} > \text{Ca} > \text{Na} > \text{Mg} > \text{N} > \text{S} > \text{P}$. In the Sf WE, $\text{K} > \text{Cl} > \text{Ca} > \text{Na} > \text{Mg} > \text{N} > \text{S} > \text{P}$. The Tf E presented the following order: $\text{K} > \text{Cl} > \text{Na} > \text{Ca} > \text{Mg} > \text{N} > \text{S} > \text{P}$. For SfE $\text{K} > \text{Cl} > \text{Na} > \text{Ca} > \text{Mg} > \text{N} > \text{S} > \text{P}$. Considering the sum of throughfall plus stemflow in the WE treatment the amount of nutrients (kg ha^{-1}) was 16.6 for Cl, 0.1 for P, 1.7 for S, 8.1 for Na, 23.1 for K, 2.9 for Mg, 9.2 for Ca and 2.5 for N. As for treatment E, there was a contribution ($\text{kg ha}^{-1} \text{ yr}^{-1}$) of 9.3 for Cl, 0.02 for P, 1.1 for S, 5.0 for Na, 15.6 for K, 2.1 for Mg, 4.9 for Ca, 1.8 for N.

Regarding nutrient input via rainfall, it was observed that there was a significant increase in nutrients in the aqueous solution, whose input sequence was $\text{K} > \text{S} > \text{Ca} > \text{N} > \text{Mg}$. These inputs could reduce the addition of 22% and 11% of the amounts of K and N, respectively, applied to pre-planting fertilization (Dick *et al.*, 2018). The annual contribution of nutrients in the present study is similar to that found by Momolli *et al.*, (2020). For these authors, the annual contribution was 36.3 kg ha^{-1} . This small variation is justified according to the conditions: close to the ocean, emission of atmospheric pollutants by anthropic activity and even soil and environmental characteristics (Corti *et al.*, 2019; Yuan *et al.*, 2017). Possibly, the greatest

contribution of certain nutrients is related to the existence of two pulp mills, the first approximately 12 km away in a straight line located in the municipality of Telêmaco Borba, PR and the second approximately 21 km away in the municipality of Ortigueira, PR. Balieiro *et al.* (2007) in an *Eucalyptus* stand found a contribution (kg ha⁻¹) via rainfall of 12.07 N-NH₄⁺; 2.65 P; 86.00 K⁺; 12.25 Ca²⁺; 9.24 Mg²⁺; 29.81 Na⁺.

The increase in the amount of nutrients after interaction with the canopy is more significant for K⁺, which can be attributed to the high levels due to leaching of the canopy of the trees. However, some ions do not exhibit the same behavior as SO₄²⁻. The input via rainfall was 1.7 kg ha⁻¹ and 1.6 kg ha⁻¹ via TfWE. According to Gay and Murphy (1985), approximately between 30 - 70% of the dry deposition of SO₄²⁻ can be retained in the canopy. Corrêa *et al.* (2019) evaluating an *E. dunnii* stand 16.5 months old, found that due to the concentration of ions there was a greater contribution of elements after the interaction of precipitation with the forest canopy.

4. CONCLUSION

There was an enrichment of nutrients as the water interacted with the forest canopy. Considering the average levels of ions, the degree of enrichment had the following decreasing order: stemflow > throughfall > rainfall. The concentration of ions is seasonal and is especially determined by the volume of water in each partition causing the dilution effect.

The total quantity of nutrients contributed had the following order: throughfall > rainfall > stemflow. The reduction of the water treatment system in partial exclusion of precipitation (E) reduced representative nutrient input. It is important to highlight that although stemflow represents on average only 2.6% of the water volume, it is responsible for 6.7% of the amount of nutrients in relation to precipitation. Therefore, stemflow cannot be neglected in the balance of nutrient cycling.

Considering the interaction of rainwater with canopy, in a 7-year rotation there is a potential reduction of chemical fertilizers. These results point the way to greater economic and environmental sustainability.

5. ACKNOWLEDGEMENTS

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001.

6. DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

7. REFERENCES

- ALLAN, R. P.; SODEN, B. J. Atmospheric warming and the amplification of precipitation extremes. *Science*, v. 321, p. 1481–1484, 2008. <https://doi.org/10.1126/science.1160787>
- ALVARES, C. A. *et al.* Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift*, v. 22, n. 6, p. 711-728, 2014. <https://doi.org/10.1127/0941-2948/2013/0507>
- ANDRE, F.; JONARD, M.; PONETTE, Q. Effects of biological and meteorological factors on stemflow chemistry within a temperate mixed oak-beech stand. *Science of the Total Environment*, v. 393, p. 72-83, 2008. <https://doi.org/10.1016/j.scitotenv.2007.12.002>

- APHA; AWWA; WEF. **Standard Methods for the Examination of Water and Wastewater**. 20. ed. Washington, 1998.
- BALIEIRO, F. C.; FRANCO, A. A.; FONTES, R. L. F.; DIAS, L. E.; CAMPELLO, E. F. C.; FARIA, S. M. Evaluation of the throughfall stemflow nutrient contents in mixed and pure plantations of *Acacia mangium*, *Pseudosamanea guachapele* and *Eucalyptus grandis*. **Revista Árvore**, v. 31 n. 2, p. 339-346, 2007. <https://doi.org/10.1590/S0100-67622007000200017>
- BINKLEY, D.; CAMPOE, O. C.; ALVARES, C.; CARNEIRO, R. L.; CEGATTA, Í.; STAPE, J. L. The interactions of climate, spacing and genetics on clonal *Eucalyptus* plantations across Brazil and Uruguay. **Forest Ecology and Management**, v. 405, p. 271-283, 2017. <https://doi.org/10.1016/j.foreco.2017.09.050>
- BHAT, S.; JACOBS, J.; BRYANT, M. The chemical composition of rainfall and throughfall in five forest communities: A case study in Fort Benning, Georgia. **Water, Air, & Soil Pollution**, v. 218, p. 323-332, 2011. <https://doi.org/10.1007/s11270-010-0644-1>
- CHAFFE, P. L. B.; KOBIYAMA, M.; YAMASHIKI, K.; TAKARA, K. Is interception information important for rainfall runoff modeling? **Annual Journal of Hydraulic Engineering**, v. 54, p. 73-78, 2010.
- CORRÊA, R. S.; SCHUMACHER, M. V.; MOMOLLI, D. R.; BERGER, C. Aspectos da precipitação pluviométrica em um povoamento jovem de *Eucalyptus dunnii* no Bioma Pampa. **Advances in Forestry Science**, v. 6, n. 3, p. 717-721, 2019. <http://dx.doi.org/10.34062/afs.v6i3.7617>
- CORTI, G.; AGNELLI, A.; COCCO, S.; CARDELLI, V.; MASSE, J.; COURCHESNE, F. Soil effects throughfall and stemflow under Turkey oak (*Quercus cerris* L.). **Geoderma**, v. 333, p. 43-56, 2019.
- DAWOE, E. K.; BARNES, V. R.; OPPONG, S. K. Spatio-temporal dynamics of gross rainfall partitioning and nutrient fluxes in shaded-cocoa (*Theobroma cocoa*) systems in a tropical semi-deciduous forest. **Agroforestry Systems**, v. 92, p. 397-413, 2018. <https://doi.org/10.1007/s10457-017-0108-3>
- DICK, G. *et al.* Nutrient input via incident rainfall in a *Eucalyptus dunnii* stand in the Pama Biome. **Floresta e Ambiente**, v. 25, n. 3, 2018. <https://doi.org/10.1590/2179-8087.055916>
- FAN, J. L.; OESTERGAARD, K. T.; GUYOT, A.; JENSEN, D. G.; LOCKINGTON, D. A. Spatial variability of throughfall and stemflow in an exotic pine plantation of subtropical coastal Australia. **Hydrological Processes**, v. 29, p. 793-804, 2015. <https://doi.org/10.1002/hyp.10193>
- FERRAZ, S. F. B.; RODRIGUES, C. B.; GARCIA, L. G.; ALVARES, C. A.; DE PAULA LIMA, W. Effects of *Eucalyptus* plantations on streamflow in Brazil: Moving beyond the water use debate. **Forest Ecology and Management**, v. 453, p. 117571, 2019.
- FLORES, T. B. *et al.* ***Eucalyptus* no Brasil: zoneamento climático e guia para identificação**. Piracicaba: IPEF, 2016. 448p.
- GAY, D. W.; MURPHY, C. E. **The Deposition of SO₄²⁻ on Forests** (Final Report, EPRI Project R.P. 1813-2). Palo Alto: Electric Power Research Institute, 1985.
- IBÁ. **Relatório anual 2020**: ano base 2019. São Paulo: 2020. 66 p.

- JOHNSON, M. S.; LEHMANN, J. Double-funneling of trees: Stemflow and root-induced preferential flow. **Ecoscience**, v. 13, p. 324-333, 2006. <https://doi.org/10.2980/i1195-6860-13-3-324.1>
- LEVIA, D. F.; KEIM, R. F.; CARLYLE-MOSES, D. E.; FROST, E. E. Throughfall and stemflow in wooded ecosystems. *In*: LEVIA, D.; CARLYLE-MOSES, D.; TANAKA, T. (eds.). **Forest Hydrology and Biogeochemistry: Synthesis of Past Research and Future Directions**. Ecological Studies, 216). Dordrecht: Springer, 2011. <https://doi.org/10.1007/978-94-007-1363-5>
- LIKENS, G.E. **Biogeochemistry of a Forested Ecosystem**. Berlin: Springer Science & Business Media, 2013.
- LLORENS, P.; DOMINGO, F. Rainfall partitioning by vegetation under Mediterranean conditions: A review of studies in Europe. **Journal of Hydrology**, v. 335, p. 37-54, 2007. <https://doi.org/10.1016/j.jhydrol.2006.10.032>
- LU, J.; ZHANG, S.; FANG, J.; YAN, H.; LI, J. Nutrient fluxes in rainfall, throughfall, and stemflow in *Pinus densata* natural forest of Tibetan Plateau. **Clean Soil Air Water**, v. 45, p. 1600008, 2017. <https://doi.org/10.1002/clen.201600008>
- MOMOLLI, D. R.; SCHUMACHER, M. V.; VIERA, M.; LUDVICHAK, A. A.; GUIMARÃES, C. C.; SOUZA, H. P. Incident precipitation partitioning: throughfall, stemflow and canopy interception in *Eucalyptus dunnii* stand. **Journal of Agricultural Science**, v. 11, n. 5, 2019a. <https://doi.org/10.5539/jas.v11n5p372>
- MOMOLLI, D. R.; SCHUMACHER, M. V.; VIERA, M.; LUDVICHAK, A. A.; GUIMARÃES, C. C.; SOUZA, H. P. Incident Precipitation Partitioning: The Canopy Interactions Enrich Water Solution with Nutrients in Throughfall and Stemflow. **Journal of Agricultural Science**, v. 11, n. 6, 2019b. <https://doi.org/10.5539/jas.v11n6p351>
- MOMOLLI, D. R.; SOUZA, H. P.; SCHUMACHER, M. V.; LUDVICHAK, A. P.; GUIMARÃES, C. C.; MALHEIROS, A. C.; GONSALVES, J. M. W. Seasonal variation of atmospheric nutrient deposition in the western part of Rio Grande do Sul, Brazil. **Revista Ambiente & Água**, v. 15, n. 3, 2020. <https://doi.org/10.4136/ambi-agua.2524>
- NAVAR, J.; GONZALEZ, J. M.; GONZALEZ, H. Gross precipitation and throughfall chemistry in legume species planted in Northeastern Mexico. **Plant Soil**, v. 318, p. 15-26, 2009. <https://doi.org/10.1007/s11104-008-9812-0>
- NAVAR, J. Stemflow variation in Mexico's northeastern forest communities: Its contribution to soil moisture content and aquifer recharge. **Journal of Hydrology**, v. 408, n.1, p. 35-42, 2011. <https://doi.org/10.1016/j.jhydrol.2011.07.006>
- POLETO, G. C.; MOMOLLI, D. R.; SCHUMACHER, M. V.; LUDVICHAK, A. A.; SANTOS, K. F.; STAHL, J.; ALVARES, C. A. Partial exclusion of precipitation: throughfall, stemflow and canopy interception in *Eucalyptus* plantations in southern Brazil. **Revista Ambiente & Água**, v. 16, n. 5, 2021. <https://doi.org/10.4136/ambi-agua.2645>
- PREUHSLER, T.; BASTRUP-BIRK, A.; BEUKER, E. (elab.). Meteorological Measurements. *In*: United Nations Economic Commission for Europe. **Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests**. Part VII. 2006. Available at: https://www.icp-forests.org/pdf/manual/2000/Chapt7_compl2006.pdf Access: Oct. 2021.

- SCHRUMPF, M.; ZECH, W.; AXMACHER, J.; HERBERT V. M. L. Biogeochemistry of an Afrotropical Montane Rain Forest on Mt. Kilimanjaro, Tanzania. **Journal of Tropical Ecology**, v. 22, n. 1, p. 77-89, 2006. <http://www.jstor.org/stable/4092145>
- STAELENS, J.; DE SCHRIJVER, A.; VERHEYEN, K.; VERHOEST, N. E. C. Spatial variability and temporal stability of throughfall water under a dominant beech (*Fagus sylvatica* L.) tree in relationship to canopy cover. **Journal of Hydrology**, v. 330, p. 651-662, 2006. <https://doi.org/10.1016/j.jhydrol.2006.04.032>
- SU, L.; ZHAO, C.; XU, W.; XIE, Z. Hydrochemical Fluxes in Bulk Precipitation, Throughfall, and Stemflow in a Mixed Evergreen and Deciduous Broadleaved Forest. **Forests**, v. 10, n. 507, 2019. <https://doi.org/10.3390/f10060507>
- SWAFFER, B. A.; HOLLAND, K. L.; DOODY, T. M.; HUTSON, J. Rainfall partitioning, tree form and measurement scale: A comparison of two co-occurring, morphologically distinct tree species in a semi-arid environment. **Ecohydrology**, v. 7, p. 1331-1344, 2014. <https://doi.org/10.1002/eco.1461>
- TIWARI, S. *et al.* Nature and Sources of Ionic Species in Precipitation across the Indo-Gangetic Plains, India. **Aerosol and Air Quality Research**, v. 16, n.4, p. 943-957, 2016. <https://doi.org/10.4209/aaqr.2015.06.0423>
- VIERA, M.; SCHUMACHER, M. V. Deposição de serapilheira e de macronutrientes em um povoamento de acácia negra (*Acacia mearnsii* De Wild.) no Rio Grande do Sul. **Ciência Florestal**, v. 20, n.2, p. 225-233, 2010. <https://doi.org/10.5902/198050981848>
- ZHANG, Y.; WANG, X.; HU, R.; PAN, Y.; ZHANG, H. Stemflow in two xerophytic shrubs and its significance to soil water and nutrient enrichment. **Ecological Research**, v. 28, p. 567-579, 2013. <https://doi.org/10.1007/s11284-013-1046-9>
- ZHANG, Y.; WANG, X.; PAN, Y.; HU, R. Variations of Nutrients in Gross Rainfall, Stemflow, and Throughfall Within Revegetated Desert Ecosystems. **Water Air Soil Pollution**, v. 227, n. 6, p. 183, 2016. <https://doi.org/10.1007/s11270-016-2878-z>
- ZHOU, X. *et al.* Chemical composition of precipitation in Shenzhen, a coastal mega-city in South China: Influence of urbanization and anthropogenic activities on acidity and ionic composition. **Science of The Total Environment**, v. 662, p. 218-226, 2019. <https://doi.org/10.1016/j.scitotenv.2019.01.096>
- YUAN, C.; GAO, G.; FU, B. Comparisons of stemflow and its bio-/abiotic influential factors between two xerophytic shrub species. **Hydrology and Earth System Sciences**, v. 21, p. 1421-1438, 2017. <https://doi.org/10.5194/hess-21-1421-2017>