Chapter

Soil Solution Chemistry in Different Land-Use Systems in the Northeast Brazilian Amazon

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Abstract

For sustainable production systems, the nonuse of fire (where there is a greater loss of soil nutrients), would be a solution for the conservation of nutrients in the soil, with the use of management by cutting and grinding, introduction of AFSs (agroforestry systems), and maintenance of riparian vegetation. The concentrations of carbon and nutrients were evaluated in the soil solution in two small hydrographic basins in the municipality of Igarapé-Açu (Pará state) in the eastern Amazon region, Brazil. The evaluations were performed considering the biogeochemical cycling in six land-use classes—riparian forest, secondary forest (*capoeira*), pasture, slash-and-burn agriculture, chop-and-mulch agriculture, and an agroforestry system (AFS). The objective was to determine the effects of different land-use systems on the composition of the soil solution, aiming to recommend sustainable practices. The concentrations of nutrients were greater in the areas of slash-and-burn agriculture and pasture, indicating greater losses of these nutrients due to runoff and leaching. The loss of nitrate was highest in the slash-and-burn area, while the organic carbon and organic nitrogen losses were greatest in the riparian forest, then in the secondary forest and agroforestry areas.

Keywords: Agrosystems, nutrient cycling, slash-and-burn, riparian forest soil solution extractor

1. Introduction

The chemical composition of the soil solution reflects the soil–plant-organism interplay, whereby this solution transports nutrients and other elements that supply plants and the soil biota. The effects of different soil management practices on biogeochemical flows need to be monitored and understood [1]. To understand the flow of nutrients at the soil-water interface, studies of the composition of the soil solution consider the processes of entry and exit of ions in each land-use situation [2]. The chemical elements present in the soil solution from the decomposition of leaf litter and the composition of the soil depend on various factors, namely, microbial population, plant species, temperature, groundwater flow, and soil management practices.

Various processes affect the soil solution composition, especially the mineral phase of the soil, determined by the entry and exit of minerals between the solid phase (colloidal) and a liquid fraction (solution) of the chemical elements that interact with the terrestrial and aquatic components of a watershed [3]. The investigation of the spatial–temporal variations of the chemical components susceptible to leaching to the water table or subsurface flow to land areas with lower elevation, thus reaching the watercourse beds, relies on the collection of soil solution samples [4]. The microbasins of the two streams (locally called *igarapés*) studied here, Cumaru and São João, have drainage networks predominantly regulated by the volume of groundwater stored in the soil [5]. Depending on the land use and agricultural management, in periods of high rainfall, these watersheds are subject to peak flows, with a potential to increase the loss of nutrients by leaching into deep soil layers, a process also related to the capacity of the soil to retain these nutrients [6]. In natural conditions, the soils in the basins studied are chemically poor due to the material of origin, derived from nutrient-poor sediments with low cation-exchange capacity, besides the severe action of the climate (high temperature and rainfall), causing a high weathering rate, intense leaching of nutrients and water erosion [7, 8]. These factors result in the low availability of nutrients to crops. Despite this lack of nutrients, the soils in the upland areas (*terra firme*), mainly acrisols and ferralsols, have excellent physical properties, that is, they are deep, show high infiltration rates, and are permeable, penetrable, and well-drained [7].

The objective of this study was to evaluate the composition of the soil solution in two microbasins of the Maracanã River Basin, located in the municipality of Igarapé-Açu in the eastern Amazon, subject to different land-use systems. We aim to expand knowledge about the impacts of land-use systems on water resources, improve the soil and watershed management techniques, and thus contribute to the establishment of more sustainable production systems in the region, which is mainly populated by family farmers.

2. Materials and methods

2.1 Description and characteristics of the basins and areas studied

The study was conducted in two small paired basins (**Figure 1**), Cumaru (4,127 ha) and São João (2,518 ha), both of which are tributaries of the Maracanã River Basin, located in the municipality of Igarapé-Açu, Pará, Brazil. The two watersheds are located between latitudes from 1°12′00″S to 1°16′00″S and longitudes from 47°32′00″W to 47°34′00″W. Igarapé-Açu is located in the Northeast Pará Mesoregion and Bragantina Microregion, about 120 km from the state capital, Belém. The main access routes are federal highway BR-316 and state highway PA-127. The two basins have easy access by dirt roads from the municipal seat, an important logistical factor for choosing them. These areas were selected because they have the predominant land-use systems in the region. They have highly permeable soils, predominantly by acrisols and ferralsols and gently rolling topography, cut by shallow channels (igarapés), with the presence of floodable marginal areas occupied by riparian forest stands (called igapós). The coverage mainly consists of secondary forested areas with different ages (capoeiras), small farm plots, and pastures with varying dimensions [9, 10]. Burning releases chemical compounds into the soil, making it temporarily fertile for crops. However, these compounds are rapidly lost to groundwater through leaching or carried away by runoff into the igarapés due to the physical characteristics
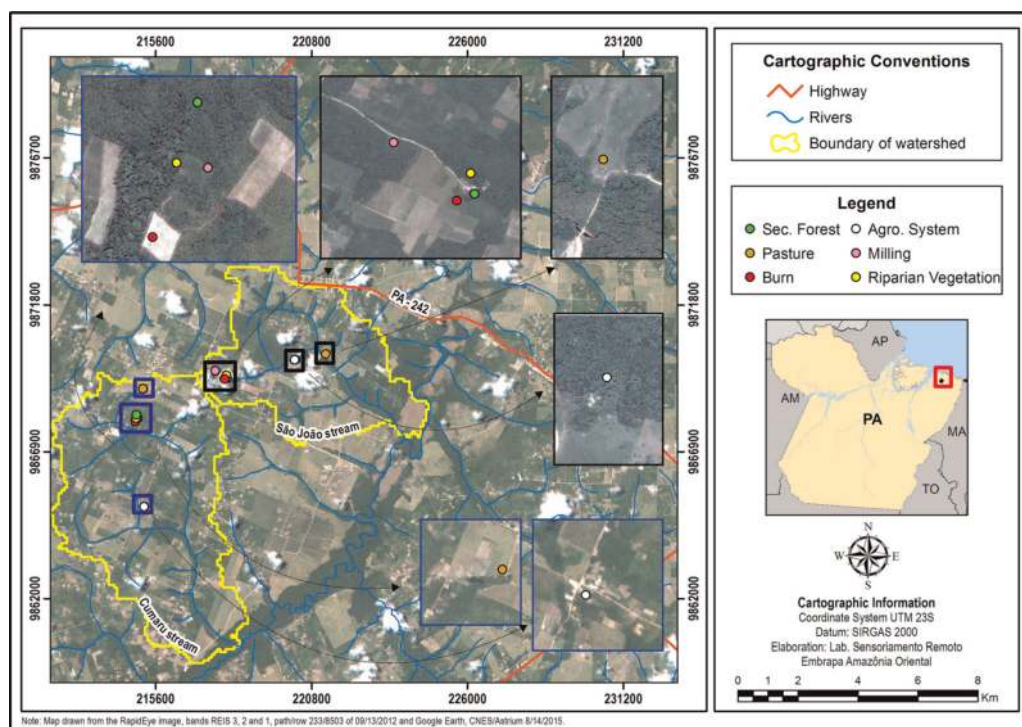
Figure 1.
The area was studied using soil solution extractors.

of the soil [11]. In a previous study, the pH of the soil in the Cumaru microbasin was found to vary from 4.8 to 4.9 at the depths studied, lower than the pH levels of the soils in the São João watershed, which ranged from 5.2 to 5.6 [7].

The predominant soils at the higher elevations of the Cumaru basin, where the relief is gently rolling, are classified as Xanthic Acrysol epicarenic, associated with a smaller proportion of Xanthic Ferralsol endoarenic, in addition to the occurrence of Petric Plinthosols. At lower elevations, the predominant soils are arenosols with hydromorphic characteristics, associated with small occurrences of Gleysols with indiscriminate texture in a narrow strip in ravines and other areas of frequent flooding of the drainage network. In the São João basin, the soils are very similar to those in the Cumaru basin, also with a predominant class of Xanthic Acrisolsepiarenic, associated with a smaller proportion of Xanthic Ferralsols endoarenic, along the soil with occurrences of lateritic concretionary horizons (Petric Plinthosols) at the higher elevations, with gently rolling terrain. At lower elevations, arenosols also prevail, with hydromorphic characteristics of sand or loamy sand texture in a very narrow strip near the streambed, widening slightly near the outlet of Igarapé São João into the Maracanã River [7]. They have acid pH, as mentioned, and low cation-exchange capacity (CEC), between 4.27 and 4.37, as described by Da Silva et al. [7].

The land-use characteristics of the areas studied are presented in **Table 1**. For each watershed, the location of the sampling points and the respective land use and agricultural management are identified, including the code assigned to each area. The two microbasins, although having similar land uses, differ regarding the intensity of these uses.

The riparian vegetation in Cumaru is near the beds of watercourses, which are classified as first and second order until reaching the Maracanã River, which is a

	Area Studied	Basin	Area Code	Latitude	Longitude
1	*Secondary Forest (<20 years)*	Cumaru	SFC secondary forest	47°33′40.48″W	1°11′30.64″S
2	*Slash-and-Burn Agriculture*	Cumaru	SBC slash-and-burn	47°33′ 41.44″W	1°11′37.92″S
3	*Chop-and-Mulch Agriculture*	Cumaru	CMC chop-and-mulch	47°33′ 39.88″W	1°11′34.59″S
4	*Pasture*	Cumaru	PC pasture	47°33′ 33.02″W	1°11′2.36″S
5	*AFS*	Cumaru	AFSC agroforestry system (rubber + cupuaçu palm)	47°33′ 32.09″W	1°13′10.03″S
6	*Riparian Vegetation*	Cumaru	RVC natural forest	47°33′ 40.73″W	1°11′34.53″S
7	*Secondary Forest (< 20 years)*	São João	SFSJ secondary forest	47°32′ 2.64″W	1°10′50.85″S
8	*Slash-and-Burn Agriculture*	São João	SBSJ slash-and-burn	47°32′ 5.28″W	1°10′50.85″S
9	*Chop-and-Mulch Agriculture*	São João	CMSJ chop and mulch	47°32′ 26.08″W	1°10′35.49″S
10	*Pasture*	São João	PSJ pasture	47°30′ 16.20″W	1°10′25.25″S
11	*AFS*	São João	AFSSJ agroforestry system (cupuaçu + peppertree)	47°30′ 49.76″W	1°10′31.50″S
12	*Riparian Vegetation*	São João	RVSJ natural forest	47°32′ 3.74″W	1°10′25.25″S

Table 1.
Location of the areas studied with different land-use classes.

third-order watercourse. The original vegetation of this basin was mainly equatorial forest, of which there are only a few remaining areas associated with the hygrophilous forest of alluvial plains around and along springs, streams, and rivers, where also exist hygrophilous floodplain forests. In the São João watershed, which also empties into the Maracanã River, the current prevailing forest regime is a secondary latifoliate forest in various development stages, resulting from clearance of the original equatorial forest, together with remnants of hygrophilous forest in alluvial plains along watercourses [7]. Riparian forest stands protect these igarapés and the fluvial water quality, and contribute to the groundwater stock, unlike what happens in areas subject to high surface runoff, mainly in unmanaged pastures, which in rainy periods suffer large losses of nutrients due to burning and the consequent absence of biomass from leaves and roots in the surface soil.

The pastures in both basins are unmanaged, without specific treatment. During the period studied, the pasture area in the Cumaru watershed contained about 1,200 head of cattle, while the pasture in the São João watershed contained only about 600 animals. For the slash-and-burn system, in both microbasins we prepared areas covering 0.5 ha in which cassava was planted. With respect to the secondary vegetation and agroforestry systems, these were already established in the two basins, so we demarcated areas of

0.5 ha. Finally, for the chop-and-mulch system, we also prepared areas of 0.5 ha, where we cut the secondary vegetation and left the biomass on the ground, composed of trunks, branches, and leaves. The ages of the secondary forest areas are given in **Table 1**.

2.2 Collection of samples and laboratory analyses

Soil solution extractors were installed six months before the monthly sampling campaigns, which occurred from March 2014 to April 2015. These extractors were installed in the Cumaru and São João watersheds in 12 areas measuring 0.5 ha in each basin, representing the land-use systems—riparian vegetation, secondary forest up to 20 years of recovering, slash-and-burn agriculture, chop-and-mulch agriculture, agroforestry system, and pasture. All told, we installed 96 extractors at depths of 30 and 60 cm (four at each depth) in the land plots in each use system.

The soil solution extractors consisted of porous capsules connected to amber glass collector jars (capacity of 250 mL) for analyses of DIC (dissolved inorganic carbon), DOC (dissolved organic carbon), and DON (dissolved organic nitrogen); and clear glass bottles (capacity of 1000 mL) for analyses of cations and anions—chloride (Cl^-), nitrate (NO_3^-), phosphate (PO_4^-), sulfate (SO_4^-), sodium (Na^+), ammonium (NH_4^+), potassium (K^+), magnesium (Mg^+), and calcium (Ca^+). The collector jars were washed after each sample collection with running water and 1% hydrochloric acid (HCl) solution, followed by Milli-Q water, and then dried and replaced.

We first measured the volume of water in the extractor jars. Then the samples were transported to the laboratory of Embrapa Amazônia Oriental in the city of Belém, for filtering and storage at ~4°C until conducting the analyses. For the analysis of DOC and DON, the samples were filtered through glass microfiber membranes (porosity of 0.7 μm), while for the other analyses, cellulose acetate membranes were used (porosity of 0.45 μm). To investigate the cations and anions, the samples were conserved in thymol ($C_{10}H_{14}O$) and submitted to ion chromatography with a chromatograph (Dionex DX120, USA).

The physical and chemical data of the soil samples from the region were obtained and described by Da Silva et al. [7].

2.3 Statistical analyses

We performed comparisons of the average concentrations in mg L^{-1} of the inorganic ions, cations, and anions, and organic and inorganic carbon dissolved in the soil solution samples from sites with different land uses over time. We also calculated correlations (Pearson correlation for parametric data and Spearman correlation for nonparametric data).

We used the Minitab 16.0 software to compute descriptive statistics and tests for normal distribution (Shapiro–Wilk test, $p > 0.05$) and comparisons of the means and variances. The parametric (normally distributed residues and homocesdatic variances) data were submitted to analysis of variance (ANOVA) for one factor (F test of statistical equality between means, Tukey test), while for interpretation of non-parametric data (not normally distributed), the Kruskal-Wallis test was used. After the mathematical transformation of the data, DON was the only parameter for which the values after this procedure had a normal distribution. The reciprocal transformation (1/Y) was used to stabilize the variance, in the sense of minimizing the effect of possibly very high values of Y. With this test, there was no evidence against the normality of the residuals because the points were all closely distributed along a

straight line. In this case, one-way ANOVA was applied for a pairwise comparison of the means between land uses of the two microbasins. On the other hand, for the variables NO_3^-, NH_4^+, and DOC, the Kruskal-Wallis test was applied to compare the means of the nonparametric data. **Table 3** reports the mean values of the concentrations of the variables measured in relation to each land-use class.

2.4 Climate data

The climate in the region is Am according to the Köppen classification, hot and humid with an average annual rainfall of about 2,500 mm [12]. The climate data (**Figure 2**) were obtained from the records of the meteorological station of the Embrapa Eastern Amazon research unit (*Embrapa Amazônia Oriental*), which is located at latitude 01°11'S, longitude 47°35'W, and an altitude of 45 m, about 10 km from the sampling point. We collected samples in four climatic periods—rainy (March to June), transition 1- TR1 (July and August), dry (September to December), and transition 2- TR2 (January and February).

3. Results

This chemical variability revealed the important influence of land management and physical, chemical, and biological characteristics of the soil, along with seasonal climate, on the processes of entry and exit of nutrients in the watersheds studied.

3.1 Precipitation

Figure 2 presents the distribution of rainfall during the study period compared with the average of the previous five years. Of particular note is the drought that lasted from September 2014 to January 2015, when the temperature fluctuated between 26 and 28°C and the relative humidity averaged 85% in the year studied.

3.2 Variability of the volume of soil solution collected in the different areas studied

The greatest volumes collected by the soil solution extractors for evaluation of DIC, DOC, and DON were in the areas of riparian vegetation, AFSs, and secondary
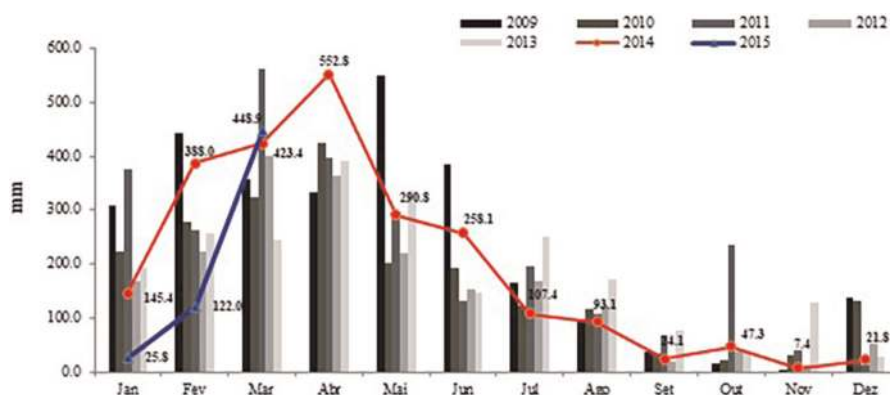

Figure 2.
Monthly precipitation from January 2009 to march 2015. Igarapé-Açu/Embrapa Amazônia oriental meteorological station.

SS — Study areas (depth 30 cm)

Variables (mg.L⁻¹)	PC	PSJ	SFC	SFSJ	AFSC	AFSSJ	RVC	RVSJ	CMC	CMSJ	SBC	SBSJ
Cl^-	4.140 (1.47)	3.290 (1.89)	3.212 (0.63)	1.979 (0.65)	1.510 (0.33)	2.107 (0.44)	7.88 (3.02)	1.747 (0.24)	1.580 (0.38)	2.89 (1.79)	3.94 (1.97)	1.242 (0.49)
NO_3^-	2.351 (0.97)	0.379 (0.11)	0.399 (0.16)	0.590 (0.25)	0.603 (0.14)	4.450 (1.74)	0.339 (012)	0.970 (0.26)	0.123 (0.10)	0.141 (*)	0.761 (0.38)	**8.227** (*)
PO_4^-	0.180 (*)	0.059 (0.02)	0.079 (0.02)	0.091 (0.04)	0.0705 (0.01)	0.051 (*)	0.100 (0.04)	* (*)	* (*)	0.879 (*)	**5.294** (*)	0.132 (0.07)
SO_4-	1.780 (1.05)	0.410 (0.12)	0.595 (0.23)	0.569 (0.125)	0.492 (0.26)	0.767 (0.20)	1.811 (0.55)	0.528 (0.07)	0.351 (0.11)	0.558 (0.38)	**1.98** (1.04)	0.857 (0.535)
Na^+	1.487 (0.73)	2.772 (0.78)	2.148 (0.40)	1.568 (0.325)	1.265 (0.16)	1.598 (0.43)	3.048 (0.84)	2.091 (0.45)	2.007 (0.83)	**3.24** (2.34)	2.46 (1.35)	0.789 (0.301)
NH_4^+	0.320 (0.11)	0.313 (0.15)	0.159 (0.07)	**0.353** (0.113)	0.1135 (0.04)	0.285 (0.01)	0.229 (0.08)	0.096 (0.03)	0.0461 (0.01)	* (*)	0.191 (0.09)	0.123 (0.001)
K^+	**4.390** (3.50)	3.037 (0.90)	2.250 (1.53)	0.730 (0.109)	0.433 (0.08)	0.692 (0.179)	0.722 (0.23)	1.415 (0.51)	0.729 (0.42)	1.64 (1.44)	6.67 (5.51)	2.677 (0.94)
Mg^{++}	0.675 (0.24)	0.801 (0.12)	0.413 (0.13)	0.386 (0.07)	0.295 (0.04)	0.487 (0.08)	0.443 (0.11)	**1.145** (0.46)	0.360 (0.12)	0.367 (0.28)	0.376 (0.24)	0.464 (0.07)
Ca^{++}	3.478 (0.66)	**3.854** (0.48)	1.754 (0.35)	1.942 (0.44)	1.731 (0.30)	2.6 (0.57)	0.954 (0.30)	1.155 (0.43)	1.351 (0.49)	1.545 (0.24)	2.049 (0.56)	2.61 (1.41)
DOC	8.020 (1.46)	27.20 (12.9)	9.900 (1.63)	19.32 (3.24)	3.305 (0.33)	8.31 (1.91)	10.21 (1.42)	16.41 (1.66)	10.86 (1.08)	8.59 (2.12)	15.32 (2.40)	**36.3** (24.5)
DON	1.147 (0.18)	2.032 (0.56)	1.151 (0.41)	1.459 (0.17)	0.916 (0.26)	0.998 (0.13)	0.812 (0.03)	1.291 (0.1)	0.916 (0.05)	1.083 (0.05)	**2.44** (1.48)	0.932 (0.12)
DIC	**1.404** (0.31)	1.136 (0.39)	0.365 (0.07)	0.406 (0.18)	0.898 (0.11)	0.938 (0.23)	0.224 (0.06)	0.291 (0.13)	0.574 (0.46)	0.833 (0.53)	0.835 (0.42)	0.639 (0.06)

SS — Study Areas (depth 60 cm)

Ions (mg.L⁻¹)	PC	PSJ	SFC	SFSJ	AFSC	AFSSJ	RVC	RVSJ	CMC	CMSJ	SBC	SBSJ
Cl^-	5.000 (3.52)	1.793 (0.44)	1.702 (0.26)	4.26 (1.73)	7.08 (5.48)	2.006 (0.96)	5.929 (0.97)	2.773 (0.80)	**7.64** (5.04)	1.604 (0.63)	2.97 (1.38)	2.258 (0.45)

SS	Study areas (depth 30 cm)											
Variables (mg.L^{-1})	PC	PSJ	SFC	SFSJ	AFSC	AFSSJ	RVC	RVSJ	CMC	CMSJ	SBC	SBSJ
NO$_3^-$	2.190 (1.89)	0.500 (0.12)	0.925 (0.34)	0.546 (0.25)	2.03 (1.84)	2.93 (2.04)	0.367 (0.12)	3.79 (1.15)	2.57 (1.60)	1.733 (0.69)	**11.97** (9.66)	3.91 (3.47)
PO$_4^-$	* (*)	0.409 (*)	0.076 (0.008)	0.066 (*)	0.040 (0.005)	0.050 (*)	0.271 (0.21)	0.354 (0.24)	**34.8** (34.4)	0.788 (*)	1.066 (0.92)	0.259 (0.20)
SO$_4$–	3.940 (2.66)	0.235 (0.03)	0.716 (0.23)	0.373 (0.06)	4.63 (4.35)	0.629 (0.16)	1.443 (0.42)	0.988 (0.25)	**5.74** (4.51)	2.030 (0.88)	1.371 (0.5)	1.224 (0.34)
Na$^+$	4.100 (3.12)	1.454 (0.53)	1.605 (0.27)	2.477 (0.51)	3.89 (2.42)	1.381 (0.30)	2.754 (0.20)	3.78 (1.62)	**4.25** (1.41)	2.887 (0.83)	1.642 (0.30)	1.044 (0.33)
NH$_4^+$	0.272 (0.12)	0.205 (0.08)	0.154 (0.07)	0.1380 (0.03)	0.1010 (0.04)	0.1570 (0.06)	0.1935 (0.05)	1.117 (0.04)	0.568 (0.26)	0.035 (0.01)	**0.929** (0.21)	0.283 (0.13)
K$^+$	5.61 (4.87)	1.99 (0.93)	0.825 (0.33)	1.085 (0.32)	2.44 (2.21)	0.3880 (0.05)	1.018 (0.38)	1.154 (0.54)	**10.02** (9.16)	2.14 (1.85)	0.925 (0.28)	1.453 (0.32)
Mg^{++}	0.715 (0.36)	0.222 (0.031)	0.368 (0.07)	0.647 (0.23)	0.3185 (0.99)	0.327 (0.12)	0.3993 (0.07)	0.398 (0.20)	**0.722** (0.39)	0.699 (0.15)	0.50 (0.08)	0.533 (0.14)
Ca^{++}	3.398 (0.7)	**4.570** (1.24)	1.819 (0.49)	1.557 (0.51)	1.791 (0.41)	1.944 (0.70)	1.113 (0.33)	1.414 (0.38)	3.65 (1.23)	1.726 (0.26)	3.79 (1.61)	3.58 (1.18)
DOC	11.080 (1.57)	* (*)	6.220 (1.26)	12.6 (0.83)	3.408 (0.51)	6.08 (1.76)	2.231 (0.50)	**19.96** (3.83)	7.702 (0.73)	8.05 (1.38)	13.05 (1.33)	18.57 (2.21)
DON	1.215 (0.16)	1.036 (0.043)	0.8215 (0.07)	1.1257 (0.10)	0.6283 (0.04)	1.183 (0.34)	0.6551 (0.05)	1.329 (0.15)	0.6887 (0.03)	0.82 (0.06)	6.94 (3.76)	**1.574** (0.37)
DIC	1.120 (0.33)	1.561 (0.352)	0.4559 (0.09)	0.3396 (0.09)	0.678 (0.16)	0.398 (0.11)	0.352 (0.11)	2.26 (1.46)	**2.61** (2.18)	* (*)	0.554 (0.21)	1.341 (0.55)

*Values in bold marked in yellow are the highest concentrations of the land-use type.

Table 2.

Concentrations of the chemical variables analyzed (mean and standard deviation) in the soil solutions of the areas studied in each basin in the different land-use classes at depths of 30 cm and 60 cm. PC = pasture Cumaru; PSJ = pasture São João; SFC = secondary Forest Cumaru; SFSJ = secondary Forest São João; AFSC = agroforestry system Cumaru; AFSSJ = agroforestry system São João; RVC = riparian vegetation Cumaru; RVSJ =riparian vegetation São João; CMC = chop-and-mulch agriculture Cumaru; CMSJ = chop-and-mulch agriculture São João; SBC = slash-and-burn agriculture Cumaru; SBSJ = slash-and-burn agriculture São João.

forest—a maximum of 198 mL and a minimum of 30 mL. In turn, for the analyses of the cations and anions, the greatest volumes were collected in the areas of riparian vegetation, AFSs, and chop-and-mulch agriculture, with a maximum volume of 850 mL and a minimum of 30 mL.

3.3 Spatial variability of nitrogen

The highest concentrations of nitrogen chemical species were found in the areas of slash-and-burn agriculture (**Tables 2** and **4**). The maximum concentration of NO_3^- in the SBC was 8.227 mg L^{-1} (at depth of 30 cm), while the concentration of NH_4^+ in this same area was 0.929 mg L^{-1} (at 60 cm), and DON was 2.44 mg L^{-1} (at 30 cm), as shown in **Table 3**. In turn, smaller concentrations of nitrogen occurred in the areas of chop-and-mulch agriculture and riparian vegetation. The concentrations of NO_3^-, considering the land-use systems, were higher than those of NH_4^+ and DON.

As can be observed in **Table 3**, there were significant differences according to the Kruskal-Wallis test in the mean values of the areas studied in the different land uses ($p \leq 0.05$) for DOC, NO_3^-, and NH_4^+. The results of the ANOVA (p-value = 0.000) provided sufficient evidence that the means were also different for DON, where $\alpha = 0.05$. According to the Tukey test, the AFS and riparian vegetation in Cumaru, as well as the pasture and riparian vegetation in São João, were different in relation to the other areas.

The boxplots in **Figure 3** present the variation of DON between the areas studied, where some discrepant data can be observed. In the Cumaru basin, it was highest in the areas of agroforestry system (AFSC) and riparian vegetation (RVC), while in São João the lowest values of DON were in the areas with secondary forest (SFSJ), pasture

| Land Use | Kruskal-Wallis Test | | | | | | One Way ANOVA-Tukey Test | |
| | DOC (p = 0.000) | | NH_4 (p = 0.018) | | NO_3^- (p = 0.004) | | 1/DON (p = 0.00) | |
	Average Rank	Z	Average Rank	Z	Average Rank	Z	Mean	Grouping
SFC	118.7	−1.16	57.5	−1.13	61.8	−0.42	1.2943	A B
SFSJ	189.7	3.5	81.1	1.1	57.8	−0.67	0.9206	B C
PC	141.6	0.26	82.9	1.16	72.7	0.53	0.9598	B C
PSJ	194.5	2.8	69.1	−0.04	52.3	−1.01	0.8598	C
SBC	187.6	3.06	102.5	2.86	90.3	1.81	0.894	B C
SBSJ	192.5	3.6	74.7	0.32	73.4	0.49	1.1291	B C
AFSC	48.9	−5.98	49.2	−1.92	54.8	−1.31	1.5886	A
AFSSJ	95.1	−2.66	74.5	0.46	89.7	2.4	1.2731	A B
CMC	143.6	0.45	78.1	0.63	51.6	−1.06	1.2805	A B
CMSJ	126	−0.37	15.8	−2.35	77.3	0.71	1.1695	A B C
RVC	75	−5.53	68.3	−0.15	41.2	−3.31	1.5226	A
RVSJ	208.7	4.44	50.3	−1.66	87.4	2.41	0.8336	C

Table 3.
Statistical tests of the variables DOC, DON, NO_3^-, and NH_4^+.

Land use/Variable (mg.L^{-1})	NO$_3^-$	SO42-	NH$_4^+$	K$^+$	CID	Mg2+	Na$^+$	COD	Cl$^-$	Ca$^+$	PO$_4^-$	NOD
PC	X	X	X	X	X	X				X		
PSJ			X	X	X	X	X			X		
SFC						X						
SFSJ			X	X		X				X		
AFSC		X			X	X	X					
AFSSJ	X					X						
RVC		X			X	X	X		X			
RVSJ	X		X			X	X					
CMC						X					X	
CMSJ						X						
SBC	X	X	X	X						X	X	X
SBSJ	X		X					X				

Table 4.
Presence of nutrients with highest concentrations (indicated by X) in the soil solution extracts according to land-use systems.
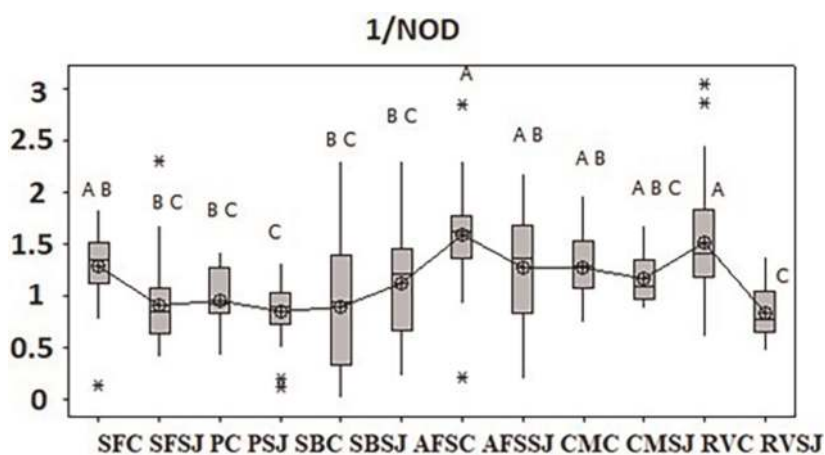
Figure 3.
Boxplots of the concentrations of dissolved organic nitrogen (DON) in the soil solution in the different areas studied after mathematical transformation (1/DON).

(PSJ), and agroforestry system (AFSSJ) in relation to the areas in Cumaru with the same land use.

3.4 Variability of DOC and DON in areas with different land-use systems

At a depth of 30 cm, there were higher concentrations of DOC in all land-use classes, but with slash-and-burn agriculture standing out more specifically in the
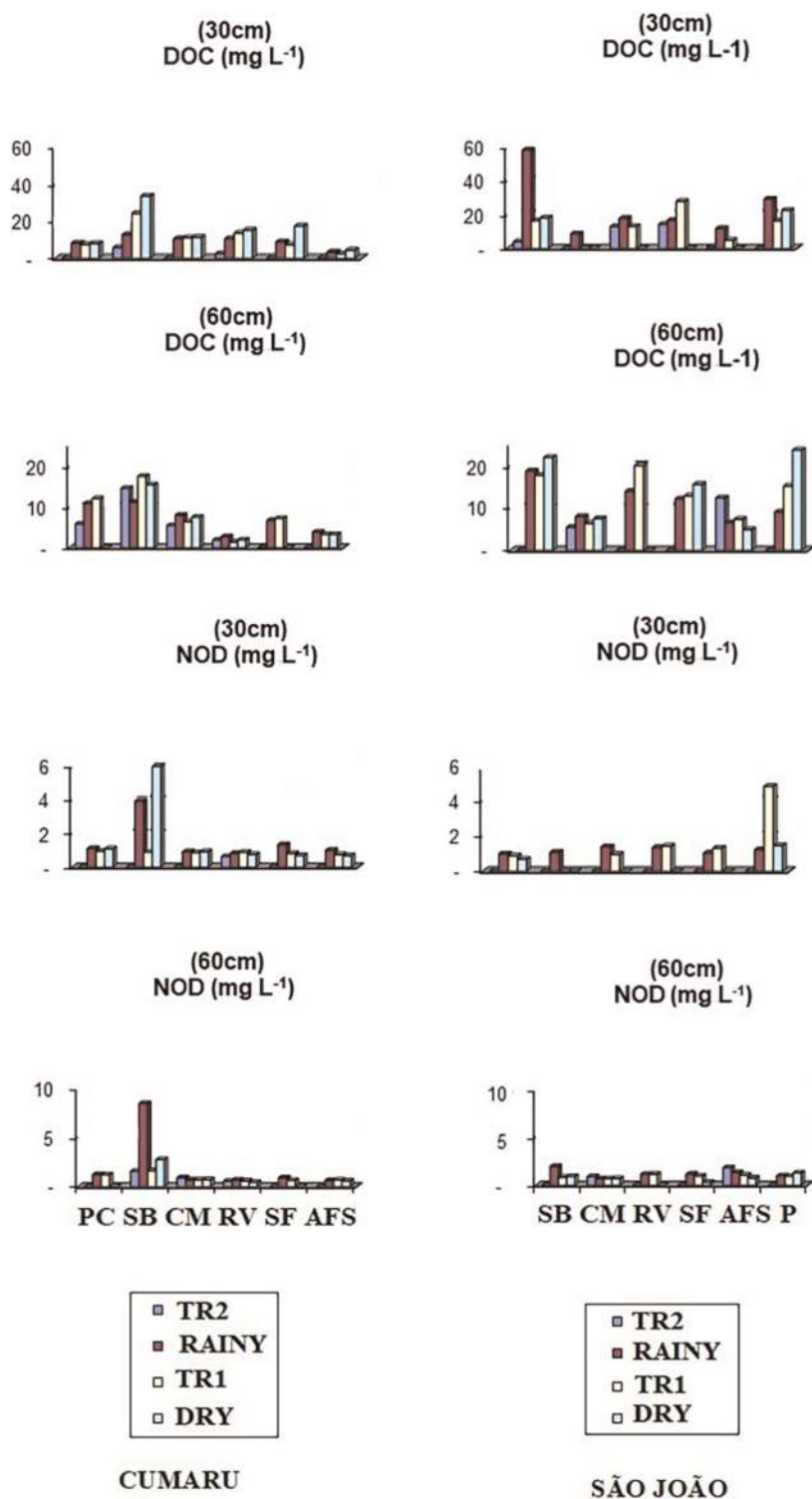
Figure 4.
Temporal and spatial variation of concentrations of dissolved organic carbon and nitrogen (in mg L^{-1}) in soil solution samples collected at depths of 30 and 60 cm in the sampling areas with different land-use classes in the watersheds studied.
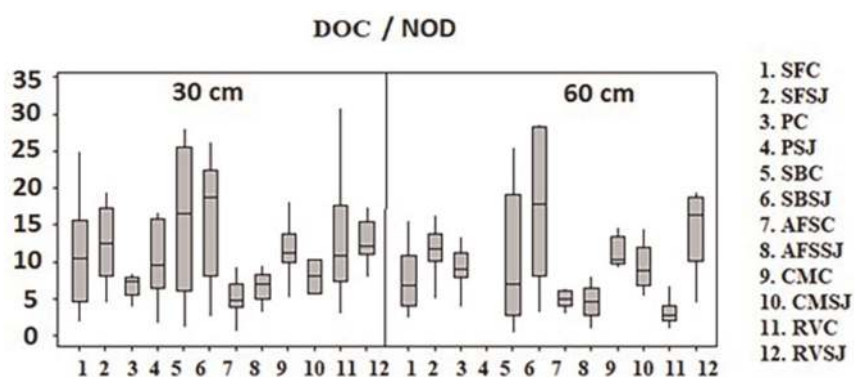
Figure 5.
The ratio between dissolved organic carbon and nitrogen in the agrosystems in the Cumaru and São João watersheds at depths of 30 cm and 60 cm.

periods of drought and transition from rainy to dry, with values above 20 mg L^{-1}. In turn, the riparian vegetation was in the second place regarding the magnitude of the concentrations of DOC. At a depth of 60 cm, slash-and-burn agriculture presented values greater than 10 mg L^{-1} of DOC in all climate periods (**Figure 4**).

In the pasture areas, the concentrations of DOC and DON were greater than 5 mg L^{-1} at both depths in the two transition periods and the rainy period, with no significant differences between depths. The DOC concentrations were lowest in the agroforestry system areas at both depths. With respect to climate, the DOC concentrations were greater in the dry period in all six land-use systems studied.

The DOC/DON ratio, in turn, was highest in the slash-and-burn agriculture areas and lowest in the riparian vegetation, AFS, and secondary forest areas (**Figure 5**).

Land Use	PC	PSJ	SFC	SFSJ	AFSC	AFSSJ	RVC	RVSJ	CMC	CMSJ	SBC	SBSJ
Anions mg.L^{-1}												
Cl$^-$												
30 cm	4.14	3.29	3.21	1.98	1.51	2.11	7.88	1.75	1.58	2.89	3.94	1.24
60 cm	5.00	1.79	1.70	4.26	7.08	2.01	5.93	2.77	7.64	1.60	2.97	2.26
NO$_3^-$												
30 cm	2.35	0.38	0.40	0.59	0.60	4.45	0.34	0.97	0.12	0.14	0.76	8.23
60 cm	2.19	0.50	0.93	0.55	2.03	2.93	0.37	3.79	2.57	1.73	11.97	3.91
PO$_4^-$												
30 cm	0.18	0.06	0.08	0.09	0.07	0.05	0.10	*	*	0.88	5.29	0.13
60 cm	*	0.41	0.08	0.07	0.04	0.05	0.27	0.35	34.80	0.79	1.07	0.26
SO$_4-$												
30 cm	1.78	0.41	0.60	0.57	0.49	0.77	1.81	0.53	0.35	0.56	1.98	0.86
60 cm	3.94	0.24	0.72	0.37	4.63	0.63	1.44	0.99	5.74	2.03	1.37	1.22

Land Use	PC	PSJ	SFC	SFSJ	AFSC	AFSSJ	RVC	RVSJ	CMC	CMSJ	SBC	SBSJ
Cations mg.L^{-1}												
Na$^+$												
30 cm	1.49	2.77	2.15	1.57	1.27	1.60	3.05	2.09	2.01	3.24	2.46	0.79
60 cm	4.10	1.45	1.61	2.48	3.89	1.38	2.75	3.78	4.25	2.89	1.64	1.04
NH$_4$$^+$												
30 cm	0.32	0.31	0.16	0.35	0.11	0.29	0.23	0.10	0.05		0.19	0.12
60 cm	0.27	0.21	0.15	0.14	0.10	0.16	0.19	1.12	0.57	0.04	0.93	0.28
K$^+$												
30 cm	4.39	3.04	2.25	0.73	0.43	0.69	0.72	1.42	0.73	1.64	6.67	2.68
60 cm	5.61	1.99	0.83	1.09	2.44	0.39	1.02	1.15	10.02	2.14	0.93	1.45
Mg^{++}												
30 cm	0.68	0.80	0.41	0.39	0.30	0.49	0.44	1.15	0.36	0.37	0.38	0.46
60 cm	0.72	0.22	0.37	0.65	0.32	0.33	0.40	0.40	0.72	0.70	0.50	0.53
Ca^{++}												
30 cm	3.48	3.85	1.75	1.94	1.73	2.60	0.95	1.16	1.35	1.55	2.05	2.61
60 cm	3.40	4.57	1.82	1.56	1.79	1.94	1.11	1.41	3.65	1.73	3.79	3.58
Organic and Inorganic Substances mg.L^{-1}												
DOC												
30 cm	8.02	27.20	9.90	19.32	3.31	8.31	10.21	16.41	10.86	8.59	15.32	36.30
60 cm	11.08	*	6.22	12.60	3.41	6.08	2.23	19.96	7.70	8.05	13.05	18.57
NOD												
30 cm	1.15	2.03	1.15	1.46	0.92	1.00	0.81	1.29	0.92	1.08	2.44	0.93
60 cm	1.22	1.04	0.82	1.13	0.63	1.18	0.66	1.33	0.69	0.82	6.94	1.57
CID												
30 cm	1.40	1.14	0.37	0.41	0.90	0.94	0.22	0.29	0.57	0.83	0.84	0.64
60 cm	1.12	1.56	0.46	0.34	0.68	0.40	0.35	2.26	2.61	*	0.55	1.34

Table 5.
Average concentrations of nutrients present in the soil solution in the Cumaru and São João basins in areas with slash-and-burn agriculture, riparian vegetation, secondary forest, chop-and-mulch agriculture, pasture, and agroforestry system.

3.5 Variability in the concentration of ions in areas with different land-use systems

The concentrations of the ions studied presented heterogeneous results in the different land-use systems, with the highest concentration found in the slash-and-burn agriculture, pasture, and riparian vegetation areas, as shown in **Table 5**.

With relation to depth, the ions concentration was variable between 30 and 60 cm. Pasture and chop-and-mulch stood out for having many high values at 60 cm (**Table 5**).

There were low correlations of DOC and DIC with Ca, R^2 = 2.1% and 15%, respectively (Spearman correlation, $p < 0.05$) (**Figure 6**).

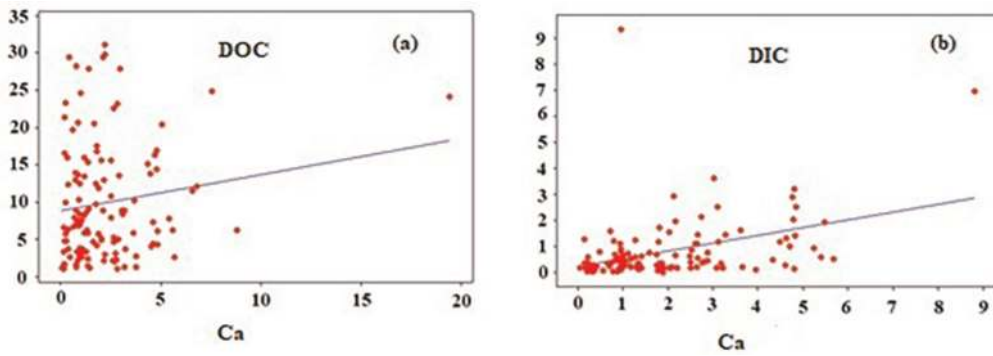**Figure 6.**
Spearman correlations between dissolved organic carbon (DOC) versus calcium (a) and dissolved inorganic carbon (DIC) versus calcium (b).
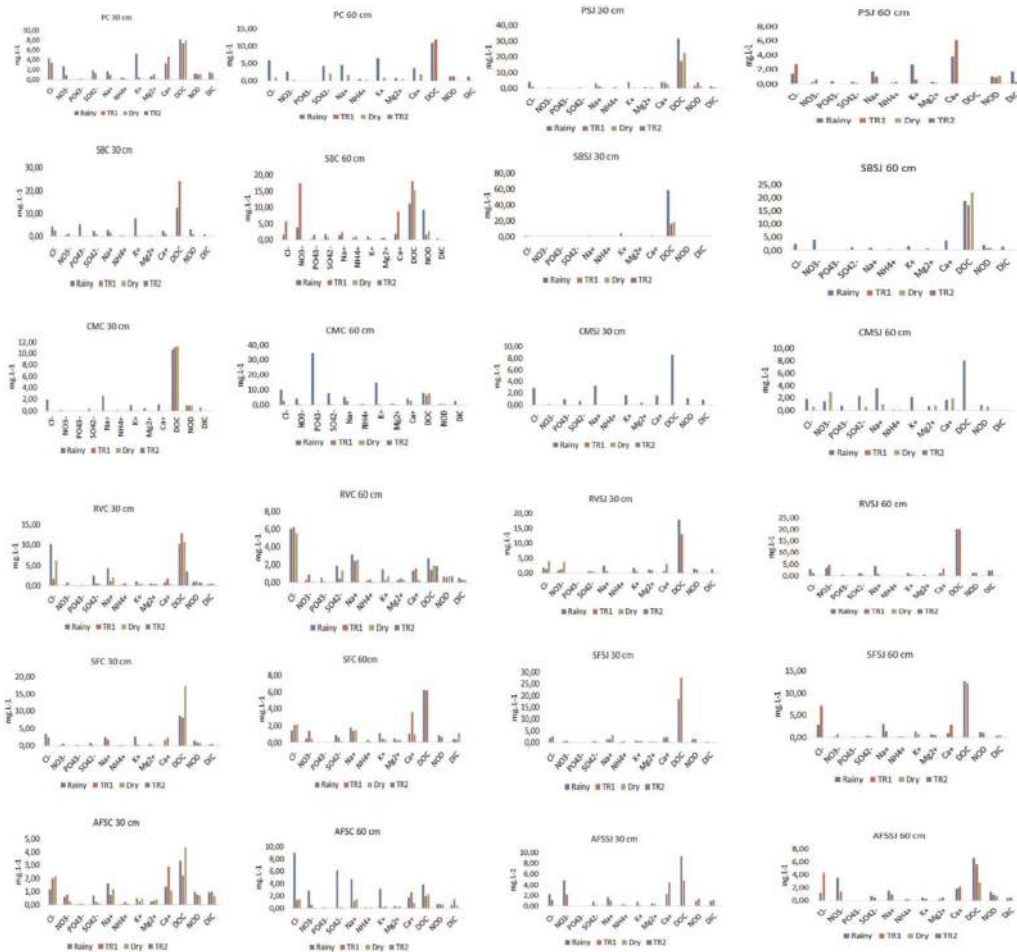

Figure 7.
Temporal distribution of the chemical constituents of the soil solution samples collected at depths of 30 and 60 cm in the 12 sampled areas.

3.6 Temporal variability of chemical compounds in areas with different land uses

With respect to the temporal variability, the highest concentrations of ions occurred in the rainy and transition to dry periods in all six land-use systems (**Figure** 7).

RV: The concentrations of DOC and DON were highest in the riparian vegetation area in both microbasins. This was the only land-use class for which we managed to obtain soil solution samples in all four climate periods. In the Cumaru microbasin, we detected all ions in the rainy and TR1 periods. The highest concentrations of Cl^- (approximately 10 mg L^{-1}) were found at 30 cm depth. In the São João microbasin, the highest concentrations of DOC, Cl^-, and NO_3^- occurred in the rainy, TR1, and dry periods.

SF: In the SFC, the concentrations of DOC and DON were highest in the rainy, TR1, and dry periods at both depths, while the inorganic ions stood out only in the rainy and TR1 periods. In SFSJ, the concentrations of these compounds were highest at depth of 30 cm, except for the phosphate levels in the secondary forest areas, which were below the limit of detection.

P: In the pastures, the concentrations of DOC and DON were highest at the 30 cm depth, principally in the São João microbasin. SO_4^{2-}, K^+, and Ca^{2+} were the predominant ions in the land-use areas in both watersheds.

SB: In the slash-and-burn agriculture areas, the concentrations of DOC were higher than 10 mg L^{-1}, with the greatest values finding at a depth of 60 cm in the rainy period and the transition from rainy to dry period in Cumaru. At the 30 cm depth, in the rainy period, the highest levels were measured of $NO_3^- \approx 16$ mg L^{-1}, $PO_4^- \approx 5$ mg L^{-1}, and $K^+ \approx 8$ mg L^{-1}). The same pattern occurred for these parameters in the São João microbasin, but with lower values in the rainy, TR1, and dry periods.

CM: In the chop-and-mulch system, phosphate stood out with the highest concentration (≈ 35 mg L^{-1}) at depth of 60 cm in the rainy period in the Cumaru microbasin. The other ions in this system had lower concentrations in the rainy, TR1, and dry periods, with values below 15 mg L^{-1} in both basins at the two depths.

AFS: In the agroforestry system, the ions had low concentrations, except for DOC, which had the highest concentrations in Cumaru at a depth of 60 cm and in São João at 30 cm, with approximate values of 9 mg L^{-1}. DOC and DON in the AFS sampling areas presented the highest concentrations in the dry period in Cumaru and the rainy period in São João.

4. Discussion

4.1 Temporal variability of C and N in the areas with different land uses

The concentrations of dissolved organic carbon at a depth of 30 cm were higher than at 60 cm; however, Marques et al. [13] did not observe differences between those two depths in a study in the Central Amazon near the city of Manaus, Brazil.

We found the concentrations of DOC in the slash-and-burn agriculture areas, mainly in the Cumaru microbasin, to be highest in the transition from the rainy to dry period (16.23–24.02 mg L^{-1}) and also in the dry season (15.39–33.48 mg L^{-1}). These are the periods when farmers most often practice burning.

In the São João microbasin, the maximum levels of DOC were also found in the slash-and-burn agriculture area at depth of 30 cm (57.86 mg L^{-1}). In this area, the

soils are predominantly sandy rather than clayey, resulting in little retention of DOC and consequently a substantial presence in the soil solution, as also observed by Sommer [11] and Wickel [5].

The secondary forest and riparian vegetation areas presented the highest concentrations of dissolved organic carbon and nitrogen, probably originating from the decomposition of leaves and roots and the activity of the microbial biomass in the soil, among other factors, such as higher temperature and flow of the soil solution in the transition period TR1 (DOC: 1.37–19.98 mg L^{-1}; DON: 0.57–1.14 mg L^{-1}) and rainy period (DOC: 2.70–17.65 mg L^{-1}; DON: 0.67–1.39 mg L^{-1}). This is similar to the findings of Marques et al. [13], $\approx$ 10 mg L^{-1} for DOC. The spatial variations, that is, according to land use, can be observed in the DOC/DON ratio, where low ratios indicate higher concentrations of DON, which stand out in the agroforestry systems. The flows of DOC and DON are connected by belonging to the same organic matter chain in the soil. Part of the DOC is used in the soil as substrate by microorganisms, causing an increase in the mineralization of DON and consequently the nitrification process. The concentration of DOC in the soil solution can also affect the speed of the denitrification process and the concentration of DON, as well as the flows of nutrients and metalloids in the soil, also depending on the pH, redox potential, and cation-exchange capacity [2, 14].

Riparian vegetation, AFS, and secondary forest systems are known to retain nutrients in the soil, with only small losses due to leaching [15] because of the quality and quantity of residues produced by the plant cover. With respect to the nitrogen compounds, the concentrations of nitrate were higher than those of ammonium and dissolved organic nitrogen in the six systems (DON: 0.6–1.7 mg L^{-1}; NH_4^+: 0.035 mg L^{-1}; NO_3^-: 0.1–12.0 mg L^{-1}). This result was expected, since NO_3^- is more soluble than DON and is not retained in clay minerals such as NH_4^+ [2, 16], where the conversion of ammonium into nitrate happens rapidly. However, the highest concentration of NH_4^+ occurred in the riparian vegetation, where the nitrification process is slow. Alfaia [17] found the presence of NH_4^+ in floodplain areas rich in clays. Gruditz and Dalhammar [18] reported that the nitrification process (the transformation of ammonium into nitrite and nitrate) occurs at a pH of approximately 8.0, a level higher than in our study (in acidic soils). In the pastures, we observed the greatest variations of DOC and DON in the dry period at both depths. This response is likely due to the concentration of aggregates transported in the soil profile because in this period there is less water available [13].

4.2 Chemical variability in soil solution extracts based on different land uses

At both depths, ion exchange probably occurred, depending on the soil chemical composition and the presence of organic matter, in which the ions were carried through the unsaturated zones where plant roots are located, reaching the groundwater.

The different land uses influenced the nutrient cycling, depending on the management and complexity of the landscapes of the areas studied. In these areas, the soil composition is more sandy than clayey, except in the AFSs and pastures. In the unmanaged pasture and slash-and-burn agriculture areas, the adsorption of ions by the soil is hampered, mainly at the depth of 60 cm. This is characteristic of weathered soils with low cation-exchange capacity and high acidity. As described by other authors, the variations of pH and ionic strength are factors that influence the release of ions from the soil to the solution, and hence influence the processes of adsorption of

cations and anions. In other words, acidic pH and low ion-exchange strength favored their release in the areas studied [5]. Besides this, the processes of nitrogen mineralization and subsequent oxidation (formation of nitrite and/or nitrate), along with the solubilization of aluminum, create conditions for the soil not to retain these ions [2]. The presence of iron and aluminum oxides in the soil can influence the electrochemical processes, resulting in increased exchange of anions and reduced exchange of cations between the soil and soil solution [16].

Competition exists between sulfate and nitrate ions, evidenced by the ionic strength and reduction of pH. This correlation was observed in the chop-and-mulch agriculture and AFS areas, with variations between these two parameters (**Table 2**). High concentrations of sulfate were observed in these areas, indicating the low competition of other anions such as phosphate and nitrate, since in these areas low concentrations of iron and aluminum predominated because the soils are sandier [7]. According to Borba et al. [16], sulfate ions are preferentially adsorbed by the soil in comparison with nitrate ions. The presence of sulfate in the soil solution in the AFS and chop-and-mulch agriculture systems can be attributed to soils with greater clay content than in areas of pasture and slash-and-burn agriculture, probably due to leaching of nutrients in soils impacted by external factors (physical–chemical destructuring) [15]. In this study, we observed a greater variation of Cl^- ions in the soil solution with lower retention, probably due to the competition for the adsorption of other negatively charged ions in the soil, such as NO_3^- and $SO4^-$.

With respect to cations, Ca^{2+}, Na^+, K^+, Mg^{2+}, and NH_4^+ had the highest concentrations in the chop-and-mulch agriculture and secondary forest systems, where the biomass left in the soil probably contributed to the incorporation of organic acids in the soil. This is an important factor for the enrichment of nutrients in the soil. With respect to the mechanism for the exchange of macronutrients and micronutrients, according to Borba et al. [16], this occurs mainly in shallower soil layers, where the greater presence of organic matter increases the cation-exchange capacity (CEC). According to Denich [19] and Cattanio [20], the level of organic material is affected by the composition of the leaf litter in secondary forest areas, in turn, determined by the plant species and their contribution of nutrients, as well as the pattern of decomposition and mesofauna in the soil. This same process probably occurred in the areas of riparian vegetation and agroforestry systems studied by us.

In the slash-and-burn agriculture areas, the concentration of nitrate in the soil solution was high, in some cases above the limits of potability (> 10 mg L^{-1}), indicating potential leaching into the soil solution, eventually reaching groundwater reservoirs. Williams et al. [21] conducted studies of the hydrochemical changes caused by land clearance through burning for agriculture in small plots in the central Amazon Basin on the northern side of the Solimões River and concluded that high leaching of nutrients occurs after slash-and-burn preparation, which gradually diminishes, mainly in the riparian zone. The authors also observed high concentrations and N and P in surface runoff, confirming the importance of riparian forests as nutrient buffers in the aquatic and terrestrial systems of the basin. In our study, in turn, we noted this same loss of micro-and macronutrients in the slash-and-burn agriculture and pasture areas.

The nitrogen in its inorganic form left after burning of vegetation is known to accelerate the decomposition of forest biomass [21], so that percolation of the solution through the soil profile in nitrate-rich soils occurs mainly in disturbed soils because this disturbance diminishes the nitrogen uptake of plants and enhance its availability. We found increased NH_4^+ in the soil solution to be common after burning and in areas with riparian vegetation of the Cumaru microbasin. This was probably due to

microbiological processes, where ammonium is released from anoxic sediments to be oxidized into nitrate by nitrifying organisms, as well as caused by competition for N by plants [21].

Borba et al. [2] reported that the combination of dissolved inorganic carbon and Ca^+ ions, where carbon is converted into carbonates, caused an increase in soil pH. This linear correlation (**Figure 6**) between dissolved carbon and calcium can be related to the availability of this nutrient by the decomposition of biomass in agricultural systems, which, depending on the soil conditions (clay percent, acidity, and water availability) can increase or decrease the productivity of crops [22].

We observed higher concentrations of calcium, magnesium, potassium, and phosphate ions in the chop-and-mulch agriculture areas, probably resulting from the mineralization of the chopped plant residues, as reported by Figueiredo et al. [23] in a study of similar areas.

The concentration of ions in the soil increased rapidly after the burning of vegetation to plant crops, with various ionic compounds remaining for brief periods [6]. Changes in soil management are clearly related to loss and mobilization of nutrients affecting soil fertility, which is also affected by factors such as soil class, degree of disturbance, and effects of burning on the biological and physical aspects of the soil. The results of this study clearly indicated the importance of research regarding nutrient flows in areas with different soil management types in tropical areas, to evaluate the efficiency of different crops to absorb these nutrients without loss or excess of these compounds in the soil and water.

4.3 Temporal variability of nutrients in different land uses

We observed differences in the concentrations of carbon and nutrients in the soil solution in areas with different land uses and different climate periods (rainy, TR1, dry, and TR2) during the year in the two microbasins. To facilitate the discussion, we have divided the elements analyzed into three groups (**Figure 7**), which are Group 1 – dissolved organic carbon, dissolved organic nitrogen, and dissolved inorganic carbon; Group 2 – ammonium, potassium, and magnesium; and Group 3 – chloride, nitrate, phosphate, sulfate, sodium, and calcium.

In all land-use areas except pasture and AFSs, where the soils had a more clayey texture, the absence or presence of biomass (influenced by leaf concentration) along with rainfall affected the ions and organic compounds in the soil solution extracts, as also observed by Markewitz et al. [1], who reported greater nutrient flows in natural and secondary forests. In the riparian vegetation in the rainy season and the transition to the dry season (TR1), mainly in the latter case, there were greater movements of DOC, DON, and DIC at 30 cm depth compared to 60 cm depth. Additionally, chloride, sodium, calcium, and sulfate were present in higher concentrations than ammonium, potassium, and magnesium. Rainwater and its interaction with the canopy and litter affect the chemical composition of the soil solution, which is enhanced by the fact that the soil is sandy, causing little influence given its lesser capacity to retain nutrients. The greater presence of calcium and DIC in secondary forest areas can be related to the different compositions of trees (fewer species), probably due to the increased pH, favoring cation concentration in the soil. These factors were also observed by Markewitz [24] and Figueiredo [23], who described a substantial increase of cationic components in secondary vegetation. Despite the losses by leaching in this type of vegetation, the roots remain in the soil, where they form a protective network, hindering the passage of nutrients to watercourses [5].

The soils in the pastures at the two depths (30 and 60 cm) stood out for high concentrations of potassium and calcium in the rainy and TR1 periods. The mobility of these ions in the soil profile is intense after heavy rainfall, so their concentration in the soil solution increases. This is common in tropical soils in unmanaged pasture areas [25]. The soils in these areas, with low CEC, sparse organic matter, and high acidity, are prone to leaching due to high water percolation [26]. This process influenced the soil solution, mainly in the pasture area of the São João microbasin, where the DOC concentration reached 30 mg L^{-1} in the rainy season. The slash-and-burn areas of the two microbasins stood out with the loss of carbon from the soil solution via DOC, and of nitrogens via nitrate (NO_3^-) and DON, at the depth of 60 cm. This probably favored the movement of these compounds to the groundwater, as also observed by other authors [23, 24]. The amounts of DON and DOC lost to the soil solution in the process of burning vegetation and the decomposition of organic matter cause an increase in the flow of nitrate. These processes in the rainy season and transition to the dry season in the burned areas resulted in the loss of these compounds, which were intensely released from the soil surface by rainwater, rather than resulting from processes in the deeper soil levels, where they are transported to the groundwater.

In both microbasins, there were greater concentrations of phosphate at a depth of 60 cm in the chop-and-mulch agriculture areas in the rainy season, as well as of DOC with origin in the biomass on the soil surface, as also reported by Kato et al. [6]. According to Markewitz et al. [24], phosphorus can be converted to its inorganic state during the decomposition of organic matter. In our case, this nutrient in the soil came from the chopped branches and leaves. This process was also reported by Neill et al. [27] as the result of burning. This did not occur in this study, where it only happened in the chop-and-mulch area when the biomass supplied phosphorus to the surface soil and consequently to the soil solution. Kato et al. [6] noted a positive balance of nutrients, mainly phosphorus, through the cutting and mulching of secondary vege-tation, which served as a source of organic matter to the soil. We also observed intense retention of water by the soil in this system, which hampered the collection of samples by the soil extractors. This was expected of the chop-and-mulch system as a factor of water conservation.

In the agroforestry systems, the concentrations of all ions were lower in the rainy, TR1, and dry seasons in relation to the other land uses. Ca^{2+}, Cl^-, Na^+, NO_3^-, and SO_4^- were present, along with DOC, DON, and DIC. The diversity of leaves from different plant species in the soil promotes the entry of nutrients because the presence of roots and microorganisms favors their absorption with less water availability [28]. Because of the presence of many arboreal species, studies of nutrient cycling in this complex composition are still scarce, but AFS models, implemented mainly by family farmers, have proven to be well-adapted, helping to improve local socioeconomic conditions [29].

5. Conclusions

- The presence of cations and anion were greater in the soil solution samples in the two transition periods (rainy to dry and vice versa).

- The cations were retained more in systems with a greater diversity of plants (riparian vegetation, secondary forest, and AFS).

- The sandier soils characteristic of these areas facilitated the leaching of nutrients into the soil solution, mainly with the practice of slash-and-burn agriculture.

- According to the data obtained, the systems in which there is more vegetation, such as secondary vegetation, riparian, and agroforestry systems, are the ones that retain nutrients in the soil, also preserving a greater amount of water in these systems. Unmanaged pasture and the use of burning for plantations have the risk of enhancing leaching rates by impoverishing the soil, so the use of crushed biomass in the soil agroforestry system and secondary vegetation can favor more sustainable management of the soil, in addition to the preservation of riparian forests.

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