

# Spatial and temporal patterns in Carbon and Nitrogen inputs by net precipitation in Atlantic Forest, Brazil

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## Research

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## Abstract

**Background** Forests are important for governing local and regional water and nutrient dynamics. Thus, studying precipitation-forest interactions is essential to understand the consequences of land-use and climate change for the hydrological and nutrient cycles. This study aimed to quantify the contribution of the net precipitation on Atlantic Forest's total carbon (C) and total nitrogen (N), identifying potential differences between these chemistry inputs regarding temporal (seasonal and monthly) and spatial scales.

**Results** The rainfall was enriched after crossing the forest canopy. For gross rainfall and net precipitation, respectively, statistical differences were found between annual inputs of carbon ( $104.13 \text{ kg ha}^{-1}$  and  $193.18 \text{ kg ha}^{-1}$ ) and nitrogen ( $16.81 \text{ kg ha}^{-1}$  and  $36.95 \text{ kg ha}^{-1}$ ). Moreover, there was a seasonal variability in the inputs of C and N since 75% occurred in the wet season. November and December concentrated the largest nutrient contribution throughout the year. The spatial variability of C and N was higher in the wet season. Overall, the spatial patterns revealed that the same locations had the highest inputs regardless of the analyzed period.

**Conclusion** Our findings reinforce that forests promote rainfall enrichment with C and N. The forest-rainfall interactions provide constant input of these nutrients, especially in the wet season, being fundamental for maintenance of ecological processes. Despite the nutrient inputs presented some variability, this study provides useful information on the changes of C and N inputs after forest-rainfall interactions. Thus, it can support the estimation of atmospheric deposition and advance the knowledge of the contribution of the leaching and absorption processes by canopies.

## Background

Forests maintain the entire ecosystem balanced by controlling the biogeochemical cycles and decreasing the transport of nutrients to watercourses (Tundisi and Matsumura-Tundisi 2013). In this regard, forests are important because they are the first rain contact with terrestrial ecosystems, conducting singular biogeochemical processes (Van Stan and Stubbins 2018).

When rainwater interacts with the forest canopy, a portion is stored in it, returning to the atmosphere through evaporation (wet canopy evaporation). The water routed to the soil surface by dripping off the canopy, along with rainfall that crosses the forest without hitting the vegetation, composes the "throughfall" (Van Stan and Friesen 2020). Finally, the "stemflow" is the rainfall portion that drains through the tree trunks (Muzylo et al. 2009). Therefore, "net precipitation" (NP) is the portion of rainfall that reaches the forest floor (throughfall plus stemflow) (Sadeghi et al. 2020).

The nutrient input occurs preferentially by rainfall, highlighting NP as the major pathway of nutrients into forests (Sadeghi et al. 2020; Haag 1985). Although stemflow is a small portion of NP, it is a highly concentrated flux, responsible for water and nutrients inputs near the trees. Thus, it can directly change the roots' physical, chemical and biological properties and accelerate the redistribution of nutrients in the forest ecosystem (Germer et al. 2012; Terra et al. 2018a; Su et al. 2019). Every process of rainfall partitioning and nutrient input rely on both forest characteristics and canopy-rain interactions (Terra et al. 2018a; Sadeghi et al. 2020). Therefore, NP flux and chemistry are generally affected by vegetation type, trees morphological traits, atmospheric deposition and materials derived from the canopies and trunks (Hofhansl et al. 2012; Marques et al. 2019; Su et al. 2019).

The nitrogen and carbon cycles are essential for living organisms and for sustaining a number of processes that occur on the planet. The importance of the forest as carbon sinks and its role on climate change mitigation have been widely discussed recently (Silveira et al. 2019; Sullivan et al. 2020). However, forests are susceptible to different types of extreme events that could affect the carbon balance in the atmosphere such as droughts and fires, that might reduce productivity and increase tree mortality (Phillips et al. 2010; Reichstein et al. 2013). The natural presence of nitrogen in tropical forests is less limited than in temperate forests (Hietz et al. 2011). However, the nitrogen cycle has been changed in the last centuries due to the contribution of anthropogenic sources (Jaffe and Weiss-Penzias 2003). The increase of nitrogen might improve ecosystem productivity by fertilization or decrease by acidification, eutrophication, or unbalance (Galloway et al. 2004).

However, there are knowledge gaps regarding the process of storing and distributing nutrients in forest stands, that must be fulfilled. Despite the considerable increase in studies, only a few addresses the spatial and temporal variability of nutrient concentration in throughfall and stemflow in tropical areas (Levia and Frost 2006; Zimmermann et al. 2007; Ponette-González et al. 2020). This kind of research and data is scarce due to difficulties imposed by logistic and costs as continuous data collection and lab analysis are necessary (Levia and Frost 2006). The few initiatives usually take into account only punctual rain events or selected events in a time period (Schroth et al. 2001; Tobón et al. 2004; Germer et al. 2007; Hofhansl et al. 2011; Hofhansl et al. 2012), specific periods data like wet seasons (Ciglasch et al. 2004; Möller et al. 2005; Oziegbe et al. 2011), and weekly or each two weeks samplings (Lilienfein and Wilcke 2004;

Schwendenmann and Veldkamp 2005; Goller et al. 2006; Dezzeo and Chacón 2006; Fujii et al. 2009; Souza et al. 2015; Neu et al. 2016). Moreover, this source of study is particularly scarce for total carbon and total nitrogen concerning Neotropical forests.

The Brazilian Atlantic Forest is a world biodiversity hotspot (Myers et al. 2000) and the second-largest South American rainforest, encompassing tropical and subtropical regions with different altitudes and rainfall amounts (Ribeiro et al. 2009; Oliveira-Filho and Fontes 2000). The Atlantic Forest is composed of two types of forest – rainforests and semideciduous forests –, that have idiosyncrasies related to seasonality. Rainfall, temperature, and altitude are the main drivers of the distribution of these vegetation types (Oliveira-Filho and Fontes 2000; Terra et al. 2018b). Atlantic rainforests are restricted to Brazilian coasts and mountain range regions, while the semideciduous forests extend across the southeastern Brazil. These latter forests are composed by tree species that have strategies to cope with the up-to-six-months dry season (Morellato and Haddad 2000), notably the leaf loss of up to 50% of the trees during the dry season (Veloso et al. 1991; IBGE 2012). Despite the well-known ecosystem services provided by these environments, the Atlantic forest has been threatened by anthropic activities (Ribeiro et al. 2009). For improving the protection programs and management strategies, studies for understanding the Atlantic forest intrinsic dynamics is urgent.

Thus, this research aimed to assess the contribution of net precipitation on the chemistry (C and N) of an Atlantic Forest remnant relying on data collected throughout one hydrological year. In this context, we sought to: i) compare the changes in concentration and inputs of C and N as the rainfall is partitioned by forest canopy; ii) identify the impacts of seasonality on C and N inputs considering the dry and wet periods and also monthly; and iii) to assess the spatial behavior of C and N inputs across the forest stand.

## Methods

### Site description

The study site is a 6.30 ha Atlantic Forest remnant (AFR) located in Southeastern Brazil (21°13'40"S and 44°57'50"W) with an average elevation of 925 m. This forest remnant is classified as “montane seasonal semideciduous forest” (Oliveira-Filho et al. 1996). This forest type is widespread throughout the more inland portion of the Atlantic Forest biome in Southeastern Brazil, where the seasonal rainfall makes up to 50% of trees in these forests to lose their leaves in the dry season (Scolforo and Carvalho 2006). The relief is gently undulated and the soil classified as Dystrophic Red Latosol (Rhodic Hapludox) (Junqueira Junior et al. 2017). The Köppen-type climate of the studied region is Cwa with well-defined seasons, characterized by rainfall concentration in the summer (December to March) (Junqueira Junior et al. 2019). Long-term average annual precipitation (1981–2010) is 1461.8 mm in which 85% of it falls during the wet period (October to March) (INMET 2018). The mean annual temperature is 20.3°C ranging from 16.9°C (June and July) to 22.5 °C in February (INMET 2018).

### Gross rainfall (GR), Throughfall (Tf), and Stemflow (Sf) measurements

The gross rainfall (rainfall not affected by trees canopy - GR), throughfall (Tf), and stemflow (Sf) were monitored from May 2018 to April 2019, totalizing 86 daily rainfall events. The monitoring was performed the day after each rainfall event (at approximately 9:00 AM local time) or at least 4 hours after the rainfall event had ceased to avoid events overlapping.

For measuring SF, 10 trees were selected from the three most abundant species to better represent the characteristics of the AFR. According to Oliveira-Filho et al. (1996), the most abundant species in the AFR are *Copaifera langsdorffii* Desf. (Fabaceae), *Xylopia brasiliensis* Sprengel (Annonaceae) and *Miconia pepericarpa* DC. (Melastomataceae) (Table 1). The selected trees were well-distributed in the site (Fig. 1) and can be classified according to their DBH (diameter at 1.3 m above ground; see Table 1). For Sf measurements, collectors built with a hose slit open toward the length was nailed in a spiral around the tree trunk and connected to a collection bin (Fig. 2a).

Table 1  
Identification of trees species in the Atlantic Forest remnant.

Tree code	Scientific name	DBH (cm)
01	<i>Xylopia brasiliensis</i>	27.37
02	<i>Copaifera langsdorfii</i>	32.15
03	<i>Copaifera langsdorfii</i>	14.96
04	<i>Copaifera langsdorfii</i>	31.83
05	<i>Miconia pepericarpa</i>	21.65
06	<i>Miconia pepericarpa</i>	12.10
07	<i>Xylopia brasiliensis</i>	50.29
08	<i>Xylopia brasiliensis</i>	11.46
09	<i>Miconia pepericarpa</i>	24.19
10	<i>Xylopia brasiliensis</i>	8.91

Figure 1. The geographical location of the AFR in Brazil and the positions of the measuring points.

GR was measured through 3 fixed Ville de Paris-type rain gauges placed around the forest remnant (Fig. 1 and Fig. 2b). Thereafter, the GR over the AFR was assessed by means of the Thiessen Polygon approach. In the case of gaps in the dataset, the climatological station from the "Brazilian National Meteorological Institute" (INMET 2019) was used to fill them. In addition, for Tf, 10 fixed Ville de Paris-type rain gauges were installed near the selected trees 1.5 m above the forest floor to avoid splash-in (Fig. 2a).

GR and Tf were converted to depth by dividing the collected volume (L) by the rain-gauge catchment area (m<sup>2</sup>). On the other hand, for Sf, the volume stored in the bin (L) was divided by the total projected crown area (m<sup>2</sup>). This projected area was determined according to the methodology described by Shinzato et al. (2011) in which 8 vertical projections far-between 45° were set in the ground. Then, the area for each canopy was calculated as follow:

$$A \text{ (m}^2\text{)} = \sum \left( a * b * \frac{\sin 45^\circ}{2} \right) \quad (1)$$

where A is the projected crown area; "a" and "b" are the vertical projections with far-between 45°. This measurement was performed twice, by considering the projected crown areas in the dry (July 2018) and wet (March 2019) periods.

## Chemical analysis

GR, Tf, and Sf water samples were collected for events with at least 5 mm of rainfall due to the minimum necessary volume for lab analysis, summing up 60 events. GR were composed by the samples of the three external rain gauges (Fig. 1).

The evaluated physical and chemical parameters included pH, Electric Conductivity (EC), Total Carbon (C), Nitrate (NO<sub>3</sub><sup>-</sup>), Nitrite (NO<sub>2</sub><sup>-</sup>), and Total Kjeldahl Nitrogen (which refers to Ammonia and Organic Nitrogen; TKN). Regarding pH, EC, and carbon, the samples were analyzed after every rainfall event (i.e. single samples). On the other hand, for analyzing NO<sub>3</sub><sup>-</sup>, NO<sub>2</sub><sup>-</sup>, and TKN, the samples were firstly accumulated on a monthly scale (i.e. composite sample) before the analysis could be carried out. All procedures concerning the samples (taking, preserving, and analyzing) followed the *Standard Methods* (APHA 2014) criteria (Table 2). These ensured that the nitrogen was not lost during storage.

Table 2

Physical and chemical water variables evaluated, preservation procedures, the lab method used, and respective reference.

Variable	Preservation procedures	Lab Method	References
pH	Refrigerated at 4 °C	Eletrometric method (Method 4500 H <sup>+</sup> )	APHA (2014)
EC		Conductimetric method (Method 2510 B)	APHA (2014)
C	Filtered and refrigerated at 4 °C	Shimadzu total carbon analyzer (TOC-V CPH) (Method TC-IC)	Shimadzu (2003)
NO <sub>3</sub> <sup>-</sup>	Filtered and frozen	Yang et al. (1998) Method	Yang et al. (1998)
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TKN	Acidification and refrigerated at 4 °C	NBR 13.796:1997 Method	ABNT (1997)

## Data analysis

For some events, it was not possible to measure Tf and Sf because the rain gauge remained open and/or the collectors were knocked over by animals. Thus, with GR data, linear regressions were fitted to overcome these issues and to fill the unavoidable gaps in the measuring points. The regressions have been performed for each point separately, resulting in R<sup>2</sup> greater than 0.78 and 0.54 for Tf and Sf, respectively.

For pH, EC, and C, which were analyzed in all the rainfall events, the mean monthly values of the concentrations in GR, Tf, and Sf were estimated by the volume-weighted mean (VWM), as follows:

$$VWM = \frac{\sum_{n=1}^i C_{i,e} \cdot V_{i,e}}{\sum_{n=1}^i V_{i,e}} \quad (2)$$

where C represents the concentration of the parameters (pH, EC, and C) at collector *i* for event *e*, and V represents the total volume at collector *i* for event *e*. As abovementioned, the chemical analyses for TKN, NO<sub>3</sub><sup>-</sup>, and NO<sub>2</sub><sup>-</sup> were carried out in a month scale. Then, with the total concentration of nitrogen (N = TKN + NO<sub>3</sub><sup>-</sup> + NO<sub>2</sub><sup>-</sup>) and carbon (C) together with the total volume of rainfall collected in the analyzed period, it was possible to estimate the monthly inputs of N (kg.ha<sup>-1</sup>) and C (kg.ha<sup>-1</sup>) by means of the following equation:

$$I = \frac{C \cdot D}{100} \quad (3)$$

where *I* represent the input of Nitrogen or Carbon (kg.ha<sup>-1</sup>); *C* represents the monthly concentration average (mg.L<sup>-1</sup>) of N or C; and *D* represents the monthly GR, Tf and Sf (mm).

## Temporal analysis

The temporal analysis was assessed through the monthly inputs of GR and NP. For this, NP was firstly averaged across the area from the 10 sample points (Tf + Sf) inputs. Then, statistical differences in C and N inputs (kg.ha<sup>-1</sup>), between GR and NP (objective i) as well as the NP differences between the dry and wet season, and monthly were assessed by means of the analysis of variance (one-way ANOVA). Further, Tukey's test was applied to analyze whether NP differentiates throughout the months (objective ii). All the statistical analyses were performed on R environment (version 3.6.2) (R Core Team 2018).

## Spatial analysis

Spatial analysis was performed to identify the spatial patterns of C and N inputs (kg.ha<sup>-1</sup>) in the AFR. Thus, the samples were accumulated to account for three periods of analysis: annual; the dry season; and the wet season (objective iii). Spatial variability was assessed by means of the coefficient of variation (CV). Moreover, the Inverse Distance Weighting (IDW, specifically inverse of the square of the distance) interpolation method was applied for mapping the spatial distribution of N and C to highlight areas of greater contribution on the nutrient cycle. This method considers only the distance between the points to predict a value for any unmeasured location. The interpolations were performed in the Quantun GIS software (QGIS Version 3.14.0).

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## Results

### Hydrological monitoring

GR was monitored from May 2018 to April 2019, summing up 86 events, which corresponded to 1601.6 mm. Total precipitation for the same period in a meteorological station (MS) located at 1 km from the forest edge was 1535.3 mm (INMET 2019). Considering that the long-term annual average rainfall (1981-2010) is 1461.8 mm, the sampling year represented a typical year in terms of rainfall, with almost 10% above the average (Table 3). Approximately 85% of gross rainfall in the AFR occurred in the wet season (October to March) which is in accordance with the expected pattern of the region (Table 3).

Table 3. Comparison of the monitored dry and wet seasons (INMET and AFR) against the long-term average (1981-2010).

	INMET meteorological station (mm)	Atlantic Forest remnant (AFR) (mm)	Long-term average rainfall (1981-2010) - (mm)
Dry season	226.4	241.0	218.0
Wet season	1308.9	1360.5	1243.8
Total	1535.3	1601.6	1461.8

The maximum and minimum GR were monitored in December (328.4 mm) and July (0.0 mm), respectively (Fig.3). *Tf* was the main portion of GR across the monitoring period, totalizing 1278.6 mm, which represents 79.8% of it, ranging from 70.78% (June) to 85.72% (December).

Interception loss totalized 319.7 mm (20.0% of GR), with a maximum percentage in June (29.17%) and a minimum in December (14.05%). *Sf* totalized 3.2 mm, representing 0.20% of GR, with a maximum contribution in August (0.42 %) and a minimum in June (0.04%).

## Chemical analysis

For chemical analysis, rainfall samples were collected from 60 events (only those with more than 5 mm) totalizing 1529.6 mm of GR, 1232.1 mm of *Tf*, and 3.1 mm of *Sf*, which represents approximately 96% of the entire monitoring period (Table 4).

Table 4. Gross rainfall (GR), average throughfall (Tf) and average stemflow (Sf) with their respective standard deviations and coefficients of variation (CV).

Months	GR (mm)	Tf (mm)	Sf (mm)
May 2018	10.61	8.32 ± 1.84 (22%)	0.005 ± 0.006 (120%)
Jun 2018	14.08	11.13 ± 2.62 (24%)	0.007 ± 0.007 (100%)
Jul 2018	0	0.00 ± 0.00 (0%)	0.000 ± 0.000 (0%)
Aug 2018	60.2	46.39 ± 9.34 (20%)	0.287 ± 0.209 (73%)
Sep 2018	46.37	38.25 ± 5.18 (14%)	0.079 ± 0.060 (76%)
Oct 2018	205.95	164.11 ± 21.26 (13%)	0.364 ± 0.188 (52%)
Nov 2018	240.64	182.03 ± 32.19 (18%)	0.638 ± 0.576 (90%)
Dec 2018	319.86	276.54 ± 35.08 (13%)	0.699 ± 0.389 (56%)
Jan 2019	147.76	117.89 ± 22.64 (19%)	0.342 ± 0.215 (63%)
Feb 2019	201.5	159.57 ± 32.35 (20%)	0.277 ± 0.173 (62%)
Mar 2019	199.21	160.88 ± 23.49 (15%)	0.292 ± 0.246 (84%)
Apr 2019	83.39	67.00 ± 11.49 (17%)	0.119 ± 0.097 (82%)
Entire period (mm)	1529.57	1232.11	3.109

The annual average pH of GR was 7.16. For Tf and Sf, this value was 6.96 and 5.23, respectively. The average EC of GR was 16.23  $\mu\text{S}/\text{cm}$ , while the EC of Tf and SF was 46.86  $\mu\text{S}\cdot\text{cm}^{-1}$  and 53.46  $\mu\text{S}\cdot\text{cm}^{-1}$ , respectively. These values are 2.9 and 3.3 times greater than GR, considering Tf and Sf, respectively (Table 5).

Table 5. pH and electric conductivity (EC) of gross rainfall (GR), average throughfall (Tf) and average stemflow (Sf) with their respective standard deviations and coefficients of variation (CV).

Months	GR		Tf		Sf	
	pH	EC ( $\mu\text{S}\cdot\text{cm}^{-1}$ )	pH	EC ( $\mu\text{S}\cdot\text{cm}^{-1}$ )	pH	EC ( $\mu\text{S}\cdot\text{cm}^{-1}$ )
May 2018	7.44	32	7.18 ± 0.37 (5.2%)	182.10 ± 47.36 (26%)	7.47 ± 0.44 (6%)	301.20 ± 278.12 (92%)
Jun 2018	7.29	58	7.30 ± 0.31 (4.2%)	206.00 ± 271.08 (132%)	7.15 ± 0.51 (7%)	117.44 ± 54.60 (46%)
Jul 2018	0.00	0.00	0.00 ± 0.00 (0%)	0.00 ± 0.00 (0%)	0.00 ± 0.00 (0%)	0.00 ± 0.00 (0%)
Aug 2018	5.56	15.57	5.40 ± 1.31 (24.3%)	81.24 ± 30.46 (37%)	5.05 ± 0.48 (10%)	138.25 ± 48.44 (35%)
Sep 2018	7.35	34.3	7.17 ± 0.05 (0.7%)	78.92 ± 15.59 (20%)	5.51 ± 0.34 (6%)	153.88 ± 48.88 (32%)
Oct 2018	7.26	19.22	7.04 ± 0.08 (1.1%)	56.24 ± 16.93 (30%)	5.37 ± 0.47 (9%)	69.73 ± 31.36 (45%)
Nov 2018	7.13	17.22	6.93 ± 0.07 (1.0%)	40.83 ± 14.24 (35%)	5.09 ± 0.66 (13%)	43.88 ± 19.85 (45%)
Dec 2018	6.86	15.23	6.71 ± 0.09 (1.3%)	33.88 ± 7.71 (23%)	5.11 ± 0.44 (9%)	29.50 ± 17.40 (59%)
Jan 2019	7.61	21.48	7.40 ± 0.15 (2.0%)	43.56 ± 10.03 (23%)	5.56 ± 0.31 (6%)	31.52 ± 17.18 (55%)
Feb 2019	7.48	10.26	7.17 ± 0.08 (1.1%)	42.45 ± 6.58 (16%)	5.24 ± 0.62 (12%)	45.86 ± 28.17 (61%)
Mar 2019	7.24	8.88	7.06 ± 0.05 (0.7%)	37.75 ± 8.66 (23%)	5.19 ± 0.85 (16%)	35.55 ± 18.56 (52%)
Apr 2019	7.36	13.84	7.20 ± 0.05 (0.7%)	46.70 ± 10.07 (22%)	5.38 ± 0.34 (6%)	35.15 ± 12.50 (36%)
Mean annual	7.16	16.23	6.96	46.86	5.23	53.46

The C and N concentrations were higher in Sf, followed by Tf and GR, respectively (Table 6). For all months, excepted May, Sf concentration of N was higher than the concentration in Tf (Figs. 4a and 4b). Considering annual average concentration ( $\text{mg.L}^{-1}$ ) in GR, C was almost three times higher in Tf, and more than five times higher in Sf, whereas N concentration was more than twice in Tf and more than four times in Sf.

Table 6. Carbon and Nitrogen concentration from gross rainfall (GR), average throughfall (Tf), and average stemflow (Sf) with their respective standard deviations and coefficients of variation (CV).

	GR ( $\text{mg.L}^{-1}$ )		Tf ( $\text{mg.L}^{-1}$ )		Sf ( $\text{mg.L}^{-1}$ )	
	C	N	C	N	C	N
May 2018	18.0	9.2	111.6 $\pm$ 3.02 (29%)	13.8 $\pm$ 6.9 (50%)	126.8 $\pm$ 76.5 (60%)	11.5 $\pm$ 16.6 (144%)
Jun 2018	22.9	2.3	50.6 $\pm$ 13.2 (26%)	5.4 $\pm$ 3.9 (72%)	70.0 $\pm$ 28.4 (41%)	12.1 $\pm$ 14.2 (118%)
Jul 2018	0.0	0.0	0 $\pm$ 0 (0%)	0 $\pm$ 0 (0%)	0 $\pm$ 0 (0%)	0 $\pm$ 0 (0%)
Aug 2018	14.0	1.7	32.7 $\pm$ 17.1 (52%)	8.9 $\pm$ 4.4 (49%)	83.4 $\pm$ 35.9 (43%)	14.0 $\pm$ 6.5 (47%)
Sep 2018	12.8	1.9	30.5 $\pm$ 9.8 (32%)	3.8 $\pm$ 1.7 (46%)	96.7 $\pm$ 52.0 (54%)	11.8 $\pm$ 7.7 (66%)
Oct 2018	6.0	0.8	18.4 $\pm$ 6.4 (35%)	2.9 $\pm$ 1.5 (52%)	45.9 $\pm$ 22.2 (48%)	8.9 $\pm$ 5.9 (67%)
Nov 2018	7.8	0.8	14.2 $\pm$ 4.8 (34%)	4.0 $\pm$ 2.2 (54%)	27.3 $\pm$ 13.4 (49%)	10.9 $\pm$ 5.8 (53%)
Dec 2018	6.5	0.9	12.2 $\pm$ 3.5 (29%)	2.5 $\pm$ 1.5 (59%)	24.9 $\pm$ 13.9 (56%)	6.8 $\pm$ 5.9 (87%)
Jan 2019	6.2	1.1	12.4 $\pm$ 3.7 (29%)	3.0 $\pm$ 1.3 (42%)	22.7 $\pm$ 11.3 (50%)	4.9 $\pm$ 2.8 (56%)
Feb 2019	5.4	1.1	12.7 $\pm$ 3.3 (26%)	1.5 $\pm$ 0.3 (19%)	33.0 $\pm$ 18.5 (56%)	4.1 $\pm$ 3.2 (77%)
Mar 2019	4.3	1.2	10.8 $\pm$ 3.6 (34%)	1.7 $\pm$ 0.6 (33%)	27.7 $\pm$ 17.1 (62%)	3.4 $\pm$ 1.9 (55%)
Apr 2019	4.7	1.1	11.6 $\pm$ 2.7 (23%)	2.4 $\pm$ 1.1 (48%)	23.0 $\pm$ 11.4 (49%)	3.2 $\pm$ 2.2 (70%)
Annual average	9.06	1.84	26.47	4.17	48.46	7.64

The total annual C and N in GR was  $104.13 \text{ kg.ha}^{-1}$  and  $16.81 \text{ kg.ha}^{-1}$ , respectively; in Tf, they were, respectively,  $191.97 \text{ kg.ha}^{-1}$  and  $36.69 \text{ kg.ha}^{-1}$ ; and in Sf,  $1.21 \text{ kg.ha}^{-1}$  and  $0.27 \text{ kg.ha}^{-1}$ , respectively (Table 7). The total annual flux of C and N in NP (Tf + Sf) increased by 86% and 120%, respectively, regarding GR. Analyzing the seasonality of nutrient inputs, we observed that 74.3% ( $143.52 \text{ kg.ha}^{-1}$ ) of C and 75.1% ( $27.76 \text{ kg.ha}^{-1}$ ) of N reached the forest floor during the wet season.

Table 7. Monthly inputs of Carbon and Nitrogen from gross rainfall (GR), throughfall (Tf), and stemflow (Sf) in the AFR.

Months	GR (kg.ha <sup>-1</sup> )		Tf (kg.ha <sup>-1</sup> )		Sf (kg.ha <sup>-1</sup> )	
	C	N	C	N	C	N
May 2018	1.91	0.97	8.94	1.10	0.00	0.00
Jun 2018	3.23	0.32	5.47	0.55	0.00	0.00
Jul 2018*	0.00	0.00	0.00	0.00	0.00	0.00
Aug 2018	8.43	1.01	15.53	4.46	0.25	0.04
Sep 2018	5.95	0.87	11.48	1.42	0.09	0.01
Oct 2018	12.43	1.74	29.65	4.63	0.19	0.04
Nov 2018	18.84	1.96	26.04	7.18	0.20	0.08
Dec 2018	20.89	2.88	34.56	7.18	0.19	0.05
Jan 2019	9.21	1.59	14.09	3.40	0.07	0.02
Feb 2019	10.80	2.11	20.84	2.49	0.11	0.01
Mar 2019	8.55	2.41	17.50	2.68	0.09	0.01
Apr 2019	3.89	0.94	7.88	1.60	0.02	0.00
Annual total	104.13	16.81	191.97	36.69	1.21	0.27

\*Means no observed rain in the month.

## Temporal analyses

ANOVA detected significant differences for C ( $p = 0.027$ ) and N ( $p = 0.022$ ) inputs between GR and NP. For NP, significant differences between dry and wet seasons for C ( $p = 2.72E-06$ ) and N ( $p = 2.81E-06$ ) inputs, as well as monthly (C:  $p = 1.19E-18$ ; N:  $p = 2.38E-15$ ), were found. Based on Tukey's test, it was possible to group months without differences for C and N inputs in NP (Fig. 5 and Fig. 6).

Considering NP, the months with the highest C inputs were December, October, and November respectively (a), whereas the months with the lowest contributions were September, May, and June (f). C inputs followed the climatic seasonality of the region, meaning that months with higher precipitation have higher inputs.

The highest N inputs by NP were observed in November and December (a), and these months showed no statistical differences. August and October were statistically similar (ab), which the same observed in January, February, and March (bc). Apart from August, N inputs were greater throughout the wet season (October to May). Thus, the months with the lowest inputs were April, May, June, and September, which no statistical differences among them (c).

## Spatial analyses

The spatial variability of N and C inputs (kg.ha<sup>-1</sup>) was assessed through the coefficient of variation (CV) regarding the monthly, the seasonal (dry and wet seasons), and the annual scales (Table 8). In general, the annual and the wet season demonstrated the same variability for both, C and N inputs. However, in the dry season, the spatial variability of N (26%) was higher than that of C (18%). Considering the seasonality, for both C and N, the variability was higher in the wet season than in the dry season. Throughout the year, the CV of C ranged from 19% (January) to 47% (August), while N varied from 17% (February) to 60% (September).

Table 8. Coefficient of variation (CV) of C and N inputs (kg.ha<sup>-1</sup>) in the AFR.

Coefficient of variation (%) in C and N inputs from net precipitation		
Months	Carbon	Nitrogen
May 2018	22	43
Jun 2018	22	52
Jul 2018*	0	0
Aug 2018	47	44
Sep 2018	29	60
Oct 2018	29	44
Nov 2018	38	50
Dec 2018	39	58
Jan 2019	19	31
Feb 2019	29	17
Mar 2019	41	20
Apr 2019	24	27
Dry season	18	26
Wet season	30	30
Annual total	26	27

\*July 2018 there was no rainfall events

IDW method was carried out to assess the spatial distribution of C and N inputs ( $\text{kg}\cdot\text{ha}^{-1}$ ) regarding the dry and wet seasons and the entire period (total annual) (Fig. 7). Overall, there is a consensus between the spatial patterns of N and C in the dry season. However, in the wet season, the spatial patterns of C and N presented remarkable differences, especially in the southwest and the northeast regions of the AFR. Regardless the analyzed period, the greatest inputs for both C and N occurred in the same places, in the central, southwestern and eastern areas (near the points 3, 4 and 8).

## Discussion

This study aimed to (i) compare the changes in C and N inputs before and after the rainfall passes through the forest canopy; (ii) identify differences in C and N inputs in net precipitation considering the dry and wet seasons and also the monthly scale; and (iii) identify spatial differences in C and N inputs within the Atlantic forest remnant. Our main findings are (i) statistical differences in C and N inputs between gross rainfall and net precipitation, with an increase in the inputs after rainfall passes through the canopy; (ii) statistical differences were also observed in the seasonal and monthly scales, as a higher input occurred during the wet season, accounting for almost 75% of the total contribution; and (iii) the spatial variability was higher in the wet season which the largest inputs for both C and N occurring in the same places (near the points 3, 4 and 8).

## Gross Rainfall x Net Precipitation

The concentration of  $\text{NO}_3^-$ ,  $\text{NO}_2^-$ , TKN, total nitrogen and total carbon in gross rainfall, throughfall and stemflow were similar to what have been found by other studies in Tropical and Temperate forests worldwide (Hölscher et al. 2003; Markewitz et al. 2004; Lilienfein and Wilcke 2004; Oziegbe et al. 2011; Tu et al. 2013; Ukonmaanaho et al. 2014; Neu et al. 2016; Izquieta-Rojano et al. 2016; Limpert and Siegert 2019; You et al. 2020). Our results show that the rain is enriched with N and C when crossing the forest canopy because the average annual concentration of these nutrients is higher in throughfall and stemflow than in gross rainfall. These results are in accordance with other studies in both temperate and tropical forests that indicate leaching of N and C from the forest (Schroth et al. 2001; Hölscher et al. 2003; Goller et al. 2006; Hofhansl et al. 2011; Liu and Sheu 2003; Heartsill-Scalley et al. 2007; Izquieta-Rojano et al. 2016; Van Stan et al. 2017; Limpert and Siegert 2019). However, specifically for nitrogen forms, the results found do not corroborate with some other studies, in which

N concentrations decreased in throughfall and stemflow, indicating retention of N by the forest (Parron et al. 2011; Tu et al. 2013; Ukonmaanaho et al. 2014; Su et al. 2019). We observed that concentrations decrease only for  $\text{NO}_2^-$  in stemflow ( $0.05 \text{ mg. L}^{-1}$ ) comparing with throughfall ( $0.11 \text{ mg. L}^{-1}$ ). Results regarding  $\text{NO}_2^-$  concentrations in rainfall partitioning are extremely rare in the literature, which hampers further comparisons. As the results of nitrogen are variable in the literature, future studies are necessary to deepen in the relationship between the nitrogen and the hydrological cycles in tropical forests.

The increase of C and N concentrations in throughfall and stemflow results from the washing process of atmospheric dry deposition accumulated in forest canopy between rainfall events and from the leaching process of the trees' materials (Parker 1983; Schroth et al. 2001; Liu and Sheu 2003; Corti et al. 2019, You et al. 2020). The main sources of C in net precipitation are derived from the forest system (Parker 1983; You et al. 2020). Although the forest system also has a contribution to increase N concentration in net precipitation, it is remarkable the influence of the atmospheric gaseous and aerosol deposition (Parker 1983; Schroth et al. 2001). In this regard, rainfall that crosses the canopy is an important source of nutrients for forests, and has a great significance in the nutrient cycle, because tree canopy works like a funnel capturing rain and transferring dry deposition from the canopy to the soil surface. This process is controlled by biotic and meteorological factors (Parron et al. 2011; Van Stan and Stubbins 2018).

The process of nutrients enrichment in net precipitation can be reinforced by pH results. We observed that pH decreases when the rainwater passes through the forest canopy, resulting in relevant decrease in the average annual pH. This pH reduction is similar to what happens in other types of forests: Brazilian Cerrado, Amazonia Rainforest, and Temperate Oak Forest (Lilienfein and Wilcke 2004; Tobón et al. 2004; Corti et al. 2019). Organic matter presence is the main cause of the decrease in pH, since organic acids are leached from the leaves of canopies, branches, and trunks (Liu and Sheu 2003; Tobón et al. 2004). Furthermore, the annual average of EC for throughfall and stemflow are, respectively, 2.9 and 3.3 times greater than that of gross rainfall, which shows that the rain was enriched with solid particles, similar to that observed by Su et al. (2019).

Considering total annual C and N inputs to the canopy (GR) and forest floor (Tf, Sf), we observed that, in general, the amount found in our study is in agreement with that found for other tropical and temperate forests (Table 9). For total C, the annual input in gross rainfall ( $104.13 \text{ kg. ha}^{-1} \cdot \text{year}^{-1}$ ) was similar to that found by Neu et al. (2016) in an evergreen tropical forest ( $121 \text{ kg. ha}^{-1} \cdot \text{year}^{-1}$ ). Results of the total carbon are scarce in the literature; however, Neu et al. (2016) observed that 32% of total C found in gross rainfall is from inorganic sources, and the organic carbon fraction is influenced by agricultural activities and fires. The climate seasonality of the study region, summed to the drier vegetation of the surrounding areas, may contribute to the incidence of natural or non-natural fires. In this regard, the carbon present in rainfall may be related to biomass burn (condensation nuclei) as we found results slightly lower than those of regions strongly influence by fires, like Cerrado and Amazonian Rainforest (Markewitz et al. 2004; Germer et al. 2007; Neu et al. 2016).

Table 9

Summary of the key N and C inputs ( $\text{kg}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ ) in rainfall parts (Gross rainfall, Throughfall and, Stemflow) in forests around the world.

Reference	Forest type	Rainfall		Gross rainfall ( $\text{kg}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ )							
		Long-term (mm)	Mean annual (mm)	$\text{NH}_4^+$	$\text{NO}_3^-$	$\text{NO}_2^-$	DON	TKN	N	DOC	C
This study	Atlantic Forest	1461.8	1601.6	-	2.82	0.81	-	13.08	16.81	-	104.13
Schroth et al. (2001)	Amazonia Rainforest	2622	2672	1.8	1.4	-	2.3	4.1*	5.5	-	-
Hölscher et al. (2003)	Rainforest	2812	2900	1.4–2.2	1.7–2.0	-	-	-	-	-	-
Markewitz et al. (2004)	Tropical Moist Forest	1803	-	1.5	0.2	-	-	-	4	123.4	-
Lilienfein and Wilcke (2004)	Cerrado	1550	1815	2.7–3.1	2.1–2.4	-	-	-	5.7–6.4	47–55	-
Schwendenmann and Veldkamp (2005)	Tropical Wet Forest	4200	4073	-	-	-	1–6	-	5–14	22–36	-
Schrumpf et al. (2006)	Rainforest	1840	1960 to 2600	-	-	-	3.36–5.97	-	-	59.4–143.9	-
Germer et al. (2007)	Tropical Rainforest	2300	2286	4.46	0.8	-	-	-	-	106.45	-
Souza and Marques (2010)	Atlantic Rainforest	2240.1	2406.96	-	2.3	-	-	-	-	-	-
Hofhansl et al. (2011)	Wet Tropical Rainforest	5810	5720	-	-	-	-	-	7.7	30.9	-
Oziégbe et al. (2011)	Rainforest	1413	1079	-	10.43	-	-	-	-	-	-
Parron et al. (2011)	Cerrado	-	1400	-	-	-	-	-	12.6	-	-
Souza et al. (2015)	Atlantic Forest	2800	2649	6	5	-	4.1	10.1*	15.1	-	-
Zhou et al. (2016)	Tropical Forest	1557	-	-	-	-	-	-	-	41.9	-
Neu et al. (2016)	Evergreen Tropical Forest	1905	1829	-	-	-	-	-	-	82.3	121.2
Liu and Sheu (2003)	Subtropical Forest	2300 to 2700	-	-	-	-	-	-	-	142.8	-
Tu et al. (2013)	Subtropical Forest	1490	1984.2	61.9	24.9	-	26.9	88.8*	113.8	-	-
Izquieta-Rojano et al. (2016)	Evergreen Holm Oak Forests	364–840	-	0.68–6.55	1.08–3.54	-	1.08–12.27	1.76–18.82*	-	-	-

Legend: C: carbon; N: nitrogen; TKN: total kjeldahl nitrogen; DON: dissolved organic nitrogen; DOC: dissolved organic carbon;  $\text{NH}_4^+$ : ammonia;  $\text{NO}_3^-$ : nitrate;  $\text{NO}_2^-$ : nitrite.

\*TKN = DON +  $\text{NH}_4^+$

		Rainfall		Gross rainfall (kg.ha <sup>-1</sup> .year <sup>-1</sup> )							
You et al. (2020)	Coniferous, Deciduous and Evergreen forest	1416.4	-	-	-	-	-	-	30.4	22.6	-
		Rainfall		Throughfall (kg.ha <sup>-1</sup> .year <sup>-1</sup> )							
Reference	Forest type	Long-term (mm)	Mean annual (mm)	NH <sub>4</sub> <sup>+</sup>	NO <sub>3</sub> <sup>-</sup>	NO <sub>2</sub> <sup>-</sup>	DON	TKN	N	DOC	C
This study	Atlantic Forest	1461.8	1601.6		8.89	1.54	-	26.25	36.68	-	191.97
Schroth et al. (2001)	Amazonia Rainforest	2622	2672	2.2	1.9	-	7.2	9.4*	11.3	-	-
Hölscher et al. (2003)	Rainforest	2812	2900	2.4–5.7	0.6-1	-	-	-	-	-	-
Markewitz et al. (2004)	Tropical Moist Forest	1803	-	2.9	1.7	-	-	-	9.5	83.1	-
Tobón et al. (2004)	Tropical Rainforest	3100	3400	9.72–12.98	17.07–31.98	-	-	-	-	148.43–190.42	-
Lilienfein and Wilcke (2004)	Cerrado	1550	1815	2.3–3.4	3-3.9	-	-	-	9.9–11	66–70	-
Schwendenmann and Veldkamp (2005)	Tropical Wet Forest	4200	4073	-	-	-	9	-	17	232	-
Schrumpf et al (2006)	Montane Rainforest	1840	1960 to 2600	-	-	-	6.24–10.31	-	-	102.8–218.5	-
Germer et al. (2007)	Tropical Rainforest	2300	2286	5.71	2.11	-	-	-	-	301.59	-
Fujii et al. (2009)	Tropical Forest	-	2187–2427	-	-	-	-	-	-	97–182	-
Souza and Marques (2010)	Atlantic Rainforest	2240.1	2406.96	-	2.51–5.93	-	-	-	-	-	-
Schmidt et al. (2010)	Subtropical Montane Forest	2000 to 5000	4169	1.9	2.8	-	3.4	5.3*	-	106	-
Hofhansl et al. (2011)	Wet Tropical Rainforest	5810	5720	-	-	-	-	-	10.5–13.8	74.7–94.9	-
Oziegbe et al. (2011)	Rainforest	1413	1079	-	39.27	-	-	-	-	-	-
Parron et al. (2011)	Cerrado	-	1400	-	-	-	-	-	5.9–8.3	-	-
Diniz et al. (2013)	Atlantic Forest	1300	1533.3	-	-	-	-	-	-	-	23.1–30.5
Souza et al. (2015)	Atlantic Forest	2800	2649	9.1	5.3	0.2	19.7	28.8*	34.3	-	-

Legend: C: carbon; N: nitrogen; TKN: total kjeldahl nitrogen; DON: dissolved organic nitrogen; DOC: dissolved organic carbon; NH<sub>4</sub><sup>+</sup>: ammonia; NO<sub>3</sub><sup>-</sup>: nitrate; NO<sub>2</sub><sup>-</sup>: nitrite.

\*TKN = DON + NH<sub>4</sub><sup>+</sup>

		Rainfall		Gross rainfall (kg.ha <sup>-1</sup> .year <sup>-1</sup> )							
Zhou et al. (2016)	Tropical Forest	1557	-	-	-	-	-	-	-	113.5	-
Neu et al. (2016)	Evergreen Tropical Forest	1905	1829	-	-	-	-	-	-	150.8	167.4
Liu and Sheu (2003)	Subtropical Forest	2300 to 2700	-	-	-	-	-	-	-	188.8-231.3	-
Tu et al. (2013)	Subtropical Forest	1490	1984.2	80.1	13.7	-	20.1	-	113.8	-	-
Izquieta-Rojano et al. (2016)	Evergreen Holm Oak Forests	364-840	-	0.44-3.7	1.66-8.81	-	5.3-11.91	-	-	-	-
Van Stan et al. (2017)	Oak - Cedar Forest	750 to 1200	-	-	-	-	-	-	9-29	230-480	-
You et al. (2020)	Coniferous, Deciduous and Evergreen Forest	1416.4	-	-	-	-	-	-	22.92-27.38	52-75.94	-
		Rainfall		Stemflow (kg.ha <sup>-1</sup> .year <sup>-1</sup> )							
Reference	Forest type	Long-term (mm)	Mean annual (mm)	NH <sub>4</sub> <sup>+</sup>	NO <sub>3</sub> <sup>-</sup>	NO <sub>2</sub> <sup>-</sup>	DON	TKN	N	DOC	C
This study	Atlantic Forest	1461.8	1601.6	-	0.05	0.001	-	0.21	0.261	-	1.21
Hölscher et al. (2003)	Rainforest	2812	2900	0.1-0.4	0.1	-	-	-	-	-	-
Tobón et al. (2004)	Tropical Rainforest	3100	3400	0.18-0.26	0.32-0.62	-	-	-	-	2.82-6.14	-
Hofhansl et al. (2012)	Tropical Rainforest	5810	-	-	-	-	-	-	0.16	2.75	-
Diniz et al. (2013)	Atlantic Forest	1300	1533.3	-	-	-	-	-	-	-	0.93-1.55
Neu et al. (2016)	Evergreen Tropical Forest	1905	1829	-	-	-	-	-	-	1.5	2.1
Liu and Sheu (2003)	Subtropical Forest	2300 to 2700	-	-	-	-	-	-	-	6.7-15.3	-
Van Stan et al. (2017)	Oak - Cedar Forest	750 to 1200	-	-	-	-	-	-	0.15-2.4	7-75	-
You et al. (2020)	Coniferous, Deciduous and Evergreen forest	1416.4	-	-	-	-	-	-	0.14-0.91	0.43-4.43	-
Legend: C: carbon; N: nitrogen; TKN: total kjeldahl nitrogen; DON: dissolved organic nitrogen; DOC: dissolved organic carbon; NH <sub>4</sub> <sup>+</sup> : ammonia; NO <sub>3</sub> <sup>-</sup> : nitrate; NO <sub>2</sub> <sup>-</sup> : nitrite.											
*TKN = DON + NH <sub>4</sub> <sup>+</sup>											

The total N inputs in gross rainfall ( $16.81 \text{ kg. ha}^{-1} \cdot \text{year}^{-1}$ ) was in good agreement with that found in the Brazilian Cerrado biome ( $12.6 \text{ kg. ha}^{-1} \cdot \text{year}^{-1}$ ) by Parron et al. (2011) and for an Atlantic forest ( $15.1 \text{ kg. ha}^{-1} \cdot \text{year}^{-1}$ ) by Souza et al. (2015). However, our results were lower than those found in China in Subtropical forests by Tu et al. (2013) ( $114 \text{ kg. ha}^{-1} \cdot \text{year}^{-1}$ ) and by You et al. (2020) ( $30 \text{ kg. ha}^{-1} \cdot \text{year}^{-1}$ ). The major proximity of our results with Parron et al. (2011) and Souza et al. (2015) could be related with the activities that condition atmospheric emissions of reactive nitrogen, from global to local scale. For instance, on a global scale, the increase in emission of anthropogenic nitrogen was observed especially in North America, Europe, and Asia (Van Aardenne et al. 2001) in the last decades, but the natural presence of nitrogen in tropical regions is higher than in temperate ones (Galloway et al. 2004; Van Aardenne et al. 2001). On the regional and local scale, such as our study, the main anthropogenic nitrogen sources are related to the economic characteristics of the Southern Minas Gerais state, with urban influence (automobilist exhaust), industries (fossil fuel combustion), fires, and agricultural activities such as fertilizer use and cattle breeding.

Similarity with other studies was also observed when we consider nitrogen forms separately. The  $\text{NO}_3^-$  annual flux in gross rainfall ( $2.82 \text{ kg. ha}^{-1} \cdot \text{year}^{-1}$ ) was very close to that observed in the Brazilian Cerrado biome ( $2.1$  to  $2.4 \text{ kg. ha}^{-1} \cdot \text{year}^{-1}$ ; Lilienfein and Wilcke 2004) and in an Atlantic Rainforest ( $2.3 \text{ kg. ha}^{-1} \cdot \text{year}^{-1}$ ; Souza and Marques 2010). Considering TKN ( $\text{DON} + \text{NH}_4^+$ ) the annual input in gross rainfall ( $13.08 \text{ kg. ha}^{-1} \cdot \text{year}^{-1}$ ) was similar to that of an Atlantic forest ( $10.1 \text{ kg. ha}^{-1} \cdot \text{year}^{-1}$ ; Souza et al. 2015). The similarity between our results with other studies in Brazil may be related to the influence of regional and local anthropogenic sources and singular conditions of the tropical regions. When studies of gross rainfall consider N forms separately, it is possible to improve the understanding of the local sources and the processes that controls N depositions. The anthropogenic activities are considered the most important sources of anthropogenic N since food production and fossil fuels demands are increasing constantly (Galloway et al. 2004). This reinforces the importance and urgency of these studies.

We found statistical differences between gross rainfall and net precipitation annual inputs ( $\text{kg. ha}^{-1}$ ) for both C ( $p = 0.027$ ) and N ( $p = 0.022$ ). The vegetation structure, the leaching of dry deposition in the forest, and the exchange with trees surface can explain these differences. (Parker 1983). Forest-rainfall interaction can be responsible for an increase of  $89 \text{ kg. ha}^{-1} \cdot \text{year}^{-1}$  of C and  $20 \text{ kg. ha}^{-1} \cdot \text{year}^{-1}$  of N to the forest floor. This enrichment of C and N inputs in net precipitation was approximately to 86% and 120%, respectively. Regarding N inputs, almost the same was identified in an Atlantic Forest (127% by Souza et al. 2015). Further analysis demonstrated that the increment of N was superior than that of C which may be explained by the fact that dry deposition of N is enhanced in the region (Parker 1983; You et al. 2020; Schroth et al. 2001).

The total C input in net precipitation ( $193.18 \text{ kg. ha}^{-1} \cdot \text{year}^{-1}$ ) was 1.85 times greater than in gross rainfall ( $104.13 \text{ kg. ha}^{-1} \cdot \text{year}^{-1}$ ). According to Neu et al. (2016), organic C is more representative in net precipitation, attaining up to 90% of total C, than in gross rainfall with only 68%. The presence of organic C in forests is the result of several sources, as forest metabolism, decomposition processes, and animal excrement (Parker 1983; Neu et al. 2016). Moreover, the leaching process of the organic matter contributes to an increase in C inputs in net precipitation (Schrumpf et al. 2006; Mellec et al. 2010).

The inputs of total N ( $36.95 \text{ kg. ha}^{-1} \cdot \text{year}^{-1}$ ), TKN ( $26.46 \text{ kg. ha}^{-1} \cdot \text{year}^{-1}$ ),  $\text{NO}_3^-$  ( $8.94 \text{ kg. ha}^{-1} \cdot \text{year}^{-1}$ ), and  $\text{NO}_2^-$  ( $1.54 \text{ kg. ha}^{-1} \cdot \text{year}^{-1}$ ) in net precipitation were 2.2, 2, 3.2 and 1.9 times greater than in gross rainfall, respectively, demonstrating significant dry deposition and leaching processes in the Atlantic Forest remnant. Besides dry deposition of reactive nitrogen forms ( $\text{NO}_3^-$  and  $\text{NH}_4^+$ ) derived from the anthropogenic sources, the increase in N in net precipitation could be attributed to the leaching of the organic N provided by biological processes (Mellec et al. 2010). Despite  $\text{NO}_2^-$  represents a small portion of total N (4%), the enrichment in net precipitation could be attributed to fog and dew formations which withdraw the dry depositions from the leaves' surface (Acker et al. 2008).

Considering the total area of the Atlantic Forest remnant (6.3 ha), the annual inputs of C and N in gross rainfall can reach up to  $656 \text{ kg. yr}^{-1}$  and  $106 \text{ kg. yr}^{-1}$ , respectively, whereas for net precipitation an amount of  $1217 \text{ kg. yr}^{-1}$  and  $233 \text{ kg. yr}^{-1}$ , respectively. The Atlantic Forest remnant is responsible for the considerable increase of local C and N, directly influencing the nutrient cycle, the availability of N and the stocking of C in the soil. Thus, Atlantic forest environments outstand as an important sinking for C and N.

## Temporal variations of the net precipitation in AFR

There was a seasonal variability of total C and N in gross rainfall (Fig. 4). These concentrations were higher in the dry season (April to September) and decreased throughout the wet season (October to March). Such pattern was also observed for throughfall and stemflow according with other forest stands in seasonal climate regions (Neu et al. 2016; Germer et al. 2007; Lilienfein and Wilcke 2004).

This seasonal variability in net precipitation is more common in semideciduous and deciduous forests than in evergreen forests according to Van Stan and Stubbins (2018). This is the result of some factors explained as follows. The accumulation of particles in the atmosphere and in the canopies surfaces in the dry season ensures the high concentrations in the first rainfalls after long dry periods. These events are called “first flush events” and are responsible for “washing” the atmosphere and the forests canopy (Neu et al. 2016; You et al. 2020). This accumulation starts decreasing in the wet season as the time between rainfall events decreases (rainfall events are more frequent), explaining the behavior in the wet season (You et al. 2020). In addition, intense rainfall events are more common in the wet season which causes dilution of the compounds and further reductions in concentration (Michalzik and Matzner 1999; Zhang et al. 2016).

Furthermore, there were statistical differences ( $C p = 2.72E-06$  and  $N p = 2.81E-06$ ) in net precipitation regarding the dry and wet season. Such differences could be explained by the semi-deciduousness, as up to 50% of the trees lose up their leaves in the dry season. This behavior influences the dry deposition, the amount of rainfall that passes through the canopy and, hence, the interactions between rainfall and forest. In the dry season, trees with few leaves drain more water by the trunk (Terra et al 2018a), however, the presence of more leaves increases interactions between rainfall and forests, affecting the nutrient inputs in the wet season. These conditions drive the dynamics of nutrient transport from the atmosphere to the forest floor in the dry and wet seasons as they are strictly associated with the characteristics of the vegetation and rainfall seasonality.

The seasonality of rainfall and the semi-deciduousness are conditioning factors for C and N inputs being more significant in the wet season, concentrating 74.3% ( $143.52 \text{ kg} \cdot \text{ha}^{-1}$ ) of total annual C and 75.1% ( $27.76 \text{ kg} \cdot \text{ha}^{-1}$ ) of total annual N. Although the concentration is considerably higher in the dry season, because of the effects from long periods between rainfall and atmospheric deposition, the considerably higher total of rainfall in the wet season is responsible for the most part of C and N that reaches the forest floor annually. In this sense, frequent precipitation is responsible for leaching C and N from the atmosphere and forest surfaces (Tu et al. 2013; Van Stan et al. 2017).

For the monthly step, it was also observed statistical differences ( $C p = 1.19E-18$  and  $N p = 2.38E-15$ ). Using the Tukey’s test, it was possible to group statistically equal months (Fig. 5 and Fig. 6). Considering net precipitation, the months with the highest C inputs were December, October, and November, respectively, with no statistical differences (a). These months represent the onset of the wet season and, thus, the greater inputs are because of the dry deposition accumulated throughout the dry season that was washed by the significant amount of rainfall events. The months with the lowest C inputs were statistically equal (f) and correspond to the beginning of the dry season (April, May, and June). The inputs of C followed the seasonality of the region, in which the higher the rainfall amount the greater the input of C.

For N in net precipitation, November and December showed no statistical differences (a). These months represented the highest inputs of N throughout the year and are the months with the highest amounts of rainfall. October and August were also statistically equal (a), both had above-average rainfall and were preceded by months with below-average rainfall. This evidenced the influence of the first rainfall events and the importance of washing-off the atmosphere and the particles deposited in the crowns and branches of the trees after a long dry period. October and August were also statistically equal (b) to January, February and March, which was also expected as these months represent the last ones of the wet season. These months (January, February and March) were also statistically equal to April, May, June, and September, the months with the lowest N inputs coinciding with the lowest rainfalls in the year. Although April had a higher rainfall amount than August, the long antecedent dry period provided a greater input of N as a consequence of the greater number of particles stored in the atmosphere and canopies. This confirms that the amount and seasonality of rainfall drive N inputs in the Atlantic Forest remnant.

## Spatial variation of the net precipitation in AFR

The spatial variability of the nutrients inputs is expressive between different types of forest (Levia and Frost 2006). Despite some studies tried to describe the spatial variability of solute depositions in forests by applying the coefficient of variation (Raaijmakers et al. 2002; Staelens et al. 2006; Zimmermann et al. 2007; Zimmermann et al. 2008), the sampling designs, collection periods, and element analysis were very different, which impair comparisons, even though our results were close to other studies carried out in temperate and tropical ecosystems. Throughout the year, the coefficient of variation ranged from 19–47% and from 17–60% for C and N inputs, respectively. These amounts are within the range (12–78%) found in other studies, where tropical forests showed the largest coefficients of variation, mainly in the wet season (Raaijmakers et al. 2002; Staelens et al. 2006; Zimmermann et al. 2007; Zimmermann et al. 2008).

Overall, the wet season presented higher spatial variability than the dry season. However, N inputs presented the lowest coefficient of variation in both the end of the wet season and the beginning of the dry season. For C inputs, the lowest coefficients of variation were during the dry season. Excepting for August, the dry months with higher CV are likely associated with rainfall above average, whereas the low CV of January is related to rainfall below the average. The potential accumulation of organic matter, the greater rainfall amounts and

the heterogeneity of the canopy are some of the factors responsible for the increased spatial variability in tropical forest (Zimmermann et al. 2008).

The Atlantic Forest remnant has a heterogeneous canopy because of the high variability of species, size, and age of the trees, which is expected in tropical forests. The high incidence of lianas and the canopy gaps caused by the fall of trees further increase the intrinsic heterogeneity of this type of forest. In the same forest remnant, Rodrigues et al. (2018) related the spatial variability of net precipitation to the semideciduous characteristics. However, Terra et al. (2018a) did not find a spatial pattern in stemflow, associating it to the Atlantic Forest remnant heterogeneity of species. The edge effect also contributes to this variability as it directly impacts the characteristic of the vegetation, altering forest structure (density and size of trees) and the abundance of species (Benítez-Malvido and Martínez-Ramos 2003). In addition to the heterogeneous structure of the canopy, the spatial pattern of nutrient inputs is also influenced by dry deposition, leaching process, and meteorological conditions (Forti and Neal 1992; Levia and Frost 2006).

Marques et al. (2019) highlighted the influence of the animals in the surrounding areas of the AFR in N forms (ammonia and ammonium), which may have increased the N inputs in the southwest and central portion of the forest. The southwest area with the higher C and N inputs may also be influenced by vehicles, as this part of the forest is closer to a busy road. The eastern portion, that has high N inputs throughout the year and high C inputs in the dry season, is located close to a “candeia” (*Eremanthus erythropappus* (DC.)) forest stand and a *Eucalyptus* stand, which can influence the high depositions in this location.

Overall, these biotic and abiotic factors interaction between rainfall and forests may be responsible for high spatial variability in inputs of nutrients to the forest floor (Levia and Frost 2006; Zimmermann et al. 2008; Zhang et al. 2019). Despite the high amounts of rainfall being responsible for the dilution, it is not possible to select only one factor that controls spatial patterns (Robson et al. 1994). Thus, the factors that influence spatial variability are uncertain, and studies of canopy structure and meteorological conditions could help to understand spatial variability of chemicals in tropical forests (Levia and Frost 2006; Zhang et al. 2019).

## Conclusions

Both concentration ( $\text{mg. L}^{-1}$ ) and inputs ( $\text{kg. ha}^{-1}$ ) of N and C were higher in net precipitation than in gross rainfall. The rainfall leaches the atmosphere and forest's structures and can be considered an important transfer pathway of C and N toward the forest floor. This forest-rainfall interaction is responsible to increase the total amount of C and N that reaches the forest floor annually.

The seasonal variability of C and N was remarkable. The inputs were higher in the wet season and represented, on average, 75% of the total annual contribution. These results confirm the hypothesis that the behavior of these nutrients is conditioned by the seasonal variability of precipitation. Analyzing inputs during the year, the impacts of extensive dry periods are more important for increasing N instead of C. This fact may be a direct result of atmospheric depositions from anthropogenic sources.

The spatial variability of C and N was higher in the wet season. The spatial patterns revealed that, in general, the same locations had the highest inputs for both C and N throughout the year. Furthermore, the canopy heterogeneity and the proximity to potential sources seem responsible for breaking any continuity in the C and N inputs in the Atlantic forest remnant.

The AFR increases the contribution of C and N that reaches the forest floor. The constant input of these nutrients, especially in the wet season, is extremely important in the nutrient cycle since it aids in the sustainability of ecological processes. Despite the nutrient inputs presented some variability, this study provides useful information on the changes of C and N inputs after forest-rainfall interactions. Thus, it can support the estimation of atmospheric deposition and advance the knowledge of the contribution of the leaching and absorption processes by canopies.

## Abbreviations

C: Carbon; N: Nitrogen; ANOVA: analysis of variance; CV: coefficient of variation; IDW: inverse distance weight; NP: net precipitation; AFR: Atlantic Forest remnant; GR: gross rainfall; Tf: throughfall; Sf: stemflow; DBH: diameter at 1.3 m above ground; EC: electric conductivity;  $\text{NO}_3^-$ : nitrate;  $\text{NO}_2^-$ : nitrite; TKN: total kjeldahl nitrogen; MS: meteorological station; DON: dissolved organic nitrogen; DOC: dissolved organic carbon;  $\text{NH}_4^+$ : ammonia.

## Declarations

## Ethics approval and consent to participate

Not applicable.

## Consent for publication

Not applicable.

## Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

## Competing interests

The authors declare that they have no competing interests.

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## Authors' contributions

Conceived and designed the study: CRdM, VAM and MdCNST. Led the research project: CRdM. Performed the experiments, collected data and samples in the field: VAM, AFR and VAdO. Processed samples in the lab: VAM. Wrote the paper: VAM and MdCNST. Critical Revision: CRdM and AFR. Statistical Support: MdCNST and LORP. All authors read and approved the final manuscript.

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# Figures

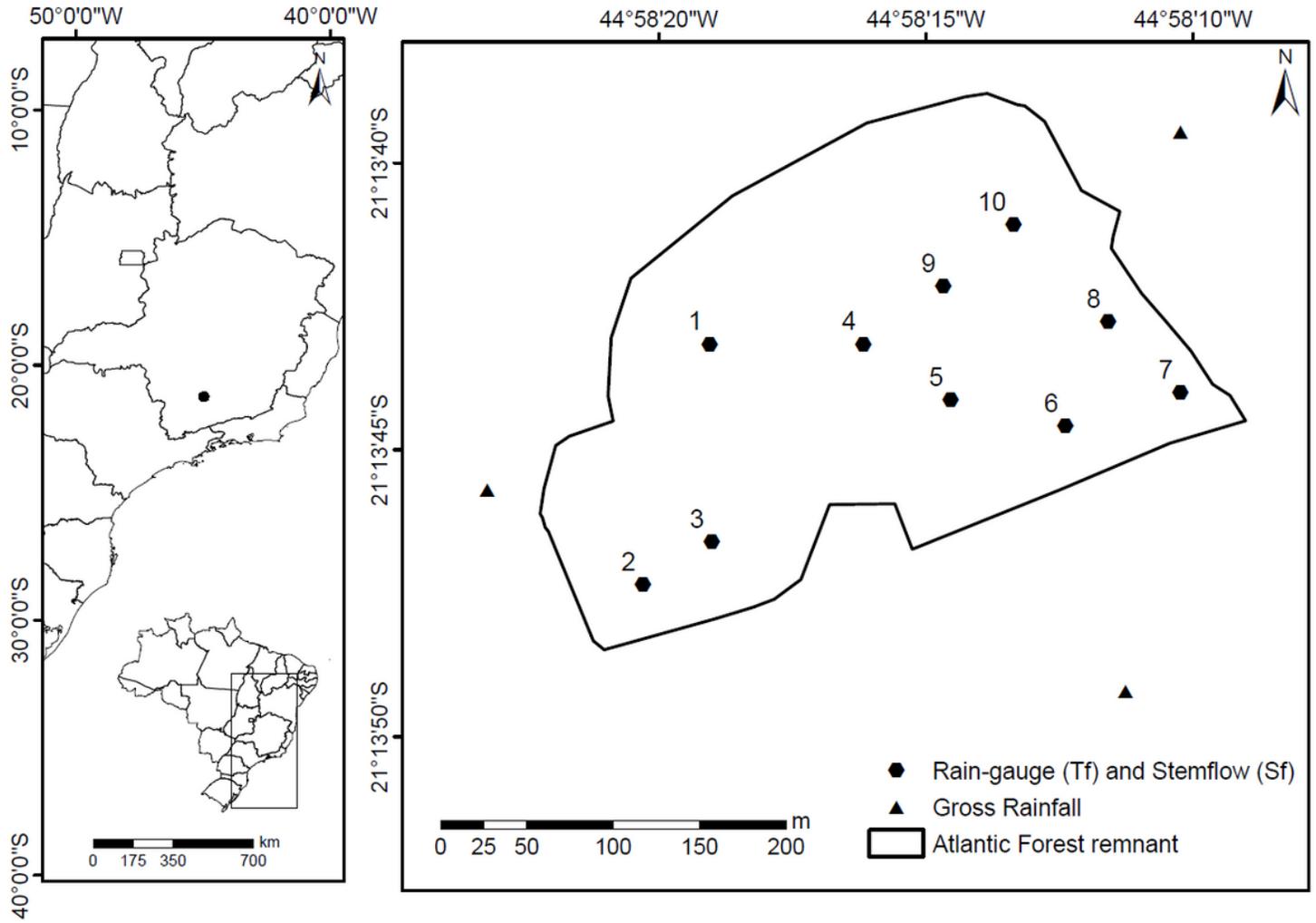


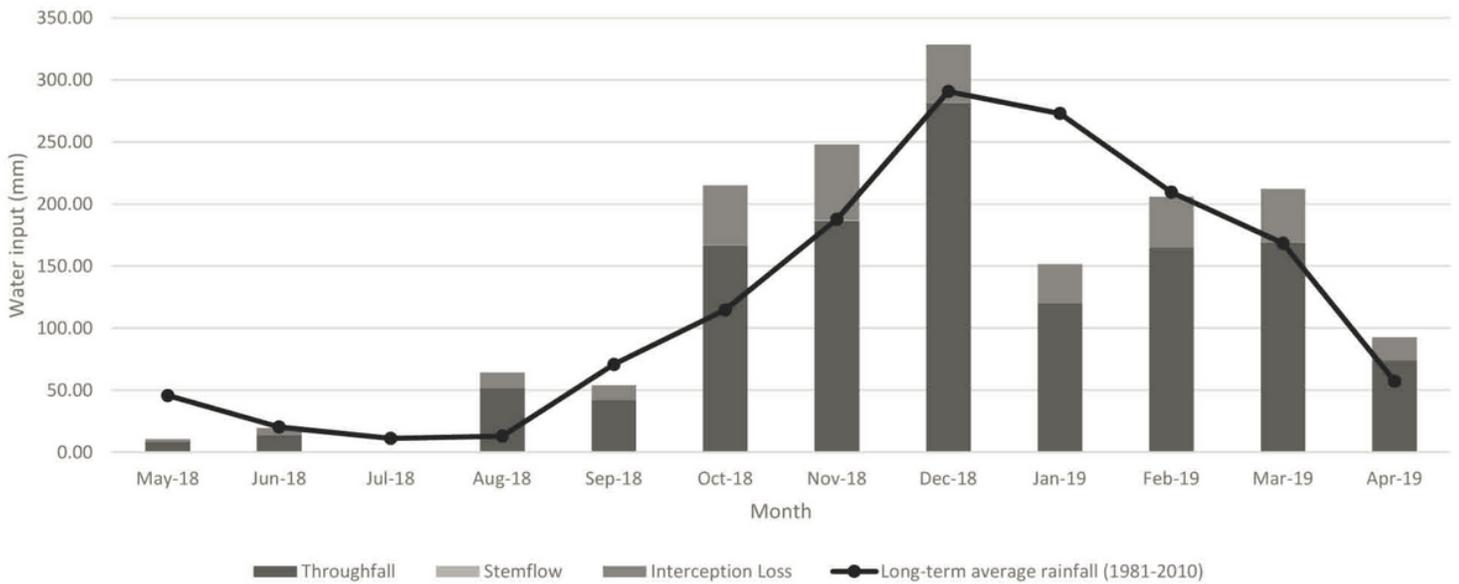
Figure 1

The geographical location of the AFR in Brazil and the positions of the measuring points.



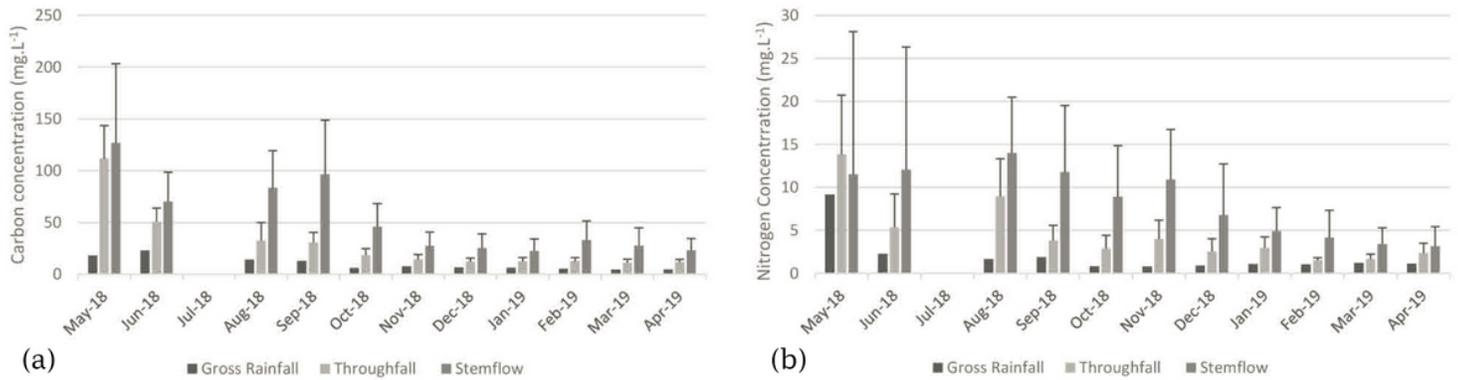
**Figure 2**

Rain gauge and stemflow apparatus for, respectively, throughfall and stemflow measurements (a) and external rain gauge for gross rainfall measurements (b).



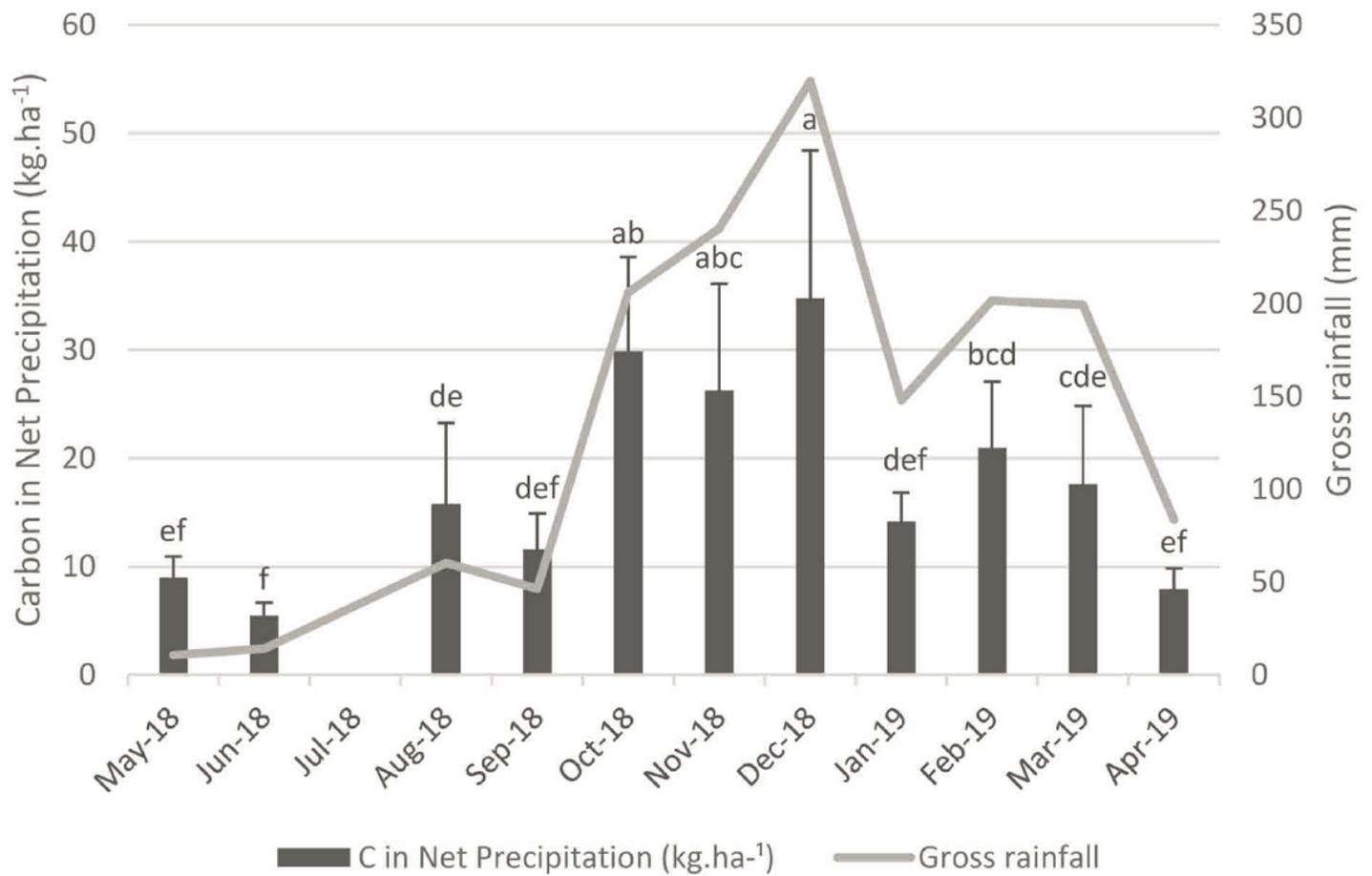
**Figure 3**

Monthly inputs of water in the Atlantic Forest remnant (AFR) through throughfall (Tf), stemflow (Sf), and the interception loss, and the long-term average rainfall of the meteorological station (MS).



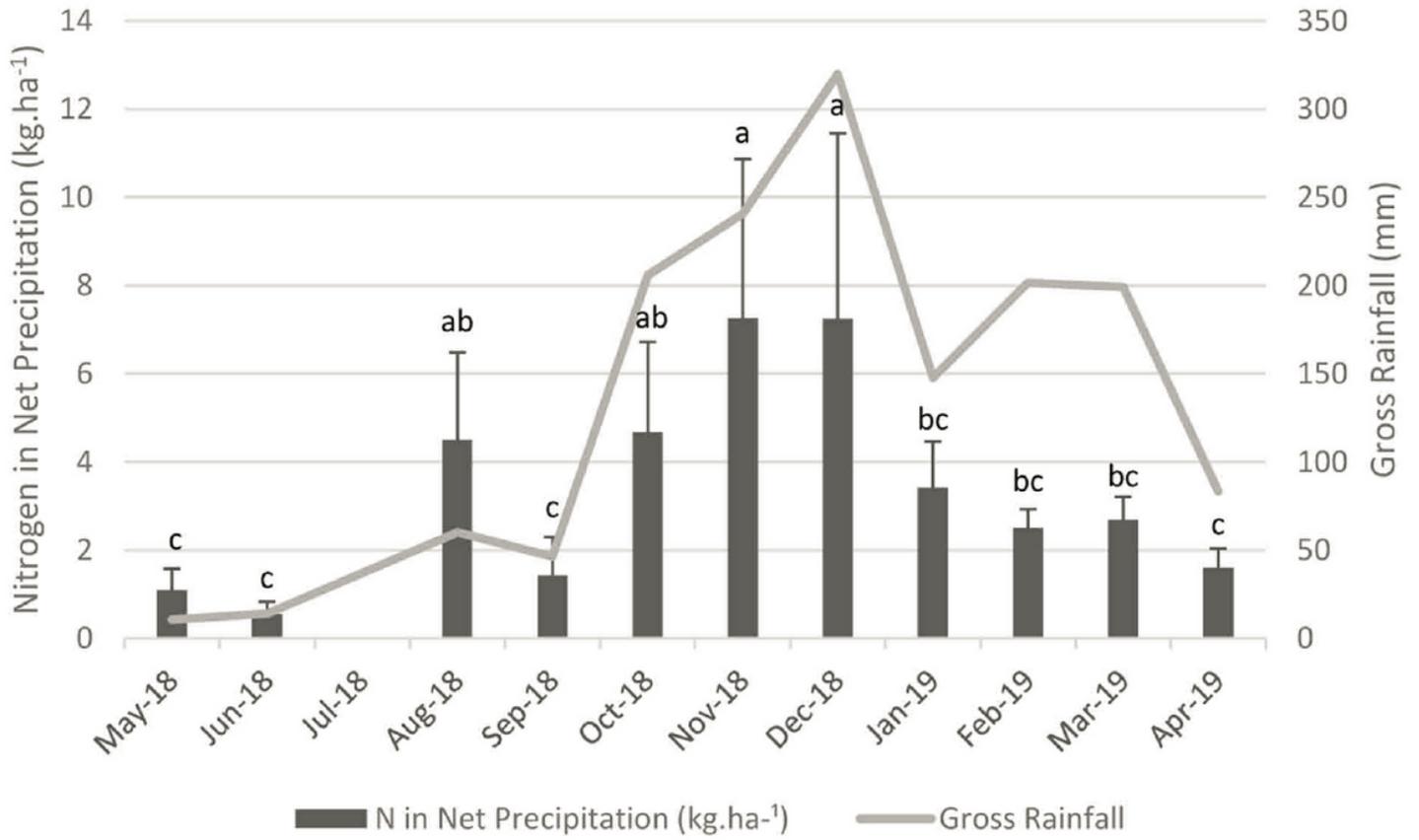
**Figure 4**

Carbon (a) and nitrogen concentrations (b) in gross rainfall (GR), throughfall (Tf), and stemflow (Sf), with their respective standard deviations.



**Figure 5**

Monthly average carbon inputs in net precipitation (NP) (kg.ha<sup>-1</sup>) and monthly gross rainfall (GR) (mm). Different letters above bars mean statistical differences ( $p = 1.19E-18$ ) between months.



**Figure 6**

Monthly average nitrogen inputs in net precipitation (NP) (kg.ha<sup>-1</sup>) and monthly gross rainfall (GR) (mm). Different letters above bars mean statistical differences ( $p = 2.38E-15$ ) between months.

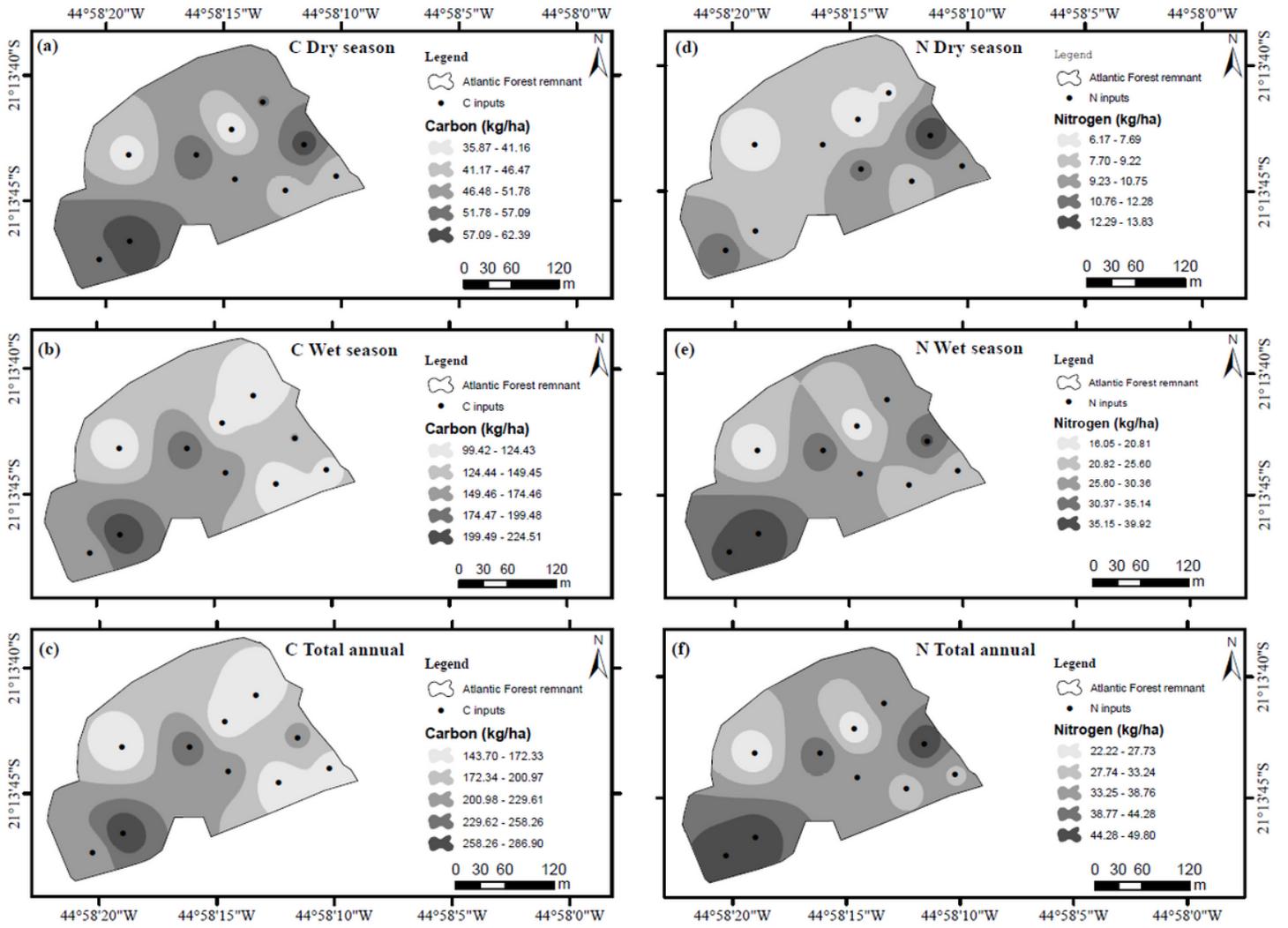


Figure 7

Spatial pattern of C and N inputs (kg.ha<sup>-1</sup>) regarding the dry and wet seasons, and the entire period (total annual).