

Nutrient input and stock by leaf litter in tropical streams in secondary forest and cocoa agroforestry systems

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Abstract

This study aimed to compare the concentration of nitrogen (N) and phosphorus (P) in the litter input and storage and the N and P of the water in secondary forest streams and the cocoa AFS. Leaf litter was collected monthly in two areas for one year. The concentration N and P in the input and stock litter and the concentration of N total and P total in the water were higher in the cocoa AFS area than in the secondary forest. The highest concentrations of N and P in leaf litter cocoa AFS may be related to the physiological demands of cacao and the rapid nutrient cycling by this cultivation system. On the other hand, in the secondary forest there tends to be a higher immobilization of nutrients due to the slow growth and high biomass production. Thus, despite the importance of AFS cocoa cabruca for the conservation of the Atlantic Forest in southern Bahia, the replacement of the forest by AFS cocoa cabruca may favor a higher input and nutrient stock in streams by leaf litter.

Introduction

The Atlantic Forest corresponds to the most threatened tropical biome in the world (1). In northeastern Brazil, especially southern Bahia, this forest stands out for having one of the greatest richness of tree species in the world and for its high degree of endemism (2, 3), distributed in small fragments (4). Most of these remnants are found in cocoa (*Theobroma cacao* L) agroforestry system (AFS) areas, locally known as “cabruca” (5). In this AFS, cocoa is inserted discontinuously, under the shade of forest trees (dominant and co-dominant strata), and is surrounded by natural vegetation, causing less impact on related natural resources (6, 7). Cocoa AFS have high tree diversity for an agroforestry system (2, 5), and the structure and species composition varies among crop farms (8).

Cocoa AFS stand out in the conservation of local biodiversity by serving as habitat and ecological corridors for several endemic species (9, 10, 11), acting in carbon sequestration (9, 10), in maintaining nutrient cycling, stabilizing soil structure and decreasing erosion (12). However, although AFS cocoa cabruca contributes to local environmental sustainability, the replacement of forests by these cropping systems can alter the ecological functions previously performed by forest cover (5). Changes in the structure and composition of tree species can influence both the patterns of litter supply in riparian zones of these agroforests (13) and alter the nutritional composition of litter (14, 15, 16) to be offered to the streams.

Leaf litter is an important energy resource transferred from riparian vegetation to aquatic ecosystems in small-order streams (17, 18 19 20). The entry of litter into streams occurs through the vertical input when the litterfall directly from the forest canopy to the stream, and the lateral input when this litter enters indirectly or linearly from the stock of thick particulate organic matter deposited in the soil of the riparian zone (18, 21, 22). In streams, litter can be retained and form the benthic stock, or be transported downstream by water flow (23). Changes in nutritional quality have implications for the functioning of aquatic ecosystems, especially in decomposition processes and in the cycling and release of nutrients in water bodies (19, 24, 25, 26). Among the nutrients, phosphorus (P) and nitrogen (N) are fundamental to

the biogeochemical cycle of ecosystems because the biota depends on these elements to carry out their vital processes (27).

O P is a limiting element of primary production in streams and is available as particulate organic phosphorus (present in cell biomass fragments, specifically in cell membranes and energy molecules), dissolved organic phosphorus, and dissolved inorganic phosphate (fraction best assimilated by phytoplankton, macroalgae and aquatic macrophytes) (28). The forms of N in streams include organic nitrogen (associated with fragments of cellular biomass, proteins, nucleic acids, and other polymers), and inorganic nitrogen (nitrate, nitrite, n-ammoniacal) (29). The transformation of N in streams is mediated by microorganisms through a series of oxidation-reduction reactions. The heterotrophic microbial community performs a coupled processing from the oxidation of carbon to the reduction of forms of nitrogen (30). However, these elements considered as limiting the metabolism of streams (31), have become harmful due to their artificial introduction. Some studies have reported that excess nitrogen in streams in agricultural areas can trigger environmental problems such as 30, 32, 33).

Past studies in cocoa AFS reported that the replacement of forests by the cropping system altered the nitrogen and phosphorus cycling of streams (34, 35, 36). However, although several studies have already been carried out on nutrient cycling in cocoa AFS (16, 37, 38, 39), so far, there is no information on the nutritional quality of litter that is contributed and stored in the streams of these areas. Thus, this study aimed to fill the gap in the understanding of how litter quality can influence nutrient supply and stock in the AFS cocoa streams, taking into account the decomposition process and its importance in nutrient cycling (40), the role of streams in the storage and processing of terrestrial carbon (40, 41), in addition to the importance of these productive areas for the conservation of tropical biodiversity (2, 3, 7).

Thus, the objectives of this study were i) to compare the concentration of N and P in litter input (vertical input) and stored in streams of a secondary forest and an area of managed cocoa cabruca AFS; ii) verify the concentration of N and P in the water of the streams, iii) verify the monthly variation of the concentration of N, P and the N:P ratio of the litter contributed and stored in the streams, iv) correlate the N and P of the water of the streams with the N and P of the litter input and storage and with the precipitation. Thus, the hypotheses defended are that i) the litter of the managed AFS cocoa area tend to be richer in N and P than those from the forest given the greater availability of these elements in the AFS cocoa areas as a result of the management, ii) the streams of the AFS cocoa cabruca tend to supply and store litter with higher percentages of N and P, as well as presenting higher N and P concentrations in the water, iii and iv) the variation in the N and P concentration litter contributed may be related to the period of greater or lesser precipitation, as well as the N and P concentration in the stored litter may be related to the N and P concentrations in the water.

Results

Concentration of N and P leaf litter inputs and stocked in streams

The nitrogen concentration (%N) in the vertical leaf litter input in the cocoa AFS (CA) was approximately twice that of the secondary forest (SF), with $0.62 \pm 0.2\%$ in CA and $0.37 \pm 0.25\%$ in SF ($Z = 3.67$, $p = 0.00024$). The P concentration (%P) in leaf litter was also higher in CA than in SF, and the values were $0.22 \pm 0.06\%$ in CA and $0.16 \pm 0.07\%$ in SF ($Z = 3.37$, $p = 0.00074$). However, the N:P stoichiometric ratio did not differ between areas and the values corresponded to 3.03 ± 1.25 in CA and 2.85 ± 2.16 in SF (Fig. 3).

As in the input, the %N of the cocoa AFS (CA) stream was also twice as high compared to the secondary forest (SF), and the values were $1.57 \pm 0.31\%$ in CA and $0.64 \pm 0.27\%$ in SF ($Z = 3.87$, $p = 0.003$). However, the difference in %P leaf litter stored between the areas was even more expressive, being 4.4 times in CA than in SF, with values $0.22 \pm 0.08\%$ in CA and $0.05 \pm 0.03\%$ in SF ($Z = 1.64$, $p = 0.00023$). The N:P stoichiometric ratio also differed between areas and was 2 times higher in SF than in CA, 17.6 ± 13.57 in SF, and 8.85 ± 7.53 in CA (Fig. 3).

N_{total} and P_{total} in stream water

The concentration of both N_{total} and P_{total} in the stream water followed the same pattern found in leaf litter with the highest values found in CA compared to SF. N:P ratio was higher in the area in SF, with 14.81 ± 14.09 in SF and 1.98 ± 0.93 in CA (Fig. 4). In SF there was a negative correlation between N_{total} streams water and %P in the leaf litter input (LI). In CA, there was a negative correlation between the N_{total} stream water and the %P in the leaf litter stock (LS) (Table 1).

Table 1
Sperman correlation matrix ($p < 0.05$) between the N and P percentages in leaf litter input (%N LI and %P LI), leaf litter stocked (%N LS and %P LS), total nitrogen in the stream water (Nt stream), total phosphorus in the stream water (Pt stream) and precipitation

Area		Nt stream	%N LI	%N LS	Pt stream	%P LI	%P LS
SF	%N LI	0,44					
	%N LS	-0,16	0,43				
	Pt stream	0,55	0,01	-0,07			
	%P LI	-0,85	-0,12	0,08	-0,26		
	%P LS	-0,54	-0,17	-0,43	-0,60	0,33	
	Prec	0,20	0,14	0,52	0,18	-0,06	-0,22
CA	%N LI	-0,43					
	%N LS	-0,05	-0,31				
	Pt stream	0,35	-0,37	0,15			
	%P LI	0,01	0,15	-0,09	-0,18		
	%P LS	-0,71	0,55	0,03	-0,45	0,15	
	Prec	-0,51	0,58	-0,08	-0,25	0,19	0,45
*Black values indicate significant correlation.							

In both areas, %N and N: P in leaf litter stocked in a stream were higher than leaf litter input to stream ($p = 0.0035$ and $p = 0.0000$ in SF; $p = 0.0000$ and $p = 0.000$ in CA). %P between leaf litter input and stock and concentration in stream water did not differ in CA, whereas in SF the %P was higher in leaf litter input than leaf litter stock ($p = 0.0000$) (Fig. 5).

Precipitation and monthly variation in the concentration of N, P and N:P of leaf litter

The annual precipitation for the period was 1135 mm in SF and 1040 mm in CA. The wettest months were November (191mm in SF and 185 mm in CA) and December (134 mm in SF and 130 mm in CA) and the driest months were February (31mm in SF and 33 in CA) and October (45 mm in CA) in SF and 53 mm in CA). The concentration of N, P and N:P of the input and stock of leaf litter in SF and CA did not vary between months. However, a peak in N concentration without litter entering CA was observed in the wettest month (February/19) (Fig. 6).

Discussion

The riparian vegetation of the cocoa AFS influenced the nutritional quality of leaf litter input and stored in the streams. The main results of this study confirmed the presented hypotheses, and demonstrated that i) leaf litter input and stock in AFS cocoa presented higher concentrations of N and P than secondary forest; ii) the water from the stream of the cocoa AFS had higher concentrations of N_{total} and P_{total} than that of the FS; iii) monthly variations were not observed in the %N and %P in the debris contributed and stored in the streams of both areas. Thus, the riparian zone of the cocoa AFS presented itself as a system more enriched in N and P compared to the secondary forest.

One of the likely factors that contribute to the higher N concentrations in the leaf litter of the AFS cocoa may be related to management practices. Among these practices, the high abundance of legumes in the cocoa AFS can be highlighted and, consequently, the high levels of symbiotic relationships with bacteria that promote greater fixation of N in this system (1). The integration of legumes in agroforestry systems is a strategic alternative to increase the availability of N in the systems, dispensing with the use of mineral N (43). In the cocoa AFS, legume species such as *Erythrina*, *Gliciridia* and *Inga* are common in cultivation (2; 16) and in the riparian zones of these AFSs (13). In addition, cultural treatments such as pruning and disposal of plant residues in the soil of this agroforestry (42) favor the release of N in this compartment (43) and increase NO_3^- concentrations in the soil and in soil water (44).

The higher concentrations of P in the leaf litter of the cocoa AFS can be explained by the high immobilization of this nutrient in the aboveground biomass and in the cocoa leaves, which act as a P sink (16). The higher values may also be related to the adaptive strategies of tropical plants to low fertility soils by relocating high concentrations of P in the aerial parts in order to avoid nutritional stress. Study carried out by Fontes et al. (2014) revealed that high P concentration in the cocoa AFS areas showed a positive correlation with the decomposition coefficient, and this interaction was due to the high litter deposition in the agroforestry (38, 45). On the other hand, a more recent study did not find the same correlation between the coefficient of decomposition and nutrient mineralization with the chemical composition of the waste (46), and in this case, the authors attributed this low correlation to pH and soil moisture being the main regulatory factors for nutrient cycling.

The results also showed that the differences in the concentration of N and P between the forest and cocoa AFS areas were even more accentuated in the litter stocked in the streams. Leaf litter entering streams is leached (dissolution of water-soluble compounds), conditioned (colonized by fungi and bacteria), and fragmented (physical abrasion by water and sediments and fragmentation by aquatic invertebrates) (18, 21, 22, 47). The %N increase in the litter stored in both areas may be related to the conditioning stage where fungal colonization promotes the growth of microbial biofilms on the debris surface (47). This increase favors an enrichment in the nutritional quality of the detritus, thus making it a more attractive resource for detritus invertebrates (21, 47, 48).

These differences may be associated with the water characteristics of the cocoa AFS stream, which have higher total concentrations of N and P in the water compared to the forest. Studies have shown that higher concentrations of dissolved nitrogen in water increase fungal biomass (9, 49), which may explain the increase in the percentage of N in the litter stored in streams. Nutrient enrichment in water tends to stimulate colonization of litter decomposers, triggering biomass accumulation and nutrient accumulation (48, 50). The increase in the concentration of N and the reduction in the concentration P in the litter stock compared to the litter caused the N:P stoichiometric ratio to be higher in the stock than in the input in both areas.

Monthly variation in N and P leaf litter

In relation to the litter stock, an increase in the concentration of P in CA was observed, mainly in the rainy months. The highest %P in the leaf litter of AFS cocoa in November may be the result of an intense rain event (185.2 mm) that occurred in this month, days before collection. During this period, the stream channel overflowed and the cultivation area was completely flooded. According to Brandão et al. (2022) variations in litter input throughout the year in this same area were more a function of management than of climatic conditions. Studies in riparian zones of agricultural areas reinforce that cultivation practices minimize the seasonality of the input of debris due to forest characteristics, such as stage of development, growth and reproductive form (51).

The higher inputs of N and P in the rainy season may be associated with a higher input of green and biologically active leaves caused by the mechanical action of the winds and rain events (19; 52). With increasing P concentration in the rainy season, the N:P ratio decreased in this same period in CA. On the other hand, in SF, the highest concentration of N was higher in the rainy season, reinforcing the effect of soil leaching on the transport of sediments and nutrients to the streams (Brandão et al. 2015).

The riparian zones of the forest area play a filtering role in the output of nutrients from the terrestrial ecosystem to the aquatic environment, which favors the maintenance of water quality in streams (53), while the original decharacterization of these areas and the replacement by species grown in the AFS cabruca favored greater transport of phosphorus to the streams of these areas (36). Thus, despite the low environmental impacts of AFS cocoa and its importance for the conservation of Atlantic Forest biodiversity (54), differences in leaf litter N and P concentration in SAF cocoa cabruca compared to secondary forest may have ecological implications for the functioning of streams. Since, more enriched leaf litters present high respiration rates via microbial decomposers and detritivorous macroinvertebrates (9), and can reduce organic carbon (C) storage in aquatic ecosystems (50, 55) and consequently interfere in the contribution of streams to the global C cycle (41, 56).

Conclusion

The results presented in this study demonstrated that leaf litter input in the AFS cocoa stream presented higher percentages of N and P than those from secondary forest. And this difference was maintained for

leaf litter stored in the stream, being even greater for P. The nutritional quality of litter from AFS cocoa represents the capacity of this agroforest to recycle and maintain nutrients within the system, however, the higher concentrations of nutrients may have an effect on the process of litter breakdown in stream, and consequently, changes in nutrient cycling and stream carbon stock in these areas. Thus, further research is needed to elucidate whether the difference in litter quality interferes in the decomposition process of cocoa AFS compared to secondary forest.

Material and methods

Study area

The study was conducted in a stream in Secondary Forest (SF) (E 485415/N 8397615) and the other in Cocoa AFS (CA) (E 448466/N 8363187). The areas are located in the southern region of Bahia, northeastern Brazil (Fig. 1). The climate of the region is defined as type AF according to Köppen, hot and humid, with no defined dry season with rainfall well distributed along with an annual average ranging from 1100 to 2200 mm (Fig. 2). It has an average temperature of 24°C and annual rainfall ranging from 1800 mm to 2200 mm, the relative humidity of the air exceeds 80% (42). The streams studied are considered second-order according to Strahler's classification system.

The SF is located in the Serra do Conduru State Park (Uruçuca, Bahia) with an area of 36.08 ha. The forest is technical as dense submontane ombrophilous and forms a mosaic with different stages of development, including secondary forests and remnants of mature forests that had varying degrees of selective logging in the past (1). It has a uniform canopy, above 25 m in height, with few emerging individuals, many epiphytes, lianes, and a dense understory (57). The CA is located at Fazenda Nova Harmonia, in the municipality of Barro Preto, with a total area of 89.8 ha. The farm has most of its territory dedicated to cocoa production. It has a patch of forest in its central portion and two areas in the process of regeneration (58). Agricultural management of cocoa cultivation involves fertilization, liming, and the use of insecticides (2). However, through personal communication with the person responsible for the management of the studied area, they are currently only carried out as pruning, cutting the vegetation, and few liming events for soil correction. The planting has a spacing of 3x3 m and is intercropped with introduced shade trees (*Erythrina* sp). Pruning is carried out every 6 months and the biomass is removed and disposed of in the soil. Approximately 12 ha of the area are thus for cultivation with an average planting of 1000 cacao trees/ha and average commercial production of 20 arrobas/ha.

Experimental and analytical design - leaf litter

Monthly vertical input litter collections were carried out in the streams, and the litter stocked in streambed was from August 2018 to July 2019. In each area, sampling was carried out in a 100 m transect. To determine the vertical input litter in the stream, collections were carried out with the aid of buckets attached perpendicularly to the stream and placed at 1 m from the water surface (adapted from 17, 59, 60). The buckets were arranged in three sections approximately 30 m apart, in each section a set of 9 buckets were installed ($n = 27$; total sampled area – 1.9 m²; individual bucket area – 0.07 m²,

diameter of the bucket – 22cm). To determine the stock leaf litter collections were carried out at three different points in each of the streams with the aid of a Surber- type sampler ($n = 3$, sampler area = 0.09 m²).

After collected, the litter were sorted and leaf litter were used for further analysis as they represent more than 60% of the litter and correspond to the most important litter fraction for the decomposition process (60, 61). Leaf litter was oven dried for 72 hours at 60°C. Composite samples were prepared for N and P analysis of the vertical input litter. Thus, the sum of the samples of the 3 buckets in the same row was performed. Samples from the central rows were selected for chemical analysis of the leaf litters. For the determination of N and P in the leaf litters stocked in the stream, simple samples ($n = 3$) were used.

Sample processing and N and P analyzes were performed according to Flind and Lillebø (2005). Leaf litter were ground with the aid of a food crusher (Wallita brand – 800W), later sieved (1 mm mesh sieve), and weighed. N concentration was determined using the adapted N–Kjeldahl method, followed by spectrophotometric analysis. For the determination of P, the leaf litters were previously calcined in a muffle furnace at 500°C for 4 hours. The remaining ash was solubilized in HCl, followed by a reaction with ascorbic acid and spectrophotometric analysis. Concentrations were expressed as % dry mass (DM) (Sena et al. 2021).

Experimental and analytical procedure - streams water

Monthly stream water samples were collected for N and P analysis. In the laboratory, the water samples were filtered through cellulose acetate filters with a porosity of 0.70 µm and for further analysis of the dissolved and particulate fractions of these elements. The N total corresponded to the sum of the fractions of nitrate (N-NO₃⁻), nitrite (N-NO₂⁻), N-ammoniacal: (N-NH₄⁺), dissolved organic nitrogen (DON), and particulate organic nitrogen (PON). P total corresponded to the sum of the phosphate (PO₄³⁻), dissolved organic phosphorus (DOP), and particulate organic phosphorus (POP) fractions. The N and P fractions were analyzed by spectrophotometry according to the method of Grasshoff et al. (2009). Daily precipitation data were obtained by website of the Real-Time Climate Monitoring Program for the Northeast Region (PROCLIMA) and the information was acquired for the municipalities of Barro Preto and Itacaré – BA.

Data analysis

The a priori tests were applied to determine the normality of the data (Shapiro Test) and homogeneity of the variances. As an alternative to the analysis of variance, the non-parametric U-Mann-Whitney test was applied, comparing the N, P and N:P of the leaf litter of the forest and the managed cocoa-cabruca SAF, as well as the concentration of N and P in the water of the forest. streams from both areas. The dependent variable considered was N, P and the N:P stoichiometric ratio, while the independent variables were areas and months. Spearman's Correlation ($p < 0.05$) was used to verify the relationship between the nutrients that enter the streams via leaf litter, the nutrients stored in the leaf litter and the nutrients available in the water. Analyzes were performed using the Statistica software version 7.

Declarations

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Author contributions

HCRSB: Investigation; Data curation; Formal analysis; Writing - Original Draft; CAC: Investigation. JCS: Investigation; Writing - Review & Editing. JFGJ: Methodology; Investigations; Writing; DMLS: Conceptualization; Methodology; Writing - Review & Editing; Project administration; Funding Acquisition

Data availability statement

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

Additional Information

The authors have declared that no competing interests exist.

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Figures

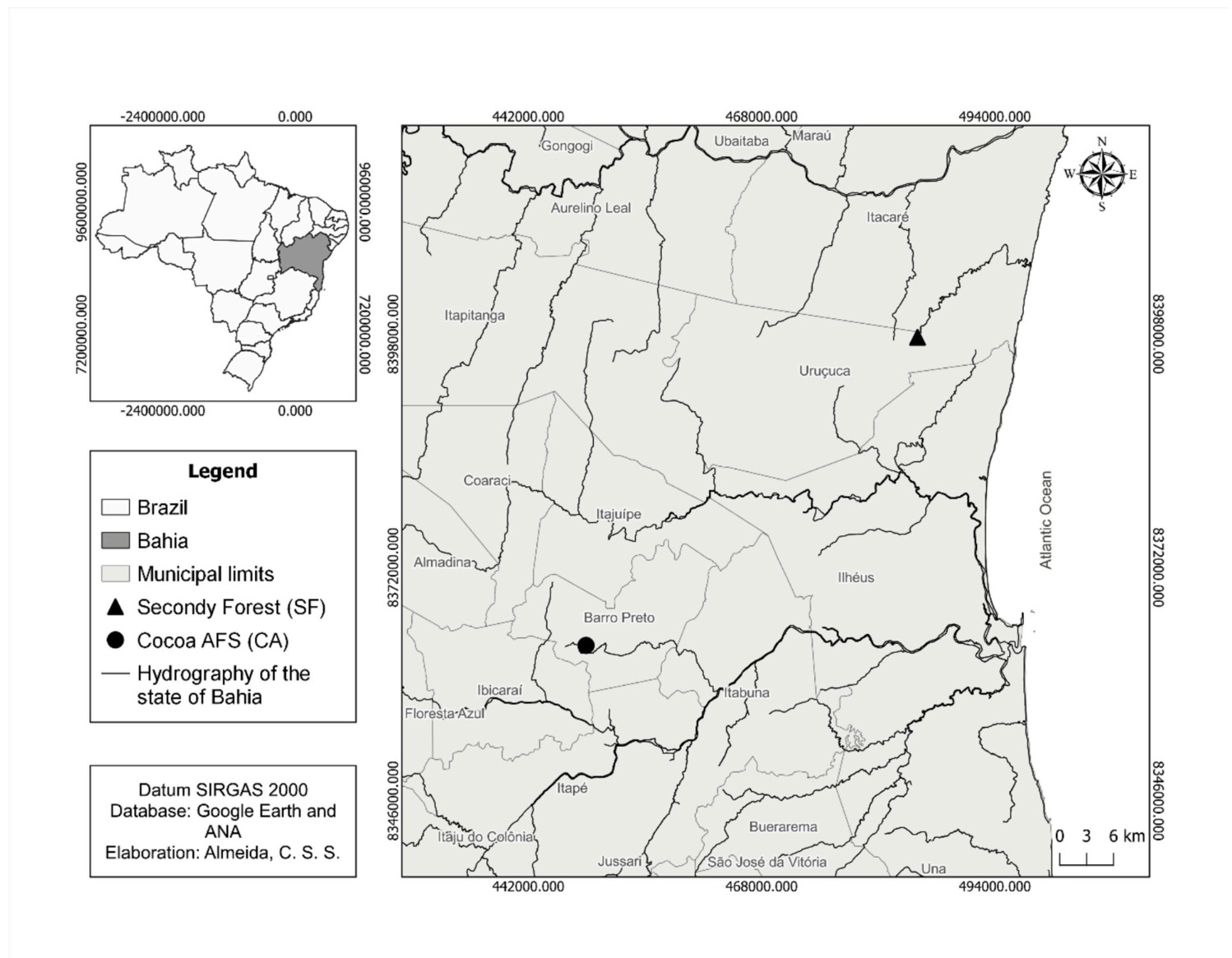


Figure 1

Location of the study area, Secondary Forest (SF) and in Cocoa AFS (CA), in the state Bahia, Brazil

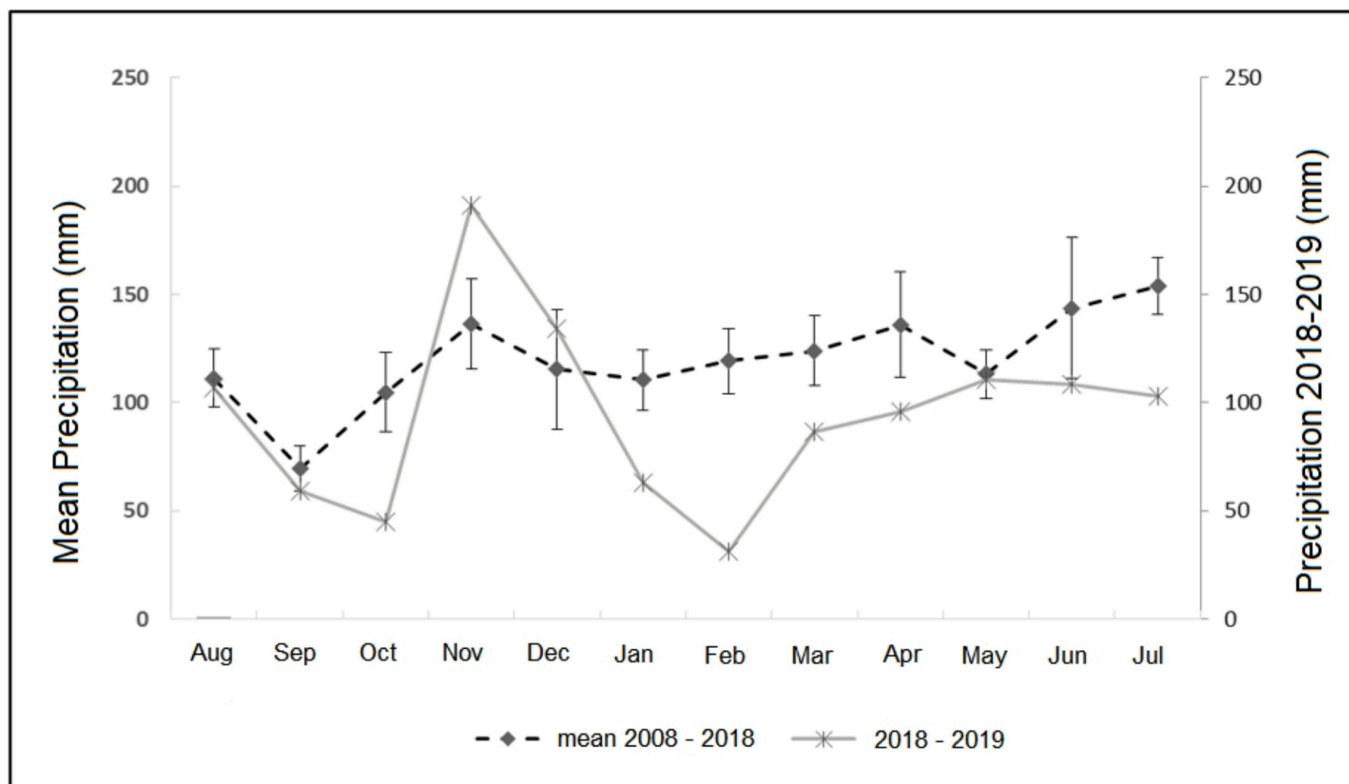


Figure 2

Monthly mean values ($\pm$ SD) for historical precipitation over the last 10 years 2008 to 2018 (dashed line), and from August 2018 to July 2019 (solid line)

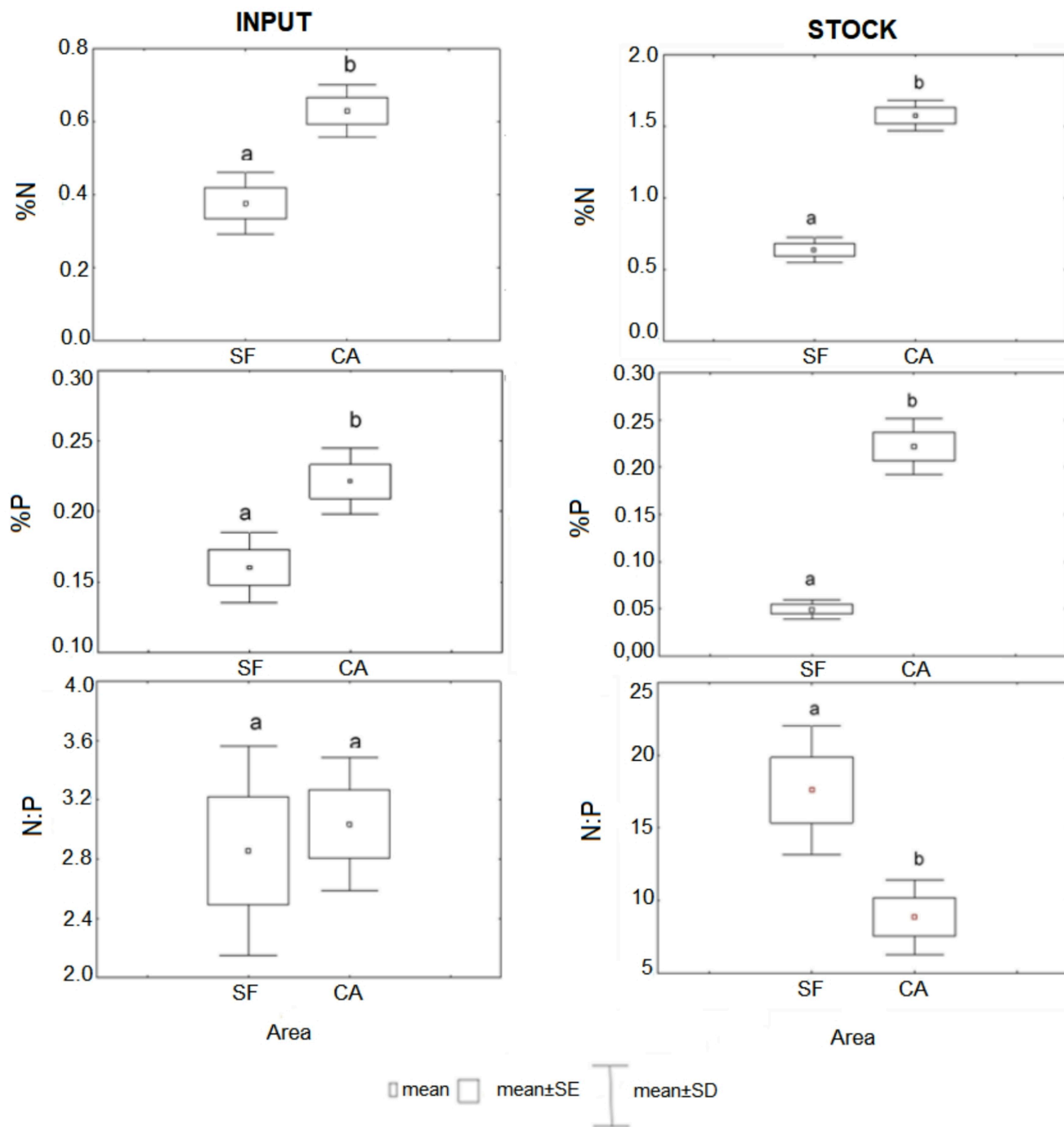


Figure 3

Nitrogen (N), Phosphorus (P) concentration (%) and N:P ratio in the input and stock of leaf litter from secondary forest (SF) and Cocoa AFS (CA) streams. Different letters represent statistical differences

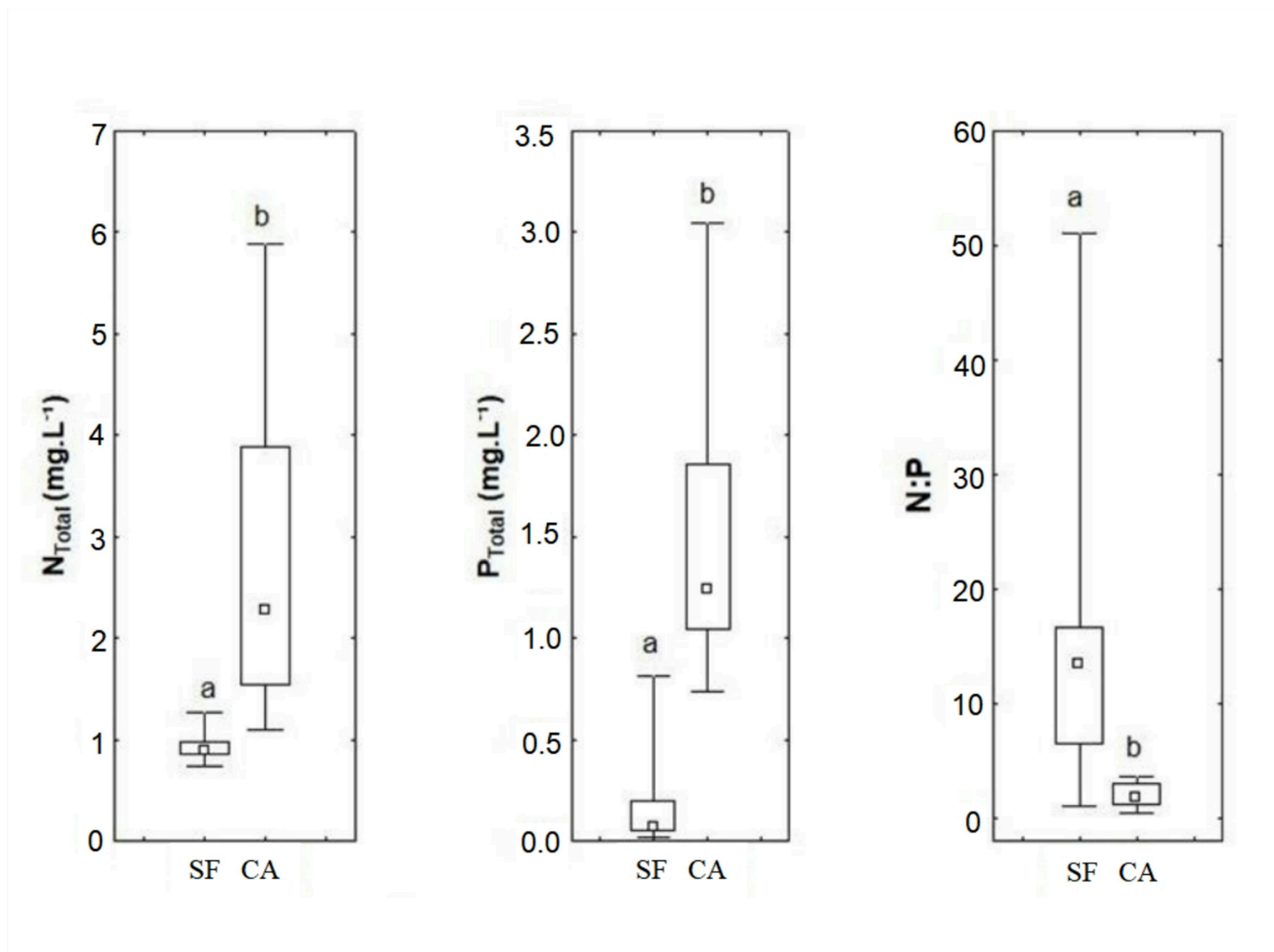


Figure 4

Total nitrogen (N_{total}), total phosphorus (P_{total}) concentration and N:P ratio in stream water from secondary forest (FS) and Cocoa AFS (CA). Different letters represent statistical differences

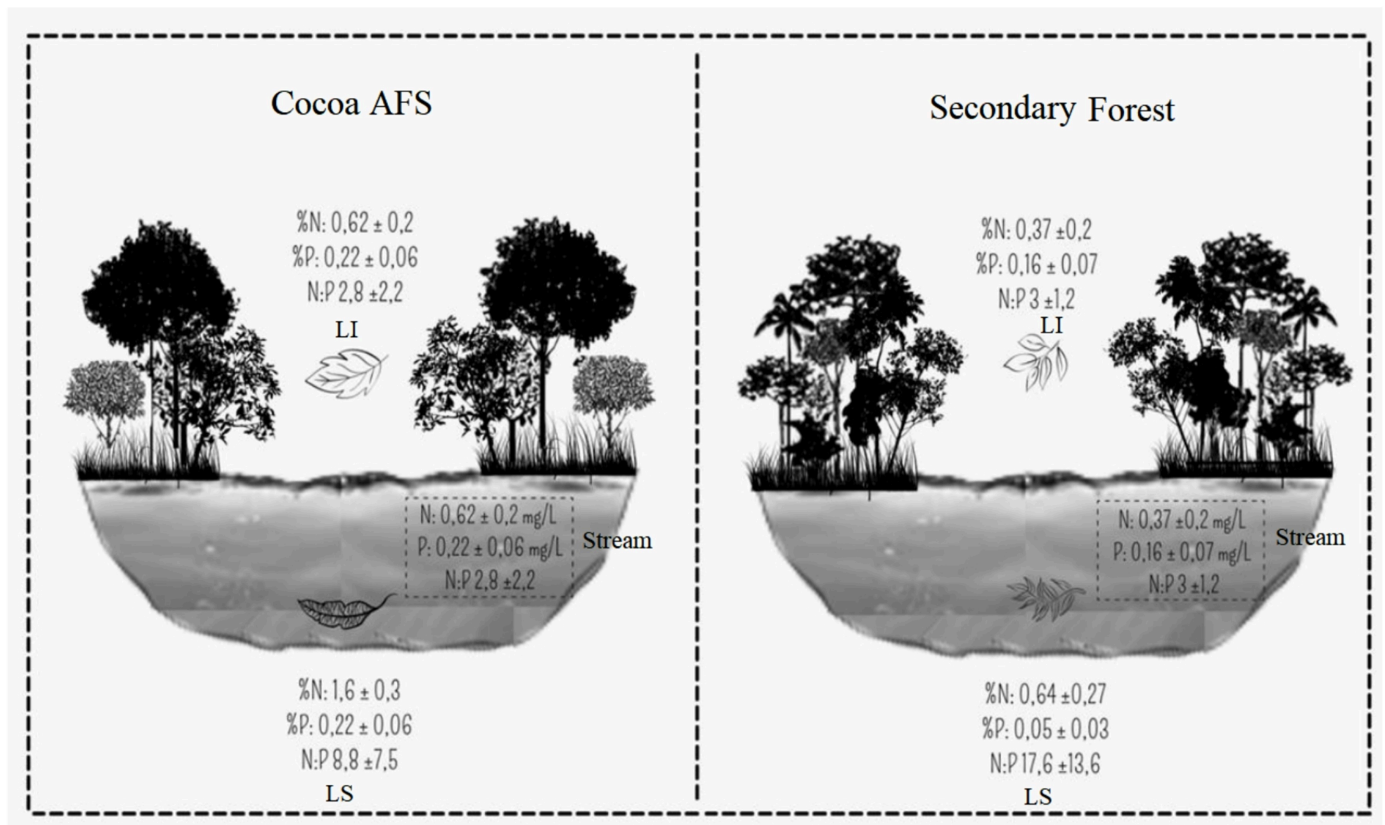


Figure 5

Nutrients in leaf litter input (LI) and stock (LS) and in the stream water of Secondary Forest (SF) and Cocoa AFS (CA)

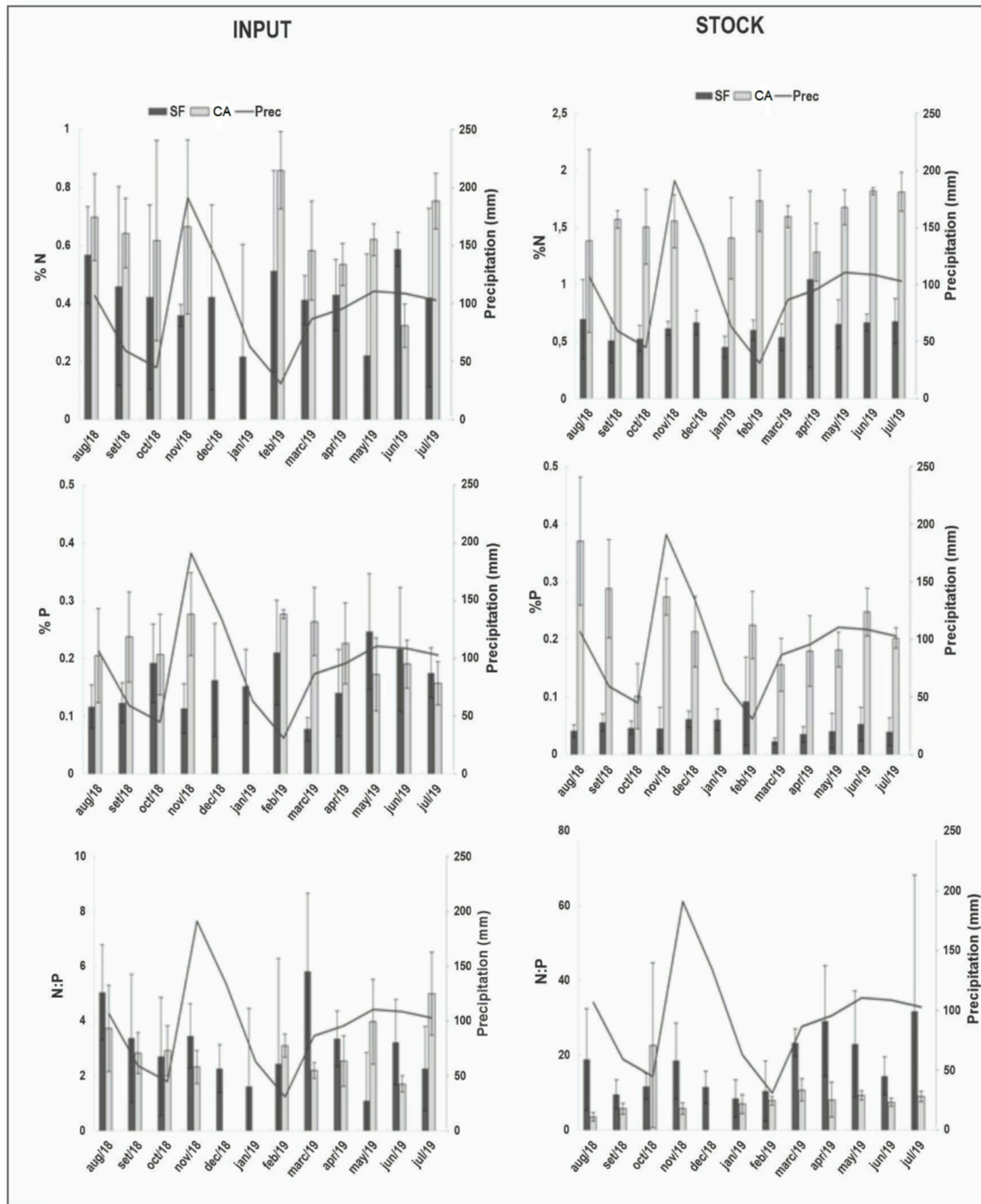


Figure 6

Temporal variation in the Nitrogen (%N) and Phosphorus (%P) percentage and N:P ratio in leaf litter input and stock in streams from the secondary forest (SF) and Cocoa AFS (CA)