



Division - Soil Use and Management | Commission - Soil and Water Management and Conservation

Chemical features of floodplain soils under different land-uses in the Solimões/Amazon River basin

Sonia Sena Alfaia^{(1)*} , Marta Iria da Costa Ayres⁽¹⁾ , Acácia Lima Neves⁽²⁾ ,
Katell Uguen⁽³⁾ , Robert Pritchard Miller⁽⁴⁾ , Juan Daniel Villacis Fajardo⁽³⁾ ,
Alexandre Pereira Bakker⁽⁵⁾  and César Augusto Ticona-Benavente⁽¹⁾ 

⁽¹⁾ Instituto Nacional de Pesquisas da Amazônia, Manaus, Amazonas, Brasil.

⁽²⁾ Instituto Nacional de Colonização e Reforma Agrária, Manaus, Amazonas, Brasil.

⁽³⁾ Universidade do Estado do Amazonas, Manaus, Amazonas, Brasil.

⁽⁴⁾ Instituto Sociedade, População e Natureza, Brasília, Distrito Federal, Brasil.

⁽⁵⁾ Instituto Nacional do Semiárido, Campina Grande, Paraíba, Brasil.

ABSTRACT: Most studies regarding the impacts of agricultural systems on soils of the Amazon region of Brazil have been carried out on upland soil, locally known as *terra firme*. Information regarding the impacts of different land-use systems on floodplain soil properties is still scarce. There is a need to broaden this knowledge to understand this Amazonian ecosystem better, especially how its soils respond to human interventions. This study aimed to describe the major chemical features of floodplain soils along the Solimões-Amazon Rivers and the effects of different land-use systems on soil nutrient levels. Sixty-two different land-use systems were sampled in 15 communities located in three different regions of the Solimões/Amazonas River floodplain complex: Upper and Middle Solimões (UMS), Lower Solimões and Middle Amazon (LSMA), and Lower Amazon (LA). Soils under cultivation showed a high availability of Ca^{2+} , Mg^{2+} , and P and low levels of exchangeable Al, in contrast to soils under forest and secondary vegetation, which were more acid and showed higher levels of exchangeable Al. Although most of the samples showed high contents of K^+ , for some areas, the low level ($\text{K}^+ < 0.15 \text{ cmol}_c \text{ kg}^{-1}$) of this nutrient can become limiting to crop production. The low levels of N found in most of the analyzed samples confirm that this element may be the limiting nutrient for agriculture in floodplain ecosystems. The use of legumes and other nutrient-rich plants, which naturally occur in the Amazon floodplain environments, could potentially address this N deficiency in these soils.

Keywords: Amazonia, floodplain, soil management, nutrients, organic carbon.

*** Corresponding author:**

E-mail: sonia.alfaia@inpa.gov.br

Received: January 20, 2022

Approved: April 05, 2022

How to cite: Alfaia SS, Ayres MIC, Neves AL, Uguen K, Miller RP, Fajardo JDV, Bakker AP, Ticona-Benavente CA. Chemical features of floodplain soils under different land-uses in the Solimões/Amazon River basin. Rev Bras Cienc Solo. 2022;46:e0220005.

<https://doi.org/10.36783/18069657rbc20220005>

Editors: José Miguel Reichert  and Marcos Gervasio Pereira 

Copyright: This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided that the original author and source are credited.



INTRODUCTION

Lowlands of the Amazon basin can be divided into two distinct ecosystems: the *terra firme* (unflooded soils) of tertiary age and the *várzea* (floodplains) of recent quaternary age. While the *terra firme* soils are of low natural fertility and high acidity due to their age, leaching processes, and parental rocks (Teixeira et al., 2019), the floodplain has fertile soils due to the annual deposition of mineral-rich sediments brought from the headwaters in the Andes, which are suspended in the “muddy waters” of the Solimões and Amazon Rivers (Sombroek, 1984; Junk, 2020). The Solimões is the continuation of the Amazonas River, as it is known in Peru, in Brazilian territory. Upon its meeting with the Negro River, it receives the name Amazonas.

The *várzea* or floodplain ecosystems in the Amazon State comprise approximately 24.8 million hectares (Cravo et al., 2002). The quality and quantity of quaternary sediments deposited by yearly flood pulses give these floodplain or beach soils a high potential for agricultural production (Furch, 1997; Cravo et al., 2002; Lopes et al., 2006). It was in this environment where natives initially settled in Amazonia, and to this day is the area where much of the non-urban population of the Amazonia lives. The *várzea* soils support many land-uses, including the continuous or near-continuous cultivation of annual crops and perennial fruits, the extraction of native forest products, and cattle ranching. Rich aquatic ecosystems complement agricultural livelihoods with several fish species.

Geological and pedological surveys during the 60's and 70's carried out by the Radar in Amazon Project (RADAMBRASIL) still remain as the major references for the characterization and classification of Amazonian floodplain soils, mainly represented by Gleysols and Fluvisols (Teixeira et al., 2019), which correspond to *Gleissolos* and *Neossolos Flúvicos*, in the Brazilian soil classification system (Santos et al., 2018). According to Sombroek (1984), Gleysols predominate in the eastern part of the sedimentary basin (the Brazilian Lower Amazonas River) and Fluvisols in the western part (Upper Solimões, Madeira, and Peruvian Amazonas River). Only in the floodplains of the rivers that originate in the Andes area, and hence carry a considerable load of rich sediments, are the Fluvisols and Gleysols non-acid, and locally even calcareous, with a high-activity clay mineral assemblage, with illite/montmorillonite.

Two types of floodplains are differentiated according to their position in relation to the river channel: “high” floodplains (*várzea alta*), located close to the margins of watercourses and corresponding to the natural levees formed by the deposition of coarser sediments (sand) during the flood stage and “low” floodplains (*várzea baixa*), located further away from the river bank and subject to more prolonged flooding (Cravo et al., 2002).

Most studies regarding the impacts of agricultural systems on soils of Amazon region of Brazil have been carried out on unflooded soils of the *terra firme*, such that information regarding impacts of different land-use systems on floodplain soil properties is still scanty. The processes through which nutrients are brought in during flooding, giving the floodplain agroecosystems their sustainability, are still not well studied (Oliveira et al., 2000; Guimarães et al., 2013). Small differences in climate, water, and nutrient regimes, and land-use can drastically change the delicate balance of tropical wetland ecosystems (Neue et al., 1997). There is a need to broaden this knowledge to understand this Amazonian ecosystem better, especially how its soils respond to human interventions.

This study is part of a larger project entitled “Agriculture and Livestock: Proposals and diagnosis for an improvement on the use and management of floodplain soils”, which was funded by the United Nations Development Program – UNDP/Provarzea, in which various soil scientists evaluated soil use and management from the technical, economic, social and ecological point of view. This paper presents the results of this project regarding *varzea* soils fertility. In this sense, the present study was carried out to evaluate the

major chemical features of floodplain soils along the Brazilian Solimões-Amazonas rivers channel, as well as, the effects of different land-use systems on soil nutrient supplies.

MATERIALS AND METHODS

Localization and characterization of study sites

The study involved sampling soil under different land-use systems in floodplain areas along the Solimões and Amazonas River's main channel, between the coordinates 04° 21' to 01° 29' S; 69° 45' to 51° 58' W, based on the identification of a set of 62 different land-use systems. These systems were then sampled in 15 communities located in three regions along with the Solimões/Amazon River floodplain complex as follows: 16 systems in the Upper and Middle Solimões, 17 in the Lower Solimões and Middle Amazon, and 29 in Lower Amazon (Figure 1). The soils of sampled regions are predominantly *Gleissolos* and *Neossolos Flúvicos* (Sombroek, 1984), according to the Brazilian soil classification system (Santos et al., 2018).

Sampling areas were chosen based on responses to a questionnaire applied to randomly selected farmers in the communities studied. Responses such as: temporal aspects of the land-use systems (for example, short cycle crops vs. fallows under secondary vegetation, native forest, and swamp areas), as well as the landscape units existing on their property, such as a high floodplain, low floodplain, pasture, and flooded forest, were taken into consideration to orient the sampling soil procedures.

Three regions encompassed examples of all the land-use systems representing the study area. The main characteristics of the five sampled systems are described in table 1. Agriculture areas were separated into agriculture in the low floodplain (LF) and high floodplain (HF). Pasture areas were restricted to the region of Lower Amazon, where livestock ranching is an ancient and widespread activity, as part of the productive systems



Figure 1. Location of the 15 communities sampled in the three regions along the Solimões/Amazon River. Upper and Middle Solimões (1, 2, 3, 4, and 5), Lower Solimões and Middle Amazon, (6, 7, 8, and 9), Lower Amazon (10, 11, 12, 13, 14, and 15).

Table 1. Main characteristics of the five land-use systems studied in three regions along in the Solimões/Amazon River basin

Land-use system	Description
Low floodplain agriculture	Areas with single or associated annual crops such as corn, cassava, bean, watermelon; semi-perennial crops (banana), intercropped annual crops, in addition to fiber crops such as malva (<i>Urena lobata</i> L. - Malvaceae) and jute (<i>Corchorus capsularis</i>) and grass crops such as a Venezuela grass (<i>Paspalum fasciculatum</i>) and Canarana grass (<i>Echinochloa polystachya</i>).
High floodplain agriculture	Field more than 20 years old, with the planting of <i>Brachiaria</i> and "imperial" grass (<i>Axonopus scoparius</i>).
Pasture	With age ranging from 50 to 70 years old, comprised of species such as diverse fruit plants, cacao (<i>Theobroma cacao</i>), rubber (<i>Hevea brasiliensis</i>), açai palm (<i>Euterpe precatoria</i>), banana (<i>Musa</i> spp.), among many others.
Homegarden	Systems composed of primary forests and secondary forests with age from 5 to 55 years old.
Forest	

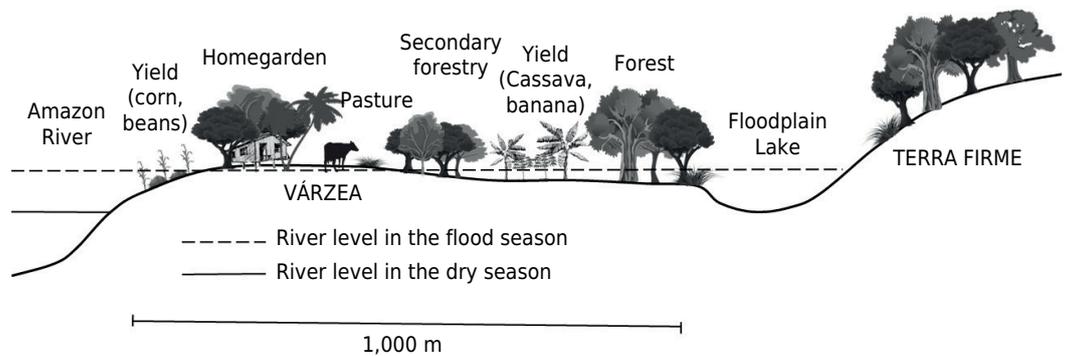


Figure 2. Spatial distribution of agricultural activities on the floodplain of the Solimões/Amazon channel.

of small producers (Folhes, 2018). Figure 2 presents a typical spatial distribution of the agricultural activities of the floodplain areas sampled.

Soil sampling and laboratory methods

In the center of each experimental unit (land-use system), a sampling plot of 45 × 30 m was installed, which was subdivided into three sub-plots (15 × 30 m). Six soil samples from each sub-plot were collected from the 0.00-0.10, 0.10-0.20 and 0.20-0.40 m layers; these samples were mixed to form sub-plot composites and analyzed separately, then averaged to represent the unit. Soil samples were air-dried, sieved through a 2 mm mesh, and taken to INPA's Soil and Plants Laboratory, where they were analyzed according to the methodology used by Donagemma et al. (2011). Soil pH was measured in water at a ratio of 1:2.5. The cations Ca^{2+} , Mg^{2+} , and Al^{3+} were extracted using KCl 1 mol L^{-1} , and their concentration was measured using atomic absorption spectrophotometry. The double acid extraction system (H_2SO_4 0.0125 mol L^{-1} + HCl 0.05 mol L^{-1}) was used to extract available P and K. Phosphorus levels were determined by spectrophotometry using ammonium molybdate. Total N and organic C contents were obtained using the self-analyzer for C, H, and N from Carlo Erba manufacturer.

Data analyses

For each soil depth, within each region, one-way analyses of variance were done for the different soil attributes, where the land-use systems were considered treatments.

Sampling points in three regions were distributed as follows: 22 in LF Agriculture, 13 in HF Agriculture, 15 in Forest, 7 in Homegarden, and 5 in Pasture. Statistical significance was determined by analysis of variance with Duncan's test at 5 % probability.

Discriminant analysis using the quadratic method was performed to verify the effectiveness of the soil characteristics in differentiating the three regions. For this purpose, the average of each chemical parameter was estimated for each 62 systems considering all soil depths. The analyses were performed with SAS 9.4 and JMP 14 software.

RESULTS

Table 2 presents the soil chemical attributes in the land-use systems sampled in the three regions studied. To evaluate soil fertility and the availability of nutrients for plants, we used the criteria established by Cochrane et al. (1985) for tropical soils.

Acidity, exchangeable Al, Ca, Mg, K, available P and total N

Soil pH in the three regions ranged between values considered low (<5.3) to medium (5.3 to 7.3). The lowest pH values were observed in soil samples from the flooded forest area. In all land-use systems, an increasing tendency in the pH with soil depth was noticed. In the Lower Solimões River/Middle Amazon River and Lower Amazon River regions, exchangeable Al ranged from low (<0.5 cmol_c kg⁻¹) to high (>1.5 cmol_c kg⁻¹), with areas under forest showing the significantly highest levels for this element. On the other hand, Upper and Middle Solimões River region had a very low concentration in all soil samples, ranging from 0.05 to 0.69 cmol_c kg⁻¹, without any land use effect.

All sampled areas had exchangeable Ca at a level considered high (>4.0 cmol_c kg⁻¹), ranging from 7.6 to 14.8 cmol_c kg⁻¹. Concentrations significant of Ca²⁺ were observed

Table 2. Mean value of pH and contents of aluminum (Al), calcium (Ca), magnesium (Mg), potassium (K), phosphorus (P), and total nitrogen (N) at three soil layers (0.00-0.10, 0.10-0.20, and 0.20-0.40 m) under different land-use systems in three regions along in the Solimões/Amazon River basin

Land use	pH(H ₂ O)			Al ³⁺			Ca ²⁺			Mg ²⁺			K ⁺			P			Total N		
	⁽³⁾ 0.10	⁽⁴⁾ 0.20	⁽⁵⁾ 0.40	0.10	0.20	0.40	0.10	0.20	0.40	0.10	0.20	0.40	0.10	0.20	0.40	0.10	0.20	0.40	0.10	0.20	0.40
cmol _c kg ⁻¹																					
mg kg ⁻¹																					
g kg ⁻¹																					
Upper and Middle Solimões River																					
⁽¹⁾ LF Agriculture	5.58ab	5.69a	6.13ab	0.18a	0.22a	0.20a	12.6a	12.0a	12.1a	3.2a	3.1a	3.5a	0.45a	0.30a	0.25a	129a	126ab	143ab	1.21a	0.88a	0.68a
⁽²⁾ HF Agriculture	5.57ab	6.28a	6.49a	0.57a	0.34a	0.35a	11.3a	10.1a	10.2a	2.7a	2.8a	2.9a	0.34a	0.24a	0.24a	165a	182a	180a	1.22a	0.66b	0.57a
Homegarden	6.10a	6.22a	6.20ab	0.05a	0.07a	0.05a	13.2a	11.9a	12.2a	4.0a	3.6a	3.5a	0.44a	0.27a	0.23a	190a	184a	182a	1.43a	0.82ab	0.75a
Forest	4.98b	5.47a	5.76b	0.69a	0.30a	0.26a	14.8a	13.7a	14.1a	4.5a	5.2a	5.7a	0.32a	0.29a	0.28a	87a	88b	101b	1.62a	0.94a	0.75a
Lower Solimões River/Middle Amazon River																					
LF Agriculture	5.30bc	5.64b	6.07a	0.37b	0.20b	0.16b	9.5a	9.6a	9.0ab	2.8a	2.9b	2.3b	0.54b	0.40a	0.31a	83b	91a	111a	0.84b	0.59b	0.57ab
HF Agriculture	6.63a	5.68ab	5.82a	0.02b	0.13b	0.11b	10.3a	12.1a	10.5ab	3.1a	2.6b	2.9b	0.98a	0.44a	0.31a	146a	105a	92a	0.96b	0.47b	0.39b
Homegarden	5.86b	6.03a	6.06a	0.04b	0.19b	0.10b	8.5a	7.7a	7.6b	2.6a	2.5b	2.5b	0.34b	0.30a	0.29a	141a	114a	125a	0.78b	0.39b	0.23b
Forest	4.75c	5.05c	5.28b	2.64a	1.74a	1.42a	10.9a	11.4a	12.4a	4.2a	4.9a	4.9a	0.52b	0.49a	0.43a	32c	28b	35b	1.75a	1.01a	0.79a
Lower Amazon River																					
LF Agriculture	5.46a	5.64a	6.01a	0.28b	0.22b	0.13b	10.6a	10.3a	10.8a	2.9a	2.7b	3.0b	0.50a	0.31a	0.29a	105a	109a	115a	1.01b	0.73ab	0.62ab
HF Agriculture	5.78a	5.98a	6.16a	0.20b	0.18b	0.17b	10.3a	9.6a	9.8a	2.9a	2.8b	2.9b	0.51a	0.37a	0.33a	115a	129a	128a	1.03b	0.68b	0.59ab
Pasture	5.52a	5.87a	6.37a	0.22b	0.01b	0.03b	8.57a	8.7a	9.1a	2.7a	2.6b	2.8b	0.40ab	0.33a	0.30a	99ab	103a	94ab	0.91b	0.62b	0.48b
Homegarden	5.80a	5.96a	6.16a	0.21b	0.18b	0.09b	9.85a	9.6a	9.9a	3.1a	3.1ab	3.1b	0.39ab	0.26a	0.21a	139a	130a	124a	1.23ab	0.73ab	0.59ab
Forest	4.80b	5.17b	5.49b	2.42a	2.18a	2.00a	10.2a	9.7a	10.8a	3.6a	4.3a	4.9a	0.28b	0.26a	0.22a	53b	48b	48b	1.50a	0.92a	0.69a

Average values within the same column, for the same region, followed by different letters differ significantly at p<0.05 for Duncan's test.

⁽¹⁾ LF: agriculture in low floodplain. ⁽²⁾ HF: high floodplain. ⁽³⁾ 0.00 - 0.10 m. ⁽⁴⁾ 0.10 - 0.20 m. ⁽⁵⁾ 0.20 - 0.40 m.

in Lower Solimões River/Middle Amazon River, only in 0.20-0.40 m layer in Forest when compared to Homegarden area. With regard to exchangeable Mg, values were also above the level considered high ($>0.8 \text{ cmol}_c \text{ kg}^{-1}$), ranging from 2.3 to $5.7 \text{ cmol}_c \text{ kg}^{-1}$, with significantly higher contents in soils from Forest area, in the regions Lower Solimões River/Middle Amazon River and Lower Amazon River.

Potassium presented concentrations between medium (0.15 to $0.3 \text{ cmol}_c \text{ kg}^{-1}$) to high ($>0.30 \text{ cmol}_c \text{ kg}^{-1}$), ranged from 0.21 to $0.98 \text{ cmol}_c \text{ kg}^{-1}$. The highest value of this nutrient was obtained in the superficial layer of the soil, in Agriculture areas located in the Lower Solimões River/Middle Amazon River and Lower Amazon River regions. Phosphorus values were considered high ($>7 \text{ mg kg}^{-1}$), in all sampled land-use systems, ranging from 28 to 190 mg kg^{-1} . In general, the P concentration in Forests areas was significantly lower than observed in cultivated areas. Total N content varied from 0.23 to 1.75 g kg^{-1} . In general, in the three evaluated soil layers, the N levels were significantly higher in the forest than in cultivated areas.

Organic carbon

In the three sampled regions the organic C content varied from medium in the surface layer (8.7 to 26 g kg^{-1}) to low ($<8.7 \text{ g kg}^{-1}$) in the subsurface layers, with significantly higher contents in Forest systems in the surface layer (Figure 3).

Micronutrients (Cu, Zn, Mn and Fe)

The levels of four micronutrients analyzed were considered high in all land-use systems studied. Significant differences were only observed in the topsoil for Zn in the Upper and Middle Solimões River regions and Cu in the Lower Solimões/Middle Amazon and Lower Amazon regions. Zinc was significantly higher in Homegarden than LF agriculture while Cu was higher in forest areas than HF agriculture and grazing systems (Table 3).

Spatial variation in chemical characteristics of soils along the Solimões/Amazonas river channel

Figure 4 shows the chemical characteristics of the soil in the three regions sampled along the Solimões/Amazon channel trough, not considering land-use systems or soil

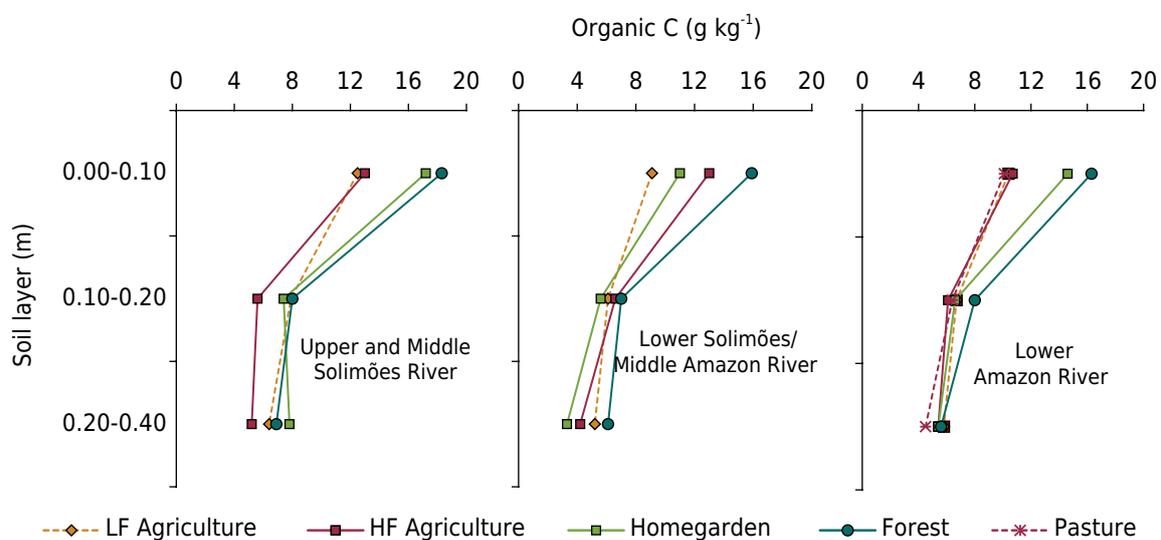


Figure 3. Mean value of organic carbon at three soil layers under different land-use systems in three regions along the Solimões/Amazon River basin.

depth. In general, Ca^{2+} , Mg^{2+} , P, N, and organic C concentrations declined significantly downstream. The pH value did not vary significantly, and the concentration of aluminum showed the opposite trend, increasing significantly downstream.

DISCUSSION

Acidity and exchangeable aluminum

Despite their excellent soil base status, within the three surveyed regions of the Solimões/Amazon floodplain complex, pH values ranged from low to medium. The high terraces of the floodplain showed a tendency to have higher pH than the lower terraces. For the most part, pH values in cultivated areas were higher than those observed in forests areas, suggesting that one of the factors for raising the pH in cultivated systems is the process of burning vegetation through the action of ash. On the other hand, in forest environments, the process of decomposition organic matter can cause natural acidification of soils (Silva Junior et al., 2012). Similar results were reported by Oliveira et al. (2000) in floodplain areas of Central Amazonia.

Within the three studied regions, the Al^{3+} contents were considered very low for the cultivated areas, and significantly higher in forest areas. Fajardo et al. (2009) observed a sharp reduction in the Al^{3+} levels in floodplain soil one month after slashing and burning of 8-year-old secondary forest for establishing a cultivated field (from 2.59 to 0.43 $\text{cmol}_c \text{kg}^{-1}$). In slash-and-burn agriculture, pH increases and the Al^{3+} content decreases after burning due to the reaction of CaCO_3 and CaO produced by the combustion of organic matter to neutralize Al^{3+} (Juo and Manu, 1996). Over time, nutrients are depleted, and these attributes tend to return to their previous state.

Table 3. Mean contents of zinc (Zn), copper (Cu), manganese (Mn), and iron (Fe) at three soil layers (0.00-0.10, 0.10-0.20, and 0.20-0.40 m) under different land-use systems in three regions along in the Solimões/Amazon River channel

Land-use	Zn			Cu			Mn			Fe		
	0.00-0.10	0.10-0.20	0.20-0.40	0.00-0.10	0.10-0.20	0.20-0.40	0.00-0.10	0.10-0.20	0.20-0.40	0.00-0.10	0.10-0.20	0.20-0.40
mg kg ⁻¹												
<i>Upper and Medium Solimões River region</i>												
LF Agriculture ⁽¹⁾	7.67b	7.26a	6.79a	8.50a	8.49a	7.24a	185a	153a	147a	685 a	624 a	474 a
HF Agriculture ⁽²⁾	8.77ab	7.31a	7.32a	5.10a	4.86a	4.76a	164a	144a	143a	733 a	602 a	575 a
Homegarden	13.31a	11.13a	8.32a	7.77a	7.15a	7.15a	231a	146a	146a	496 a	475 a	464 a
Forest	9.76ab	9.34a	8.62a	11.45a	9.00a	8.73a	195a	157a	148a	926 a	771 a	656 a
<i>Lower Solimões River/Medium Amazon River region</i>												
LF Agriculture (n=5)	8.78a	9.58a	6.84a	5.79ab	4.85a	4.16a	203a	152a	164a	1032 a	751 a	643 a
HF Agriculture (n=4)	11.0a	9.13a	8.52a	4.02b	4.50a	4.39a	217a	133a	121a	715 a	889 a	844 a
Homegarden	8.10a	7.49a	6.19a	4.42ab	4.39a	3.93a	164a	104a	79a 120.96	633 a	589 a	513 a
Forest	9.55a	8.34a	6.88a	8.05a	6.71a	6.40a	153a	134a	156a	1267 a	1070 a	985 a
<i>Lower Amazon River region</i>												
LF Agriculture (n=5)	8.25a	7.82a	7.44a	5.98ab	5.68a	5.24a	158a	141a	146a	783 a	687 a	595 a
HF Agriculture (n=4)	8.70a	7.85a	7.55a	4.18b	4.18a	7.81a	178a	153a	146a	883 a	775 a	726 a
Pasture	8.47a	8.37a	7.55a	4.17b	4.07a	3.65a	135a	127a	128a	782 a	640 a	591 a
Homegarden	10.50a	8.86a	6.80a	5.91ab	5.47a	5.08a	173a	134a	114a	761 a	722 a	596 a
Forest	9.89a	8.61a	6.85a	8.09a	6.69a	5.57a	150a	132a	104a	1030 a	871 a	532 a

Average values within the same column, for the same region, followed by different letters differ significantly at $p < 0.05$ for Duncan's test.

⁽¹⁾ LF: agriculture in the low floodplain. ⁽²⁾ HF: high floodplain.

Macronutrients (calcium, magnesium, potassium, and phosphorus)

Results showed that along the Solimões-Amazon River, Ca^{2+} and Mg^{2+} were above a level considered high. They are not limiting nutrients in those floodplain soils, confirming observations by other authors (Oliveira et al., 2000; Cravo et al., 2002; Magalhães and Gomes, 2013; Teixeira et al., 2019; Junk, 2020). In general, Ca^{2+} is the predominant cation in the floodplain exchange complex, followed by Mg^{2+} . Exchangeable Ca predominates due, in part, to the selective weathering of dolomite and calcite deposits in the Andean headwater region (Sombroek, 1984; Victoria et al., 1989). Also, the expressive contents of these nutrients can be attributed to the recent nature of the mineral constituents and the high chemical activity of the clay fraction in these soils (Sombroek, 1984; Horbe et al., 2007; Guimarães et al., 2013, Magalhães and Gomes, 2013). The clays are derived from the Andean region and are montmorillonitic-ilitic and abundant in mineral elements essential for plant growth (Sombroek, 1984). Consequently, they show the highest value for the exchangeable base and the lowest value for Al^{3+} saturation.

The data showed that within the same community, only small variations for these two nutrients were observed, even under different land-use systems. The results in figure 4 showed that the contents of these nutrients decreased downstream. Similar to what was observed by Victoria et al. (1989). These authors suggest that the downstream decline in Ca^{2+} and Mg^{2+} concentrations in floodplain soils may be due to a change in the chemical composition of the river sediments.

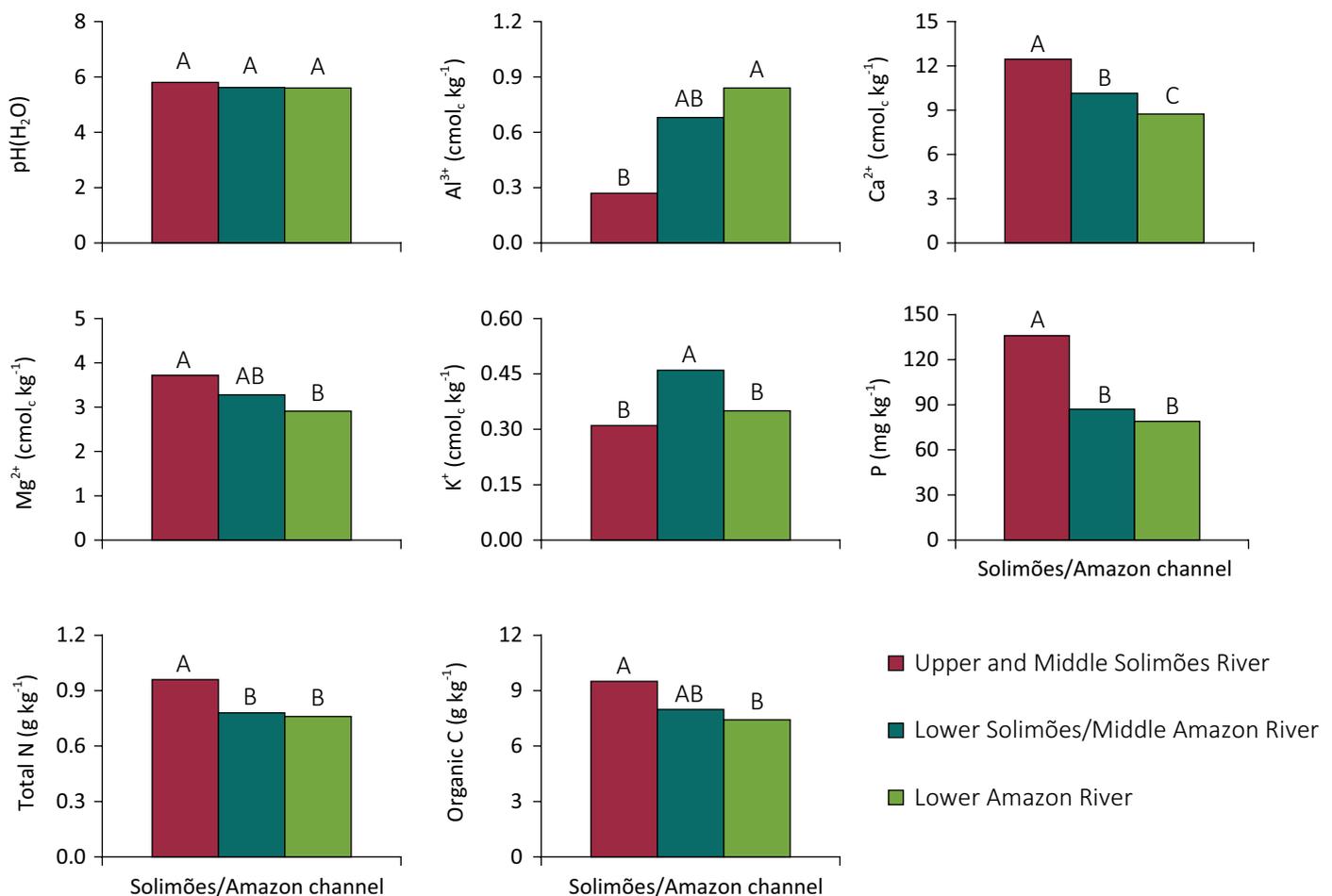


Figure 4. Spatial variation in the value of pH and concentration of Al^{3+} , Ca^{2+} , Mg^{2+} , K^+ , P, total N, and organic C of soil in three regions along the Solimões/Amazon River basin.

Although the majority of the samples analyzed had high levels of K^+ , in a few cases in the Upper and Middle Solimões River and Lower Amazon River, the level of this nutrient can become limiting to crop production (Fajardo et al., 2009). Low K values have been reported by other authors in floodplain soils (Victoria et al., 1989; Alfaia and Falcão, 1993). Lopes et al. (2006) observed that agricultural use considerably decreased the contents of K^+ to a depth of 0.30 m in the floodplain soils along the Guamá River in Pará State.

High levels of K^+ may be related to the presence of type 2:1 clays, such as illite and muscovite, in floodplain soils (Horbe et al., 2007). According to Junk (2020), the availability of K^+ in the floodplain is underestimated, because much of the non-exchangeable K^+ is stored in minerals such as illite, and can be available by plants. Unlike the other cations, the K^+ concentration along the Solimões/Amazonas channel was significantly higher in the Lower Solimões/Middle Amazon region (Figure 4), probably due to the input of the Rio Madeira, which tends to be rich in K^+ , as also observed by Victoria et al. (1989).

In the vast majority of samples, the P contents was far above the level considered high, showing a greater availability of this nutrient in floodplain soils. The highest P contents were observed in the Upper and Medium Solimões River regions. These results did not differ from other studies that also recorded high values of P in floodplain soils (Lima et al., 2006; Magalhães and Gomes, 2013; Guimarães et al., 2013), and contrast with the low values of P observed in soils in the most weathered and deep *terra firme* (unflooded) soils of the Brazilian Amazon, where 96 % are deficient in P (Sanchez and Salinas, 1981). Results of a study by Moreira and Fageria (2009) show that 83 % of the soils in Amazonas State have P contents less than 5.4 mg kg^{-1} .

Micronutrients (Cu, Zn, Mn e Fe)

The high levels of four micronutrients analyzed, for all land-use systems studied and depths, are in line with other studies (Oliveira et al., 2000; Fajardo et al., 2009; Magalhães and Gomes, 2013), demonstrating that these are not a limiting in floodplain soils. Mn and Fe, in these soils can be classified as rich to very rich, compared to temperate soils (Junk, 2020). There was not significantly difference for Mn and Fe levels in the five systems of land-use studied (Table 2). In contrast, forest soils were richer in Cu (Lower Solimões/Middle Amazon River and Lower Amazon River) and homengarden soils were richer in Zn (Upper and Middle Solimões River). This enrichment of these soils in micronutrients may be associated with the presence of clay minerals, which show to concentrate significant quantities of trace metals (Konhauser et al., 1994).

Total N and organic carbon

Low levels found in most of the samples analyzed confirm that this element may be the main limiting nutrient for agriculture, as has been observed by other authors (Melgar et al., 1992; Kern and Darwich, 1997; Teixeira et al., 2019; Junk, 2020). Studies carried out with Solimões River floodplain soils showed N deficiencies when under cultivation for consecutive years without flooding of the area (Cravo et al., 2002). Small-scale farmers generally do not use chemical fertilizers as N source for their crops, relying only on the breakdown of soil organic matter as the natural source for N. In order to restore soil fertility, many floodplain farmers use the practice of cutting and burning of forest areas, for planting short cycle crops such as corn and cassava, followed by a fallow period (Zarim et al., 1998; Fajardo et al., 2009). Despite the reduction in N amounts with the slash and burn system (Ewel et al., 1981), this practice can supply N for crops, considering the deficiency of this nutrient in the floodplain environment.

In the various land-use systems, C organic contents were very low in the cultivated areas and significantly higher in Forest areas (Table 1). In general, floodplain soils in the Amazon present low levels of organic C, because the decomposition process occurs more slowly during a period of the year, due to seasonal floods (Nascimento et al.,

2019; Teixeira et al., 2019). Organic residue decomposition usually occurs at lower rates in restricted drainage soils than in aerated soils (Neue et al., 1997; Nascimento et al., 2009). The C/N ratio is about twice as high in Oxisols than in floodplain soils due to a more advanced process of humidifying organic matter in Oxisols (Teixeira et al., 2019). On the other hand, many factors, including soil texture, drainage, nutrient content, pH, and the quantity and quality of plant residues determine the processes of soil organic matter accumulation and decomposition (Marques et al., 2015). These factors need to be better evaluated under the conditions of the Amazonian floodplain environment.

In many Agriculture systems in the Lower Amazon River region, the use of fallows with Venezuela grass (*Paspalum fasciculatum*), and Canarana grass (*Echinochloa polystachya*) to restore the soil fertility was observed. Many of these plants undergo a seasonal growth cycle with high production levels (*Paspalum fasciculatum* attains biomass value of 40 t ha⁻¹ of dry weight after a growth period of 8 months), followed by rapid decomposition (Junk, 1984). Large quantities of nutrients are presumably taken up from floodplain soils during the growth period and then returned when the plants decompose (Victoria et al., 1989). Other plants, such as aquatic macrophytes, also play an important role in transferring nutrients from the aquatic to the terrestrial phase (Junk, 1984). They can be considered natural fertilizer for terrestrial vegetation. This effect was demonstrated in Central Amazonia by Noda et al. (1978), who carried out successful experiments using aquatic macrophytes as a fertilizer for wing beans.

In addition to N cycling through the practice of fallow, as well as that found in grasses and aquatic macrophytes, the floodplain soils also have an N input through the presence of legumes, which naturally occur in the Amazon floodplain environments. Kreibich et al. (2003) observed that mineral N flow into the soil, especially at 0.00-0.20 m layer, was increased next to leguminous species compared to non-leguminous, thus indicating the importance of leguminous species in fixing this nutrient in floodplain soils areas. However, the intentional use of legumes as green manures was not seen in any of the land-use systems studied, indicating a lack of knowledge on the part of smallholders about the potential benefits of these plants to the soil. In a preliminary study, Ayres et al. (2018) observed a positive effect of green manure on lettuce production in floodplain soils in the Manaus region. Nevertheless, introducing such plants as components in crop production systems also involves a series of considerations as to the additional labor required.

CONCLUSIONS

In all studied land-use systems, high contents of Ca²⁺, Mg²⁺ and P in soil samples were observed, confirming the high availability of these elements in floodplain ecosystems, while K⁺ in some areas may be deficient. In the large majority of land-use systems studied, N and organic C levels were considered low. Although the soil under forest areas showed high fertility, these environments also had an elevated acidity, as well as high levels of exchangeable Al, unlike the other land-use systems, which showed low acidity and low levels for exchangeable Al. The Solimões/Amazon channel samples showed a significant decrease in Ca²⁺, Mg²⁺, P, N and organic C contents downstream.

ACKNOWLEDGMENTS

This research was funded by United Nations Development Program-UNDP through the Provarzea Project; Amazonas State Research Support Foundation - FAPEAM, Resolution Number 008/2021 - POSGRAD 2021/FAPEAM and Coordination for the Improvement of Higher Education Personnel (CAPES), Process Number 88881.510219/2020-01, AUXPE Number 798/2020.

AUTHOR CONTRIBUTIONS

- Conceptualization:**  Katell Uguen (equal) and  Sonia Sena Alfaia (lead).
- Data curation:**  Sonia Sena Alfaia (equal).
- Formal analysis:**  Acácia Lima Neves (equal),  Alexandre Pereira Bakker (equal),  César Augusto Ticona-Benavente (equal),  Juan Daniel Villacis Fajardo (equal) and  Marta Iria da Costa Ayres (supporting).
- Investigation:**  Acácia Lima Neves (equal),  Juan Daniel Villacis Fajardo (equal),  Marta Iria da Costa Ayres (equal) and  Sonia Sena Alfaia (equal).
- Methodology:**  Acácia Lima Neves (equal),  Juan Daniel Villacis Fajardo (equal),  Robert Pritchard Miller (equal) and  Sonia Sena Alfaia (equal).
- Resources:**  Sonia Sena Alfaia (supporting).
- Software:**  Alexandre Pereira Bakker (equal) and  César Augusto Ticona-Benavente (equal).
- Supervision:**  Sonia Sena Alfaia (lead).
- Validation:**  Acácia Lima Neves (equal),  Alexandre Pereira Bakker (equal),  César Augusto Ticona-Benavente (equal) and  Marta Iria da Costa Ayres (supporting).
- Writing - original draft:**  César Augusto Ticona-Benavente (equal),  Juan Daniel Villacis Fajardo (equal),  Alexandre Pereira Bakker (equal),  Robert Pritchard Miller (equal) and  Sonia Sena Alfaia (equal).
- Writing - review & editing:**  Alexandre Pereira Bakker (equal),  César Augusto Ticona-Benavente (equal) and  Robert Pritchard Miller (lead).

REFERENCES

- Alfaia SS, Falcão NP. Estudo da dinâmica de nutrientes em solos de várzea da Ilha do Careiro no Estado do Amazonas. *Amazoniana*. 1993;12:485-93.
- Ayres MIC, Rodrigues Filha ZR, Mota MA, Alfaia SS. Efeito da adubação verde no suprimento de nitrogênio para produção de alface em Gleissolo da Amazônia Central. In: Souza LAG, Silva Filho DF, Ticona-Benavente CA, Noda H, editors. *Ciência e tecnologia aplicada aos agroecossistemas da Amazônia Central*. Manaus: Editora do Inpa; 2018. p. 175-86. Available from: <https://repositorio.inpa.gov.br/handle/1/35625>
- Cochrane TT, Sanchez LG, Azevedo LG, Porras JA, Garver CL. *Land in Tropical America*. Cali: Centro Internacional de Agricultura Tropical, Embrapa CPAC; 1985 [cited 2020 Dec 16]. Available from: <https://www.embrapa.br/busca-de-publicacoes/-/publicacao/549413/land-in-tropical-america>.
- Cravo MS, Xavier JJBN, Dias MC, Barreto JF. Características, uso agrícola atual e potencial das várzeas no Estado do Amazonas, Brasil. *Acta Amazon*. 2002;32:351-66. <https://doi.org/10.1590/1809-43922002323365>
- Donagemma GK, Campos DVB, Calderano SB, Teixeira WG, Viana JHM. *Manual de métodos de análise do solo*. 2. ed. rev. Rio de Janeiro: Embrapa Solos; 2011.
- Ewel J, Berish C, Brown B, Price N, Raich J. Slash and burn impacts on a Costa Rican wet forest site. *Ecology*. 1981;62:816-29. <https://doi.org/10.2307/1937748>
- Fajardo JDV, Souza LAG, Alfaia SS. Características químicas de solos de várzeas sob diferentes sistemas de uso da terra, na calha dos rios Baixo Solimões e Médio Amazonas. *Acta Amazon*. 2009;39:731-40. <https://doi.org/10.1590/S0044-59672009000400001>

- Folhes RT. A gênese da transumância no Baixo Rio Amazonas: Arranjos fundiários, relações de poder e mobilidade entre ecossistemas. *Bol Goia Geogr.* 2018;38:138-58. <https://doi.org/10.5216/bgg.v38i1.52818>
- Furch K. Chemistry of Várzea and Igapó soils and nutrient inventory of their floodplains forests. In: Junk WJ, editor. *The Central Amazon floodplain - Ecological studies (analysis and synthesis)*. Berlin: Springer; 1997. p. 47-67. https://doi.org/10.1007/978-3-662-03416-3_3
- Guimarães ST, Lima HN, Teixeira WG, Neves Junior AF, Silva FWR, Macedo RS, Souza KW. Caracterização e classificação de Gleissolos da várzea do Rio Solimões (Manacapuru e Iranduba), Amazonas, Brasil. *Rev Bras Cienc Solo.* 2013;37:317-26. <https://doi.org/10.1590/S0100-06832013000200003>
- Horbe AMC, Paiva MRP, Motta MB, Horbe MA. Mineralogy and geochemistry of neogene and quaternary sediment profiles from the Solimões basin in the region of Coari, Amazonas. *Acta Amazon.* 2007;37:81-9. <https://doi.org/10.1590/S0044-59672007000100009>
- Junk WJ. Condições físico-químicas dos solos na várzea da Amazônia Central. In: Junk WJ, Ohly J, Piedade MTF, Wittmann F, Schöngart J, editors. *Várzeas Amazônicas: Desafios para um manejo sustentável*. Manaus: Editora do Inpa; 2020. p. 78-86. Available from: https://repositorio.inpa.gov.br/bitstream/1/36480/3/manejo_sustent%c3%a1vel_das_varzeas.pdf.
- Junk WJ. Ecology of the varzea floodplain of Amazonian whitewater rivers. In: Sioli H, editor. *The Amazon: Limnology and landscape ecology of a mighty tropical river and its basin*. Dordrecht: Kluwer Academic Publishers; 1984. p. 215-43.
- Juo A, Manu A. Chemical dynamics in slash-and-burn agriculture. *Agr Ecosyst Environ.* 1996;58:49-60. [https://doi.org/10.1016/0167-8809\(95\)00656-7](https://doi.org/10.1016/0167-8809(95)00656-7)
- Kern J, Darwich A. Nitrogen Turnover in the Várzea. In: Junk WJ, editor. *The Central Amazon floodplain - Ecological studies (analysis and synthesis)*. Berlin: Springer; 1997. p. 119-35. https://doi.org/10.1007/978-3-662-03416-3_6
- Konhauser KO, Fyfe WS, Kronberg BI. Multi-element chemistry of some Amazonian waters and soils. *Chem Geol.* 1994;111:155-75. [https://doi.org/10.1016/0009-2541\(94\)90088-4](https://doi.org/10.1016/0009-2541(94)90088-4)
- Kreibich H, Lehmann J, Scheufele G, Kern J. Nitrogen availability and leaching during the terrestrial phase in a várzea forest of the Central Amazon floodplain. *Biol Fert Soils.* 2003;39:62-4. <https://doi.org/10.1007/s00374-003-0670-x>
- Lima HN, Mello JWV, Schaefer CEGR, Ker JC, Lima AMN. Mineralogia e química de três solos de uma topossequência da bacia sedimentar do Alto Solimões, Amazônia Ocidental. *Rev Bras Cienc Solo.* 2006;30:59-68. <https://doi.org/10.1590/S0100-06832006000100007>
- Lopes NLE, Fernandes RA, Grimaldi C, Ruivo PLM, Rodrigues ET, Sarrazin M. Características químicas de um Gleissolo sob diferentes sistemas de uso, nas margens do rio Guamá. *Bol Mus Para Emílio Goeldi Cienc Nat.* 2006;1:127-37.
- Magalhães RC, Gomes RCM. Mineralogy and chemistry of the lowland soil and its sensibilities in the process of lands falls in community Divino Espírito Santo (Amazonas, Brazil). *Soc Nat.* 2013;25:609-21. <https://doi.org/10.1590/S1982-45132013000300013>
- Melgar RJ, Smyth TJ, Sanchez PA, Cravo MS. Fertilizer nitrogen movement in a Central Amazon Oxisol and Entisol cropped to corn. *Fert Res.* 1992;31:241-52. <https://doi.org/10.1007/BF01063298>
- Moreira A, Fageria NK. Soil chemical attributes of Amazonas State, Brazil. *Commun Soil Sci Plant.* 2009;40:2912-25. <https://doi.org/10.1080/00103620903175371>
- Nascimento PC, Bayer C, Silva Neto LF, Vian AC, Vieiro F, Macedo VRM, Marcolin E. Sistema de manejo e a material orgânica do solo de várzea com cultivo de arroz. *Rev Bras Cienc Solo.* 2009;33:1821-7. <https://doi.org/10.1590/S0100-06832009000600030>
- Nascimento WB, Campos MCC, Mantovanelli BC, Santos LAC, Cunha JCL, Lourenço IH, Oliveira FP. Physical and chemical properties of soils in different physiographic environments in the Southern Amazonas region. *Biosci J.* 2019;35:1099-109. <https://doi.org/10.14393/BJ-v35n4a2019-42153>

- Neue HU, Gaunt JL, Wang ZP, Becker-Heidmann P, Quijano C. Carbon in tropical wetlands. *Geoderma*. 1997;79:163-85. [https://doi.org/10.1016/S0016-7061\(97\)00041-4](https://doi.org/10.1016/S0016-7061(97)00041-4)
- Noda H, Junk WJ, Pahlen A. Emprego de macrófitas aquáticas (“Matupá”) como fonte de matéria orgânica na cultura do feijão de asa (*Psophocarpus tetragonolobus*), em Manaus. *Acta Amazon*. 1978;8:107-9.
- Oliveira LA, Moreira FW, Falcão NP, Pinto VSG. Floodplain soils of Central Amazonia: Chemical and physical characteristics and agricultural sustainability. In: Junk WJ, Ohly J, Piedade MTF, Soares MGM, editors. *The Central Amazon floodplain: Actual use and options for a sustainable management*. Leiden: Backhuys Publishers; 2000. p. 129-40.
- Santos HG, Jacomine PKT, Anjos LHC, Oliveira VA, Lumbreras JF, Coelho MR, Almeida JA, Araújo Filho JC, Oliveira JB, Cunha TJF. *Sistema Brasileiro de Classificação de Solos*, 5. ed. Brasília: Embrapa; 2018.
- Sanchez PA, Salinas JG. Low-input management technology for managing Oxisols and Ultisols in tropical America. *Adv Agron*. 1981;34:279-406. [https://doi.org/10.1016/S0065-2113\(08\)60889-5](https://doi.org/10.1016/S0065-2113(08)60889-5)
- Silva Junior CA, Boechat CL, Carvalho LA. Atributos químicos do solo sob conversão de floresta Amazônica para diferentes sistemas na região norte do Pará, Brasil. *Biosci J*. 2012;28:566-72.
- Sombroek WG. Soils of the Amazon region. In: Sioli H, editor. *The Amazon: Limnology and landscape ecology of a mighty tropical river and its basin*. Dordrecht: Kluwer Academic Publishers; 1984. p. 521-35.
- Teixeira WG, Lima HN, Pinto WHA, Souza KW, Shinzato E, Schroth G. O manejo dos solos nas várzeas Amazônicas. In: Bertol I, Maria IC, Souza LS, editors. *Manejo e conservação do solo e da água*. Viçosa, MG: Sociedade Brasileira de Ciência do Solo; 2019. p. 701-28.
- Victoria RL, Martinelli LA, Richey JE, Forsberg BR. Spatial and temporal variations in soil chemistry on the Amazon Floodplain. *Geojournal*. 1989;19:45-52. <https://doi.org/10.1007/BF00620548>
- Zarim DJ, Duchesne AL, Hiraoka M. Shifting cultivation on the tidal floodplains of Amazonia: impacts on soil nutrient status. *Agrofor Syst*. 1998;41:307-11. <https://doi.org/10.1023/A:1006072421536>