

Division - Soil in Space and Time | Commission - Pedometrics

Soil classes and properties explain the occurrence and fruit production of Brazil nut

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ABSTRACT: Soil properties and classes can influence the occurrence of plants and the production of Brazil nut fruits and may have a different distribution between sites. This study aimed to evaluate the relationship of plants' occurrence, production of Brazil nut fruits, and spatial variability of the properties in different soil classes in two Brazil nut stand in the state of Acre, Brazil. The study was conducted in two plots in two native Brazil nut stand, Cachoeira (CP01 and CP02 - plots 1 and 2) and Filipinas (FP01 and FP02 - plots 1 and 2). The soil profiles were described morphologically. Sixty soil samples were collected in each plot. The chemical properties, granulometry, soil density, particle density, and estimated total porosity were determined. The average fruit production was calculated by counting the fruits in a sample of Brazil nut trees. Subsequently, the trees were divided into three classes of production: low (≤ 1.5 can; the can unit has 18-L, which is able to hold 59 and 77 fruits, respectively, for Cachoeira and Filipinas), medium (1.6 to 3.9 cans), and high (≥ 4.0 cans). The can unit is the traditional measure of volume in the region and varies according to the locality. Cluster analysis was performed to determine whether there was a difference between Brazil nut stands and soil profiles, and geostatistics was used to evaluate the spatial dependence of soil properties. The highest occurrence of Brazil nut trees with high fruit production (≥ 4.0 cans) was found in the *Latossolo Vermelho Distrófico argissólico* (Oxisol) and *Argissolo Vermelho-Amarelo Distrófico típico* (Ultisol). However, the Argisol also hosted the plants with the lowest productions (≤ 1.5 can). The pH, total organic carbon, sum of bases, P, N, granulometry, and porosity showed a greater spatial variability, and FP02 showed a greater number of properties with high spatial variability compared to the other areas. Although the occurrence of plants and the production of Brazil nut fruits (*Bertholletia excelsa*) were associated with the classes and the physical and chemical properties of the soil, pyxidium production differed between areas. In general, soil physical properties were limiting factors for Brazil nut production and/or higher tree occurrence. Filipinas environment showed a low fruit production and a greater spatial variability of soil properties compared to Cachoeira.




Keywords: *Bertholletia excelsa*, Western Amazon, geostatistics, spatial variability.

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Received: January 05, 2021

Approved: May 12, 2021

How to cite: Silva CS, Silva LM, Wadt LHO, Miqueloni DP, Silva KE, Pereira MG. Soil classes and properties explain the occurrence and fruit production of Brazil nut. Rev Bras Cienc Solo. 2021;45:e0200188.
<https://doi.org/10.36783/18069657rbc20210001>

Editors: José Miguel Reichert , Luciano da Silva Souza , and Edicarlos Damacena Souza 

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INTRODUCTION

The extraction of non-timber forest products (NTFP) is a fundamental means of subsistence for traditional populations of the Amazon (Silva et al., 2016). In addition, these products contribute to forest conservation, provide medicines, shelter, and food, and have great relevance to the local economy and culture (Homma, 2014). Non-timber forest products are resources obtained in native forests, planted forests, or agroforestry systems. They may be from plant or animal, including fruits, seeds, barks, fibers, essential oils, and latex, among others (Elias and Santos, 2016).

Brazil nut (*Bertholletia excelsa* Bonpl.), endemic to the Amazon (Muller, 1981), is one of the main NTFP of the Amazon, with strong socio-economic potential. The extractivism of this species generates income for traditional populations and family farmers and establishes the commercialization of seeds between nearby cities and abroad (Ortiz, 2002). It is a species protected by law (MMA et al., 2017), and it is classified as vulnerable in the IUCN Red List of Threatened Species (Americas Regional Workshop, 1998).

Brazil nut, the edible part within the nutshells of Brazil nut trees, is the product that gives all this prominence to the species. In 2019, the north and central-western regions of Brazil accounted for 93.2 and 6.8 %, respectively, of the national production of Brazil nuts, with a production of 37.0 % in the state of Amazonas, 22.2 % in Acre, 21.2 % in Pará, 6.8 % in Mato Grosso, 5.9 % in Roraima, 5.7 % in Rondônia, and 1.2 % in Amapá (IBGE, 2020).

The species *B. excelsa* has good development in deep soils, with clayey or sandy clayey texture, in areas of dryland and high land, not tolerating areas subject to flooding or with a large accumulation of water (Neves, 1938). In natural forests, Brazil nut seeds can germinate in the understory, but the seedlings need clearing for further development (Myers et al., 2000). The fruit of the Brazil nut tree, commonly called “ouríço” (Portuguese for hedgehog), contains between 7 and 29 seeds (Peres and Baidier, 1997). Brazil nut has high nutritional value, being rich in phosphorus, calcium, magnesium, potassium (Costa et al., 2009), and selenium (Vilhena, 2004).

Recent studies, such as those conducted by Costa et al. (2017), Guerreiro et al. (2017), and Ivanov et al. (2018), have sought to understand and relate the edaphoclimatic factors with fruit production in native stands of *B. excelsa*. Explaining the variation in Brazil nut fruit production, Kainer et al. (2007) highlighted that soil and nutrient availability influence fruit production variation. The authors verified that the cation exchange capacity (CEC) of the soil was positively correlated with the increase in fruit production of *B. excelsa*. The variation in the production of Brazil nut fruits is also due to other soil properties. Staudhammer et al. (2021), comparing two populations of *B. excelsa* in the Western Amazon for understanding the variation in fruit production, found that trees in sites with higher levels of available P and K⁺ produced three times more fruit.

A method that can be used to study the spatial variability of soil properties is geostatistics. Using geostatistics to analyze the spatial distribution of soil properties in a native stand of Brazil nut in the Tapajós National Forest, Guerreiro et al. (2017) verified that silt and clay contents, macroporosity, pH values, and phosphorus, zinc, and copper contents showed a spatial relationship with *B. excelsa*. The authors observed a high density of Brazil nut trees in areas with high values of silt and clay and low values of macroporosity, pH, phosphorus, zinc, and copper.

Two tools are often used in geostatistics: semivariogram and kriging. The semivariogram is used to represent and model the spatial distribution of the variable, relating distances and semivariance through a graph (Seidel and Oliveira, 2014), while kriging estimates the variable in unsampled locations, making it possible to verify the spatial continuity of the property through variability maps (Silva et al., 2020).

Studies show that geostatistics can be used to optimize the management of species of economic interest. Pelissari et al. (2017), when estimating the spatial variability of the volume of wood assortments and identifying spatial patterns in stands of *Tectona grandis* in the state of Mato Grosso, found that geostatistical modeling helped to manage the species, such as in thinning and pruning. Oliveira et al. (2009), when analyzing the spatial variability of the macronutrient contents in the soil and plants and the potential of citrus productivity in the Eastern Amazon, found high variability in fruit production and size. The authors concluded that geostatistics contributed to managing the different sites, increasing crop productivity, and decreasing costs.

Production of *B. excelsa* fruits can vary between Brazil nut stands and over the years, interfering with the economy of traditional populations in the Amazon region who use Brazil nut as a means of subsistence (Staudhammer et al., 2021). Therefore, investigating the spatial variability of soil properties and soil classes that occur in Brazil nut stands help to understand how these variables are distributed, allowing us to associate them with the occurrence of plants and production of *B. excelsa* fruits. The objectives of this study were to evaluate the relationship between the occurrence of plants and fruit production of Brazil nut and different soil classes and the spatialization of soil physical and chemical properties in two native stands of Brazil nut (Cachoeira and Filipinas) located in the state of Acre, Brazil.

MATERIALS AND METHODS

Study areas

The study was carried out in two native stands of Brazil nut located in the state of Acre, Brazil, where a series of studies were carried out by the Kamukaia Network (Wadt et al., 2008). One is called Cachoeira, located in the Chico Mendes Agro-extractivist Settlement Project (*Projeto de Assentamento Agroextrativista - PAE*), in Xapuri, and the other is called Filipinas, located in Colocação Rio de Janeiro, Chico Mendes RESEX, municipality of Epitaciolândia, between the geographic coordinates 10° 41' 05.6" S latitude and 68° 40' 10.7" W longitude and between 10° 47' 38.2" S latitude and 68° 39' 57.7" W longitude, respectively. These are areas where traditional populations extract forest resources and practice subsistence agriculture and small-scale livestock farming (Bertwell et al., 2018).

The community where Cachoeira is located has higher anthropization levels than Filipinas due to better road access, development projects, and sustainable forest management since 2001 (Stone, 2003; Serrano, 2005). The areas have similar forest composition and cover (90 and 92 %, respectively) (Coopeagro, 2001; SEMA, 2010), but there is a greater presence of lianas in Filipinas (Neves et al., 2016; Bertwell et al., 2018). The climate of the region is "Aw" type according to Köppen's classification system, with an average annual temperature of 25 °C, decreasing to 8 °C in the dry season from June to August (Alvares et al., 2013) and average annual precipitation of 1830 mm. The predominant vegetation is humid tropical forest (Holdridge, 1978). The region has an altitude ranging between 160 and 350 m, with relief ranging from gently undulating to undulating (ZEE, 2000). The soils occur on the geological formation Solimões, being influenced by volcanic material, deposited during their genesis by Andean winds. The soil classification used in the present study was adapted from the studies conducted by Bardales et al. (2011) and Ferreira et al. (2017). The soils have been described as *Argissolo Vermelho-Amarelo*, *Latossolo Vermelho*, and *Argissolo Vermelho*, according to the Brazilian Soil Classification System — SiBCS (Santos et al., 2018), corresponding to Ultisol and Oxisol in the Soil Survey Staff (2014).

Soil chemical and physical properties

To evaluate the spatial variability of soil properties, samples were collected in plots with dimensions of 600 × 600 m (36 ha), systematically in the intersection of the 100 × 60 m

grid. In each Brazil nut stand, samples were collected in two plots, totaling 72 ha of sampled area per stand. The plots were named CP01 and CP02 - plots 1 and 2 of Cachoeira, and FP01 and FP02 - plots 1 and 2 of Filipinas. A total of 120 samples were collected in each plot, 60 disturbed samples at a layer of 0.00-0.20 m for the analysis of chemical properties and particle size and 60 undisturbed samples at a layer of 0.07-0.13 m for the analysis of bulk density, particle density, and total porosity estimation. At each sampling site, the geographic coordinates were recorded with a navigation GPS, in UTM, zone 19S, and Datum SIRGAS 2000.

Soil profiles, in a total of three and six in Cachoeira and Filipinas, respectively, were morphologically described according to Santos et al. (2015) (Bardales et al., 2011; Ferreira et al., 2017). In the samples collected at the 0.00-0.20 m layer, the following properties were analyzed and calculated: pH(H₂O), total organic carbon (TOC), available phosphorus (P), total nitrogen (N), sum of bases - SB (Ca²⁺ + Mg²⁺ + K⁺ + Na⁺), aluminum saturation index (m %), and particle size analysis for the determination of sand, silt, and clay contents. Samples collected at 0.07-0.13 m layer were analyzed for bulk density (BD) and particle density (PD), the latter by the volumetric cylinder method, and used for estimation of total porosity.

The pH was measured in a 1:2.5 (w/v) mixture of soil and water. Exchangeable Al, Ca²⁺, and Mg²⁺ were extracted with KCl 1 mol L⁻¹. The Al³⁺ was determined by titration with sodium hydroxide 0.025 mol L⁻¹, and Ca²⁺ and Mg²⁺ by titration with ethylenediaminetetraacetic acid (EDTA) 0.125 mol L⁻¹. Phosphorous, K⁺, and Na⁺ were extracted with Mehlich⁻¹. Phosphorous was determined by colorimetry, and K⁺ and Na⁺ by flame photometry. Sum of bases was obtained by the sum of Ca²⁺ + Mg²⁺ + K⁺ + Na⁺ contents. The m % was obtained by the relationship between Al³⁺ and the effective cation exchange capacity of the soil. The TOC was quantified by oxidation using potassium dichromate in sulfuric acid. The determination of N was obtained through sulfuric digestion followed by Kjeldahl distillation. The pipette method was used for the granulometric characterization of the samples. Clay, silt, coarse sand, fine sand, and total sand fractions were separated. Soil density was determined by the volumetric ring method based on the mass/volume ratio, and the particle density was determined by the volumetric flask method. The total porosity was calculated based on the relationship between the properties of particle density and soil density. These analyses followed the methods described by Teixeira et al. (2017).

Fruit production

Average fruit production was calculated by monitoring the count of fruits in a sample of Brazil nut trees with a diameter at breast height (DBH) greater than or equal to 0.50 m in both stands. In Cachoeira, the fruits of 51 reproductive trees were quantified (22 and 29 individuals in plots 1 and 2, respectively) and, in Filipinas, the fruits of 34 reproductive trees were quantified (18 and 16 individuals in plots 1 and 2, respectively), between the years 2010 and 2020, in January and February after the fall of the fruits. After the fruits were counted, the trees were divided into three production classes: low (≤ 1.5 can), medium (1.6 to 3.9 cans), and high (≥ 4.0 cans). The can unit is the traditional measure of volume in the region and varies according to the locality; the can used in our study has 18-L, which is able to hold 59 and 77 fruits, respectively, for Cachoeira and Filipinas (unpublished data).

Statistical and geostatistical analysis

Fruit production measured in cans and soil chemical and physical properties were subjected to descriptive analysis to verify data dispersion. The mean, median, minimum, maximum, standard deviation, and coefficient of variation (CV %) were obtained. Values of CV <12 %, 12 < CV <60 %, and CV >60 % were considered as low, medium, and high data variability, respectively (Warrick and Nielsen, 1980). To verify whether there was a difference between the Brazil nut stands and between the soil profiles, cluster analysis

was performed using the Euclidean distance and the complete method. The variables used were the number of individuals and production classes (low, medium, and high). To verify whether there was difference between the stands, the plots of each stand were analyzed, while for the differences between the profiles, the analysis was performed for each soil profile. Descriptive statistics and cluster analysis were performed using R 4.0.2 software (R Development Core Team, 2020).

Geostatistics was applied to verify the existence and quantify the degree of spatial dependence and spatialize the soil properties in each plot. First, to analyze the structure of spatial dependence, the semivariogram was obtained for each variable. Based on the models presented by Silva et al. (2018), three theoretical models were fitted and tested: spherical, exponential, and Gaussian. After confirming the structure of spatial dependence and fitting the model for each variable, ordinary kriging was used to estimate the variables in non-sampled sites, enabling the construction of the maps (Vieira, 2000; Silva et al., 2020). The semivariogram and ordinary kriging were performed using ArcGIS 10.5 software.

Cross-validation indexes, coefficient of determination (R^2), and degree of spatial dependence (DSD %) were used to evaluate and compare the theoretical models. In cross-validation, the following indices were used: root-mean-square error (RMSE), mean error (ME), root-mean-square standardized error (RMSSE), and average standard error (ASE). For this, RMSE and ASE values should be as close to one another and as low as possible, ME should be near 0, RMSSE should be near 1 (Mello and Oliveira, 2016), and R^2 should be the closest to 1. The DSD was calculated by the ratio $[C_0/(C_0+C) \times 100]$, with spatial dependence classified as follows: strong ($DSD \leq 25\%$), moderate ($25 < DSD \leq 75\%$) and weak ($DSD > 75\%$). If DSD is equal to 100 %, it suggests a semivariogram with pure nugget effect (PNE), that is, the variable is spatially independent, or sampling problems may have occurred (Cambardella et al., 1994).

RESULTS

Fruit production

The plots of Cachoeira had higher means of fruit production, while Filipinas had lower mean values (Table 1). In plots CP01 and CP02, there was a higher number of trees, with medium (6 and 13 trees, respectively) and high (7 trees in each plot) fruit production. On the other hand, Filipinas had a higher number of individuals with low fruit production (17 and 12 trees in plots FP01 and FP02, respectively), fewer individuals, and no tree with high fruit production.

A high standard deviation (s) was observed in both Brazil nut stands, indicating heterogeneity in the production. The difference in the means of fruit production between the Brazil nut stands was confirmed by cluster analysis, in which the plots of each Brazil nut stand were located in different clusters (Figure 1).

Table 1. Descriptive statistics of total fruit production measured in cans in the Brazil nut stands Cachoeira - Plots CP01 and CP02 and Filipinas - Plots FP01 and FP02

Plot	Mean	Median	Minimum	Maximum	s
	can				
CP01	2.66	2.20	0.00	6.30	2.10
CP02	2.76	2.60	0.10	6.70	2.00
FP01	0.73	0.35	0.00	3.50	0.80
FP02	0.97	0.65	0.00	3.90	1.10

s: standard deviation; 1 can: 18 L, which is able to hold 59 and 77 fruits for Cachoeira and Filipinas, respectively.

Soil classification

The soil classes *Latossolo Vermelho Distrófico argissólico* (LVdar) (Oxisol) and *Argissolo Vermelho-Amarelo Distrófico típico* (PVAdti) (Ultisol) had higher occurrence of Brazil nut trees with high fruit production (≥ 4.0 cans), while in the areas of *Argissolo Vermelho-Amarelo Distrófico latossólico* (PVAdla) (Ultisol), *Argissolo Vermelho-Amarelo Distrófico petroplíntico* (PVAdpe) (Ultisol), and *Argissolo Vermelho Distrófico abruptico* (PVdab) (Ultisol), all present in Filipinas, there were only Brazil nut trees with low and medium fruit production. In the area of *Argissolo Vermelho-Amarelo Distrófico plintossólico* (PVAdpl) (Ultisol), there was few individuals and only one Brazil nut tree with high fruit production (Figure 2).

In the area of *Argissolo Vermelho-Amarelo Distrófico típico*, a higher number of Brazil nut trees with low (20 individuals) and high (7 individuals) fruit production was observed. In the area of *Latossolo Vermelho Distrófico argissólico*, there was a higher number of Brazil nut trees with medium fruit production (15 individuals) compared to the other areas. The areas of *Argissolo Vermelho Distrófico latossólico*, *Argissolo Vermelho-Amarelo Distrófico petroplíntico* and *Argissolo Vermelho Distrófico abruptico* were the only ones which had Brazil nut trees with high fruit production, and these classes were present only in Filipinas. Therefore, the profiles corresponding to these areas were included in the same cluster (Figure 3). The areas of *Argissolo Vermelho-Amarelo Distrófico plintossólico*, and *Latossolo Vermelho Distrófico argissólico* were classified in the same cluster and the area of *Argissolo Vermelho-Amarelo Distrófico típico* was classified alone (Figure 3).

Soil chemical and physical properties

For the physical and chemical properties of the soil, there were similar values of mean and median. In general, low ($CV > 12\%$) and moderate ($12 < CV < 60\%$) data variability was observed, and only SB had high variability ($CV > 60\%$) in the plots CP01 and FP02 (Table 2). The values of pH, BD, PD, and porosity showed low variability in all plots, while moderate variability was detected for particle size and soil chemical properties.

In general, for the physical and chemical properties of the soil, moderate spatial dependence was verified, and the models with the best fit were spherical and exponential, followed by Gaussian (Table 3). It was not possible to fit any model for SB in the plot FP01, so it was not possible to construct the map with its spatial

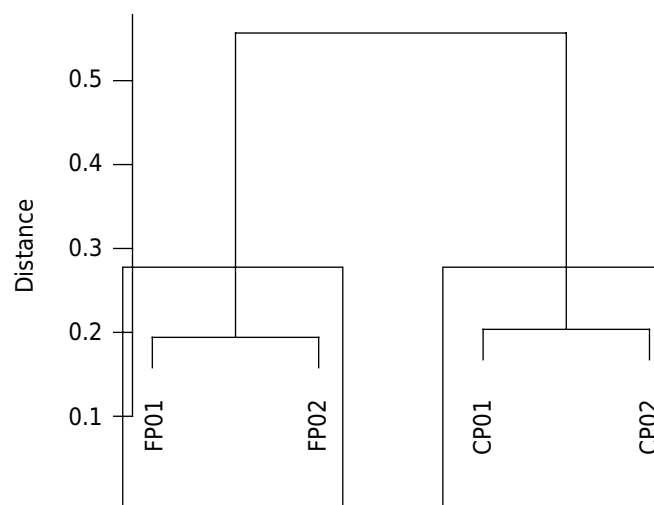


Figure 1. Dendrogram with the clustering of the plots of the Brazil nut stands Cachoeira and Filipinas related to fruit production and number of individuals. CP01 and CP02: Cachoeira; FP01 and FP02: Filipinas.

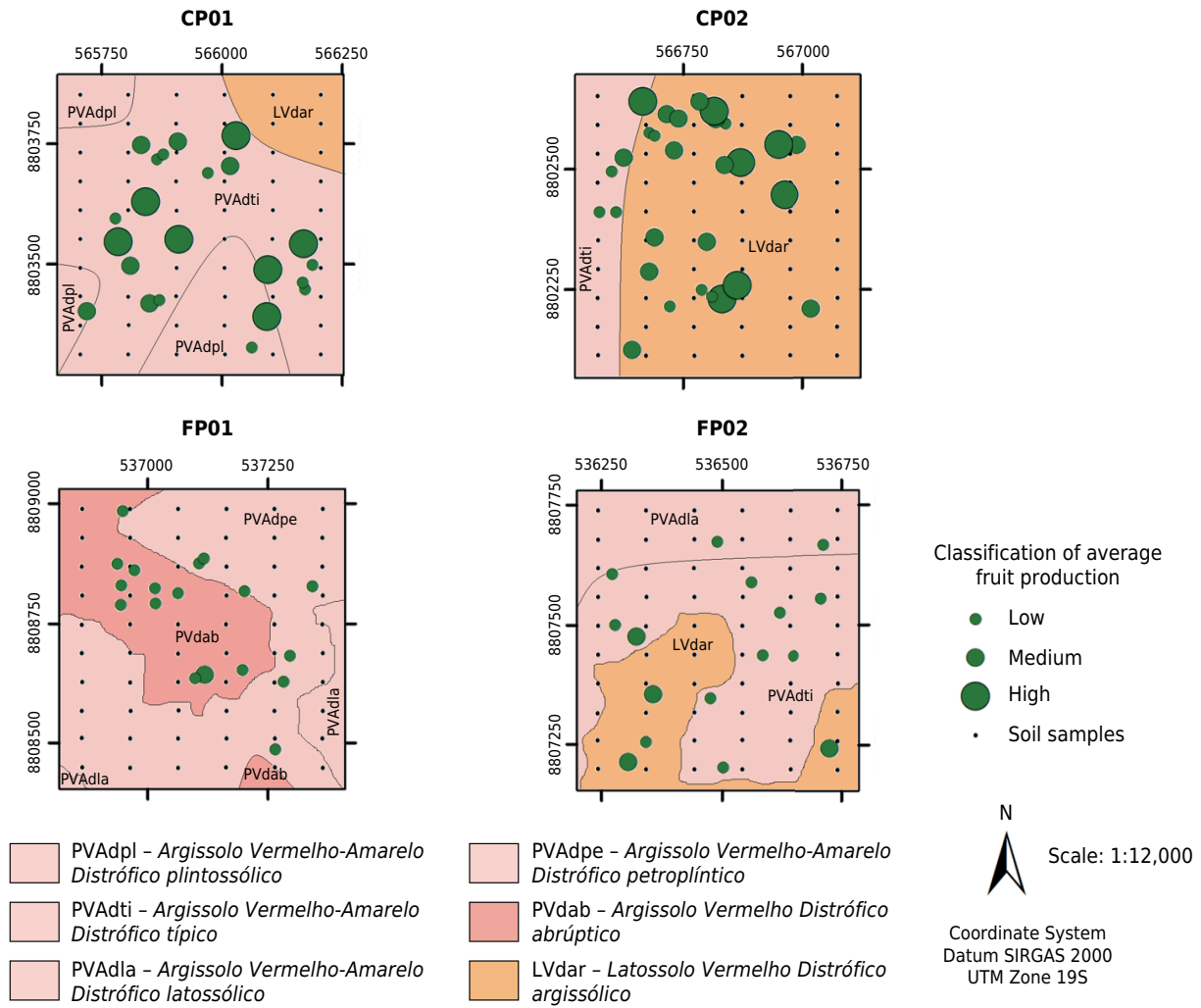


Figure 2. Map with soil profiles and average fruit production of Brazil nut trees in Cachoeira - Plots 1 and 2 (CP01 and CP02) and Filipinas - Plots 1 and 2 (FP01 and FP02). Circles on the maps correspond to the fruit production classes between the years 2010 and 2020, while points represent the locations where soil samples were collected. Source: Adapted from Bardales et al. (2011) and Ferreira et al. (2017).

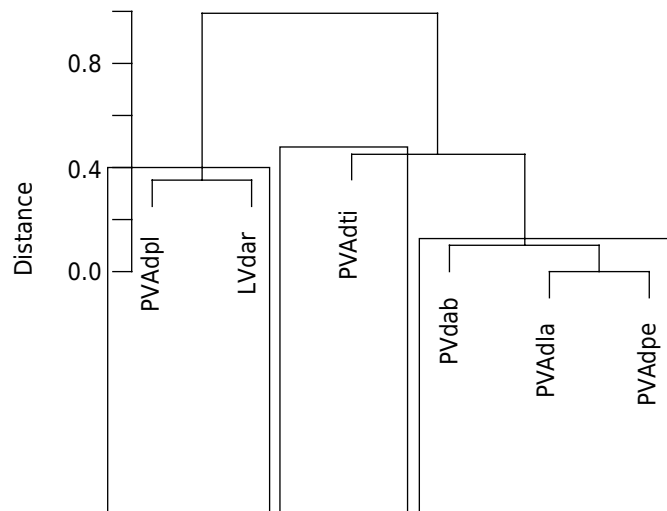


Figure 3. Dendrogram with the clustering of soil classes (profiles), in relation to fruit production and number of individuals. PVA dpl: Argissolo Vermelho-Amarelo Distrófico plintossólico; LV dar: Latossolo Vermelho Distrófico argissólico; PVA dti: Argissolo Vermelho-Amarelo Distrófico típico; PVA dab: Argissolo Vermelho Distrófico abruptico; PVA dia: Argissolo Vermelho-Amarelo Distrófico latossólico; PVA dpe: Argissolo Vermelho-Amarelo Distrófico petroplíntico.

Table 2. Descriptive statistics of soil physical and chemical properties in four plots of 36 ha each, in two native stands of Brazil nut in the state of Acre, Brazil

Variables	Mean	Median	Minimum	Maximum	s	CV %
CP01						
pH(H ₂ O)	4.49	4.48	4.02	5.69	0.29	6.40
TOC (g kg ⁻¹)	6.26	5.86	2.35	13.89	2.63	42.01
P (mg dm ⁻³)	5.24	5.13	2.80	8.57	1.13	21.65
N (g kg ⁻¹)	0.84	0.81	0.55	1.66	0.20	24.01
SB (cmol _c dm ⁻³)	0.58	0.53	0.25	3.07	0.38	66.01
m (%)	74.53	78.61	0.00	91.45	15.96	21.41
Total sand (g kg ⁻¹)	468.00	461.50	247.00	759.00	111.90	23.91
Silt (g kg ⁻¹)	403.70	406.00	188.00	577.00	103.46	25.63
Total clay (g kg ⁻¹)	128.40	123.00	46.00	228.00	32.57	25.37
BD (Mg m ⁻³)	1.38	1.39	1.22	1.67	0.09	6.34
PD (Mg m ⁻³)	2.52	2.52	2.42	2.68	0.05	2.04
Porosity (%)	45.12	44.85	32.49	53.61	3.92	8.69
CP02						
pH(H ₂ O)	4.32	4.33	3.98	4.79	0.20	4.61
TOC (g kg ⁻¹)	8.36	8.32	3.07	17.18	2.95	35.35
P (mg dm ⁻³)	5.08	4.97	2.74	7.62	1.13	22.18
N (g kg ⁻¹)	1.07	1.00	0.65	1.61	0.22	20.92
SB (cmol _c dm ⁻³)	0.71	0.60	0.24	1.79	2.95	52.76
m (%)	75.13	79.90	29.70	93.70	13.93	18.54
Total sand (g kg ⁻¹)	459.90	458.00	242.00	724.00	100.30	21.81
Silt (g kg ⁻¹)	320.60	352.50	5.00	545.00	134.53	41.96
Total clay (g kg ⁻¹)	219.60	218.00	84.00	356.00	76.48	34.83
BD (Mg m ⁻³)	1.30	1.30	1.08	1.67	0.12	9.10
PD (Mg m ⁻³)	2.65	2.67	2.47	2.78	0.08	3.02
Porosity (%)	50.59	51.00	38.48	59.86	4.65	9.20
FP01						
pH(H ₂ O)	4.06	3.99	3.73	5.00	0.24	6.04
TOC (g kg ⁻¹)	8.58	8.77	1.50	19.73	3.59	41.87
P (mg dm ⁻³)	3.94	3.70	2.81	7.33	0.79	20.04
N (g kg ⁻¹)	0.86	0.86	0.58	1.40	0.15	17.48
SB (cmol _c dm ⁻³)	0.33	0.28	0.16	1.34	0.16	50.50
m (%)	87.15	89.38	49.73	94.23	7.56	8.67
Total sand (g kg ⁻¹)	542.60	544.00	205.00	675.00	89.74	16.54
Silt (g kg ⁻¹)	320.90	317.50	214.00	568.00	69.60	21.69
Total clay (g kg ⁻¹)	136.70	130.00	87.00	238.00	32.10	23.49
BD (Mg m ⁻³)	1.28	1.27	0.99	1.53	0.10	7.86
PD (Mg m ⁻³)	2.62	2.62	2.52	2.75	0.04	1.65
Porosity (%)	51.29	51.27	41.80	61.89	3.75	7.31
FP02						
pH(H ₂ O)	4.28	4.21	3.86	6.49	0.39	9.10
TOC (g kg ⁻¹)	6.97	6.77	3.55	12.41	2.10	30.11
P (mg dm ⁻³)	3.72	3.25	2.19	7.13	1.19	31.95
N (g kg ⁻¹)	0.70	0.69	0.36	1.04	0.16	23.07

Continue

Continuation						
SB (cmol _c dm ⁻³)	0.42	0.32	0.10	2.11	0.32	76.88
m (%)	77.73	85.42	0.00	93.73	18.44	23.72
Total sand (g kg ⁻¹)	649.10	657.50	438.00	785.00	71.53	11.02
Silt (g kg ⁻¹)	221.20	208.00	140.00	430.00	55.87	25.26
Total clay (g kg ⁻¹)	129.80	126.00	48.00	217.00	39.32	30.29
BD (Mg m ⁻³)	1.35	1.35	1.23	1.65	0.07	5.39
PD (Mg m ⁻³)	2.67	2.66	2.57	2.86	0.06	2.32
Porosity (%)	49.44	49.53	42.25	54.80	2.52	5.10

CP01: Cachoeira - Plot 01; CP02: Cachoeira - Plot 02; FP01: Filipinas - Plot 01; FP02: Filipinas - Plot 02; s: standard deviation; CV: coefficient of variation; TOC: total organic carbon; P: phosphorus; N: nitrogen; SB: sum of bases; m: aluminum saturation index; BD: bulk density; PD: particle density.

distribution due to the pure nugget effect (PNE) observed. The range varied from 120.48 (TOC, SB, and porosity) to 736.20 (N and total clay) m in CP01, 120.48 (P) to 736.18 (TOC, SB, silt, and PD) m in CP02, 137.87 (total clay) to 737.20 (P, SB, total sand, silt, and PD) m in FP01, and 114.87 (pH, TOC, and N) to 737.22 (BD, PD, and porosity) m in FP02.

Regarding the spatial distribution of soil properties in the plots of Cachoeira, the occurrence of Brazil nut trees was higher in areas with lower pH (Figures 4a and 5a). In plot CP01, the Brazil nut trees occurred in the different TOC contents (Figure 4b), and, in plot CP02, in general, the individuals with higher fruit production were observed in the regions with higher TOC contents (Figure 5b). There was no pattern of distribution of P and N contents in the plot CP01 (Figures 4c and 4d); however, in the plot CP02, there was a higher number of trees where P and N contents were higher, in addition to high fruit production in areas with higher N contents (Figures 5c and 5d). In the regions with lower contents of SB, there was a predominance of Brazil nut trees with high fruit production in CP01 and low fruit production in CP02 (Figures 4e and 5e).

Brazil nut trees with high fruit production occurred in areas with higher values of aluminum saturation (m%) in the two plots of Cachoeira (Figures 4f and 5f). In general, in regions with high contents of sand, silt, or clay, few individuals were observed in plots CP01 and CP02 (Figures 4g, 4h, 4i, 5g, 5h, and 5i). Trees with low and medium fruit production were verified in areas with high values of bulk density and particle density (Figures 4j, 4k, 5j, and 5k). In Cachoeira, Brazil nut trees were distributed in soils with all levels of porosity (Figures 4l and 5l).

Based on the maps of figures 4 and 5, it was found that the relief of the plot CP01 was flatter, with little topographic variation, with no pattern in the distribution of Brazil nut trees. However, in the plot CP02, there was greater variation in altitude, with areas of higher elevation, where trees with higher fruit production were verified. The altitude in Filipinas showed a pattern similar to that observed in Cachoeira, and the FP01 plot showed a small variation in altitude, with lower areas than those observed in FP02, with most individuals located in the higher portions (Figure 6). In the plot FP02, there was a greater amplitude of altitude variation, with individuals found at all elevations; however, the most productive trees occurred in the higher regions (Figure 7).

In the plot FP01, the occurrence of Brazil nut trees was higher in areas where the pH was lower (Figure 6a), while in FP02, the trees were observed in areas with greater amplitude of pH variation (Figure 7a). In general, individuals with low and medium fruit production were observed where TOC contents ranged from low to high, respectively (Figures 6b and 7b). For SB, a distribution similar to that observed for TOC in plot FP02 was verified (Figure 7e). It was not possible to spatialize SB in FP01, due to its random distribution in the soil. In the plot FP01, the individuals occurred at different

Table 3. Theoretical models fitted and cross-validation for soil physical and chemical properties in four plots of 36 ha each, in two native stands of Brazil nut in the state of Acre, Brazil

Variable	Model	C ₀	C ₀ +C	a	DSD	R ²	RMSE	ME	RMSSE	ASE
				m	%					
CP01										
pH(H ₂ O)	Sph	0.04	0.07	210.05	60.41	0.19	0.26	0.00	1.03	0.25
TOC (g kg ⁻¹)	Exp	3.79	5.81	120.48	65.24	2.57	0.12	1.02	2.51	0.08
P (mg dm ⁻³)	Exp	0.64	1.51	512.00	42.03	0.21	1.00	0.00	0.99	1.03
N (g kg ⁻¹)	Gaus	0.04	0.05	736.20	72.69	0.04	0.20	0.00	1.02	0.20
SB (cmol _c dm ⁻³)	Sph	0.01	0.10	120.48	8.89	0.14	0.37	0.00	1.16	0.30
m (%)	Gaus	126.35	425.37	720.75	29.70	0.35	12.78	0.00	1.05	12.06
Total sand (g kg ⁻¹)	Sph	0.00	10879.97	129.49	0.00	0.24	98.07	-4.54	1.02	92.69
Silt (g kg ⁻¹)	Gaus	9.09	9097.28	128.03	0.10	0.43	79.21	2.23	1.13	66.40
Total clay (g kg ⁻¹)	Sph	705.56	1342.83	736.20	54.82	0.18	29.28	0.96	0.99	29.61
BD (Mg m ⁻³)	Exp	0.01	0.01	238.88	91.37	0.01	0.09	0.00	0.97	0.09
PD (Mg m ⁻³)	Exp	0.00	0.00	249.15	23.17	0.23	0.04	0.00	0.98	0.05
Porosity (%)	Exp	11.18	14.57	120.48	76.72	0.01	4.05	0.02	1.01	4.00
CP02										
pH(H ₂ O)	Sph	0.02	0.04	133.05	55.63	0.06	0.20	0.00	1.00	0.20
TOC (g kg ⁻¹)	Gaus	6.62	11.69	736.18	56.63	0.06	2.88	0.04	1.06	2.70
P (mg dm ⁻³)	Sph	1.15	1.25	120.48	92.31	0.00	1.19	0.04	1.01	1.18
N (g kg ⁻¹)	Exp	0.04	0.05	453.64	79.74	0.01	0.23	0.00	1.02	0.22
SB (cmol _c dm ⁻³)	Gaus	0.10	0.20	736.18	48.75	0.08	0.36	0.00	1.10	0.33
m (%)	Exp	108.11	143.63	135.18	75.27	0.18	12.63	0.03	1.01	12.50
Total sand (g kg ⁻¹)	Sph	2930.14	8917.74	146.97	32.86	0.25	86.38	-0.56	0.97	89.26
Silt (g kg ⁻¹)	Exp	0.00	26172.15	736.18	0.00	0.73	69.13	0.59	0.89	79.51
Total clay (g kg ⁻¹)	Sph	0.00	3626.24	170.12	0.00	0.62	46.92	1.26	1.04	45.61
BD (Mg m ⁻³)	Gaus	0.01	0.02	377.34	66.08	0.19	0.11	0.00	0.97	0.11
PD (Mg m ⁻³)	Gaus	0.00	0.01	736.18	25.80	0.52	0.06	0.00	0.96	0.06
Porosity (%)	Exp	11.99	24.61	514.83	48.71	0.16	4.26	0.00	1.00	4.28
FP01										
pH(H ₂ O)	Sph	0.04	0.06	299.00	58.47	0.14	0.23	0.00	0.99	0.23
TOC (g kg ⁻¹)	Gaus	6.44	14.97	390.80	42.99	0.41	2.74	0.01	0.98	2.82
P (mg dm ⁻³)	Exp	0.23	0.81	737.20	28.42	0.16	0.73	0.00	1.13	0.65
N (g kg ⁻¹)	Exp	0.01	0.03	571.38	59.24	0.09	0.14	0.00	1.00	0.14
SB (cmol _c dm ⁻³)	PNE	0.03	0.03	737.20	100.00	-	-	-	-	-
m (%)	Sph	41.95	67.63	266.90	62.03	0.03	7.52	0.11	0.98	7.66
Total sand (g kg ⁻¹)	Exp	4665.16	9687.44	737.20	48.16	0.05	88.42	-0.82	1.08	81.56
Silt (g kg ⁻¹)	Gaus	3845.70	6237.43	737.20	61.66	0.05	67.99	0.43	1.04	64.96
Total clay (g kg ⁻¹)	Sph	451.01	1067.20	137.87	42.26	0.04	32.18	1.03	1.00	32.13
BD (Mg m ⁻³)	Sph	0.01	0.01	275.80	60.97	0.10	0.10	0.00	1.01	0.09
PD (Mg m ⁻³)	Gaus	0.00	0.00	737.20	87.39	0.04	0.04	0.00	1.04	0.04
Porosity (%)	Gaus	10.17	14.48	232.01	70.23	0.08	3.59	0.11	1.01	3.57
FP02										
pH(H ₂ O)	Exp	0.03	0.13	114.87	23.45	0.00	0.42	-0.01	1.12	0.37
TOC (g kg ⁻¹)	Exp	3.60	4.23	114.87	85.09	0.02	2.13	-0.06	0.97	2.19
P (mg dm ⁻³)	Sph	0.56	1.76	140.63	31.93	0.01	1.23	0.00	0.98	1.27
N (g kg ⁻¹)	Sph	0.00	0.03	114.87	0.00	0.13	0.15	0.00	1.01	0.15

Continue

Continuation

SB (cmol _c dm ⁻³)	Exp	0.00	0.11	152.17	0.00	0.02	0.34	0.00	1.09	0.30
m (%)	Sph	208.84	351.66	277.07	59.39	0.08	17.68	-0.18	1.02	17.22
Total sand (g kg ⁻¹)	Sph	0.00	5620.90	173.69	0.00	0.45	53.00	-0.20	0.97	56.16
Silt (g kg ⁻¹)	Gaus	3.39	3389.64	134.83	0.10	0.55	37.93	0.37	1.09	37.45
Total clay (g kg ⁻¹)	Gaus	408.68	1777.23	210.36	23.00	0.51	27.37	0.37	0.99	27.83
BD (Mg m ⁻³)	Gaus	0.00	0.01	737.22	46.02	0.02	0.07	0.00	1.15	0.06
PD (Mg m ⁻³)	Exp	0.00	0.00	737.22	55.36	0.00	0.06	0.00	1.10	0.06
Porosity (%)	Gaus	5.38	7.69	737.22	69.93	0.00	2.60	0.04	1.07	2.42

CP01: Cachoeira - Plot 01; CP02: Cachoeira - Plot 02; FP01: Filipinas - Plot 01; FP02: Filipinas - Plot 02; Sph: spherical; Exp: exponential; Gaus: Gaussian; C₀: nugget effect; C₀+C: sill; a: range; DSD: degree of spatial dependence; R²: coefficient of determination; RMSE: root-mean-square error; ME: mean error; RMSSE: root-mean-square standardized error; ASE: average standard error; TOC: total organic carbon; P: phosphorus; N: Nitrogen; SB: sum of bases; m: aluminum saturation index; BD: bulk density; PD: particle density.

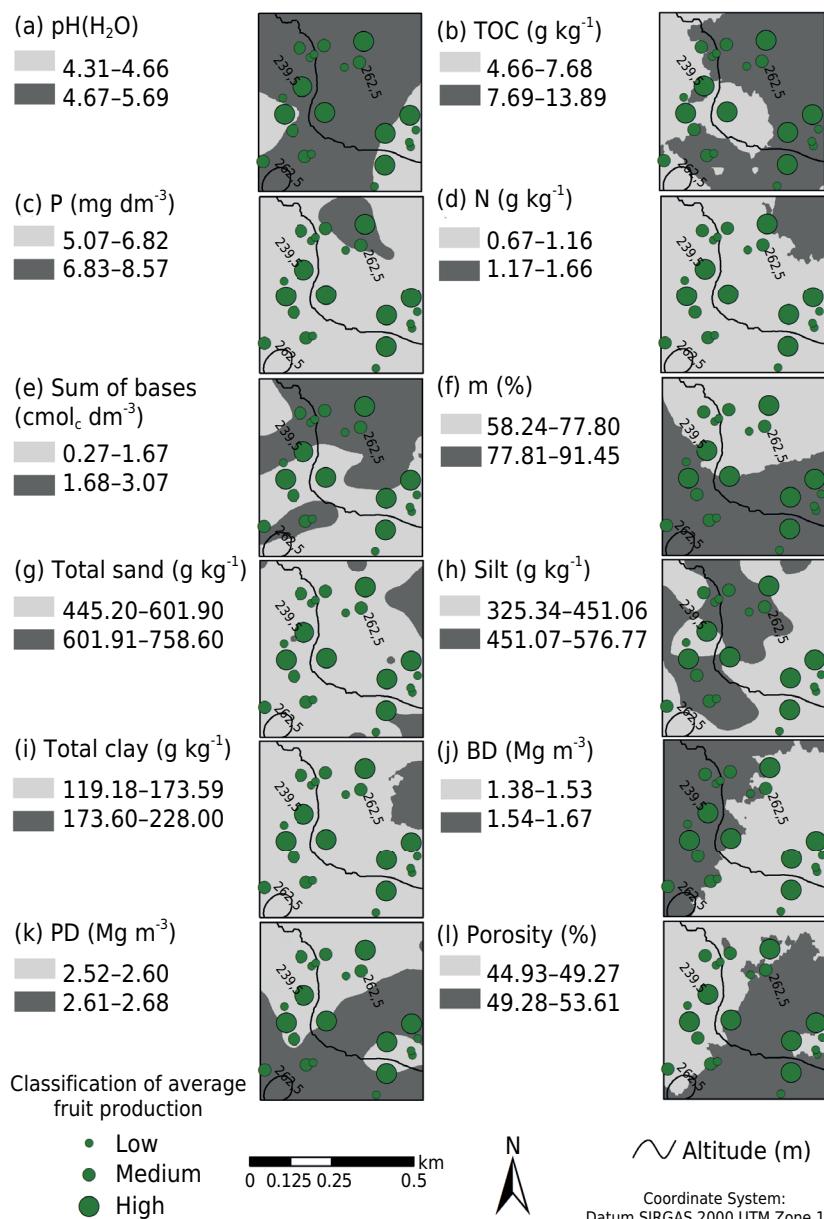


Figure 4. Spatial distribution of soil physical and chemical properties in Cachoeira - Plot 1, in the state of Acre, Brazil. Lines and values in the maps correspond to the altitude of the area, circles correspond to the average fruit production between the years 2010 and 2020, and values presented in the legends are the soil properties.

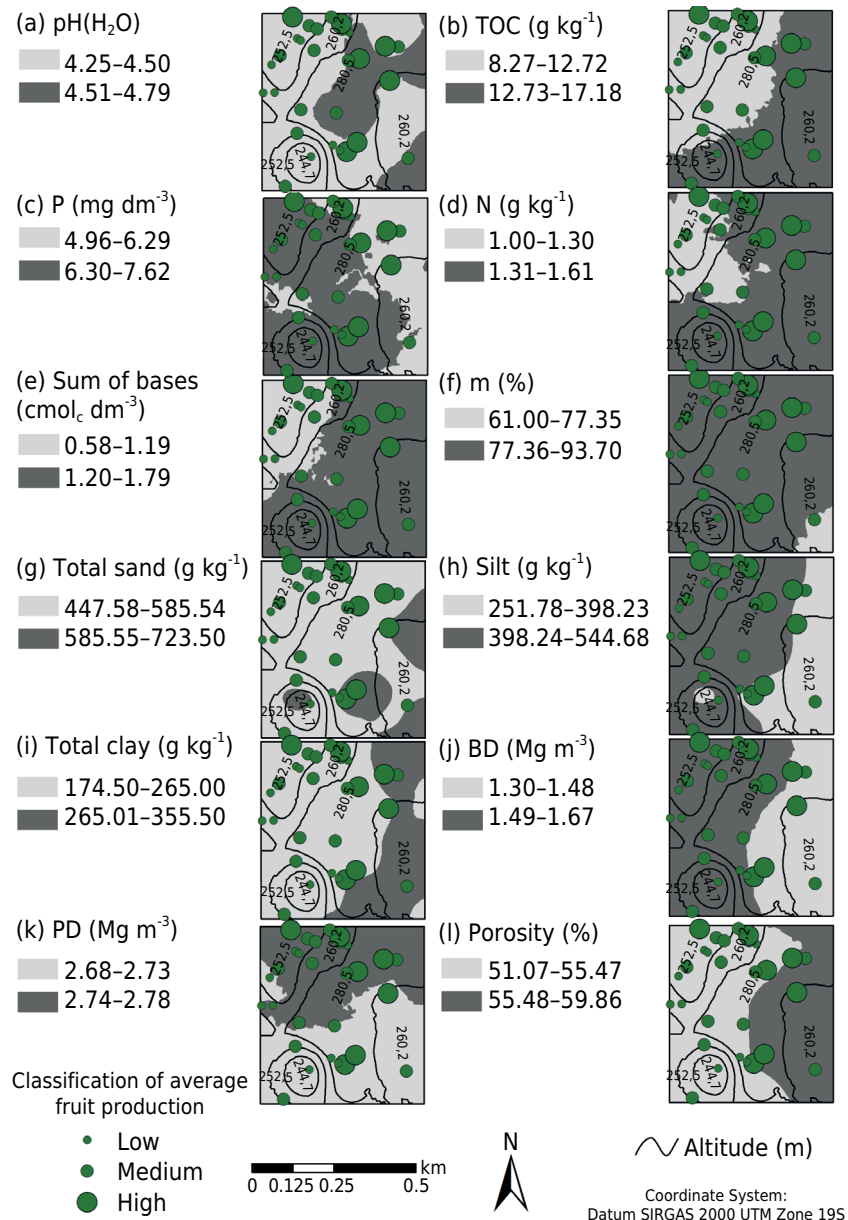


Figure 5. Spatial distribution of soil physical and chemical properties in Cachoeira - Plot 2, in the state of Acre, Brazil. Lines and values in the maps correspond to the altitude of the area, circles correspond to the average fruit production between the years 2010 and 2020, and values presented in the legends are the soil properties.

levels of P and N (Figures 6c and 6d), whereas in FP02, Brazil nut trees with low and medium fruit production were observed, in general, in areas where P and N contents were higher (Figures 7c and 7d).

In general, most Brazil nut trees occurred in regions where Al saturation contents were lower in the two plots of Filipinas (Figures 6e and 7f). For sand, silt, and clay contents, no distribution pattern was observed in the plots FP01 and FP02 (Figures 6f, 6g, 6h, 7g, 7h, and 7i). From the information of BD and PD, it was verified that the individuals occurred in areas where the values of these variables were lower in FP01 (Figures 6i and 6j). In FP02, Brazil nut trees with the highest production were observed where the values of these variables were lower (Figures 7j and 7k). It was found that the individuals occurred in the areas with higher porosity in both plots of Filipinas (Figures 6k and 7l).

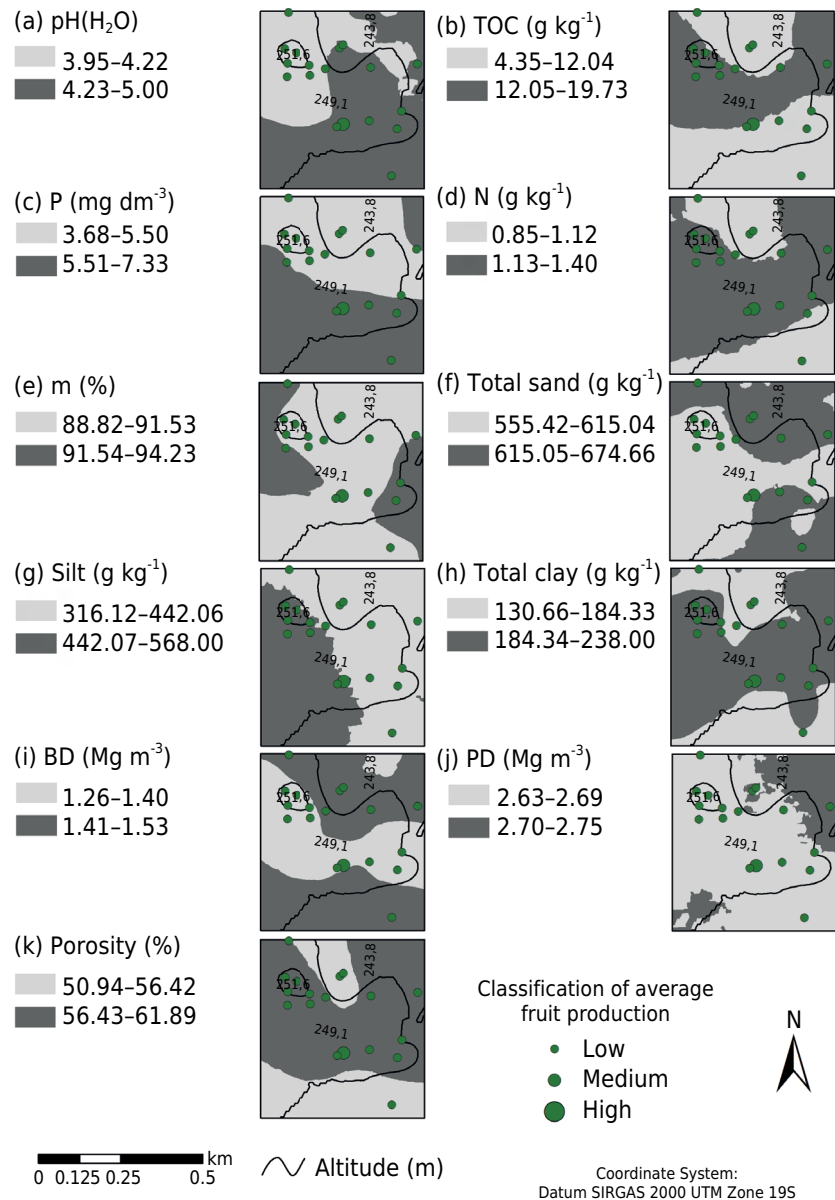


Figure 6. Spatial distribution of soil physical and chemical properties in Filipinas - Plot 1, in the state of Acre, Brazil. Lines and values in the maps correspond to the altitude of the area, circles correspond to the average fruit production between the years 2010 and 2020, and values presented in the legends are the soil properties.

DISCUSSION

The *Latosolos Vermelhos Distróficos argissólicos* of the South-Western Amazon region are very deep, well-structured, with low natural fertility, medium texture, and abundant presence of silt (Ferreira et al., 2017). Brazil nut trees can produce more seeds in deep soils with clay loam and sandy clayey texture, when compared to shallow soils (Ivanov et al., 2018). Therefore, this may explain the occurrence of Brazil nut trees with high fruit production in this soil class.

Argissolos Vermelho-Amarelos Distróficos típicos are soils prone to erosive processes and have imperfect drainage, which may lead to reduction in their effective depth (Ferreira et al., 2017). This pattern may explain the highest number of Brazil nut trees with low fruit production in this soil class. *Latosolo Vermelho* and *Argissolo Vermelho-Amarelo* were the soils that most occurred in the studied Brazil nut stands. The occurrence of Brazil nut trees in *Argissolos Vermelho-Amarelos* and *Latosolos Vermelho-Amarelos* is common

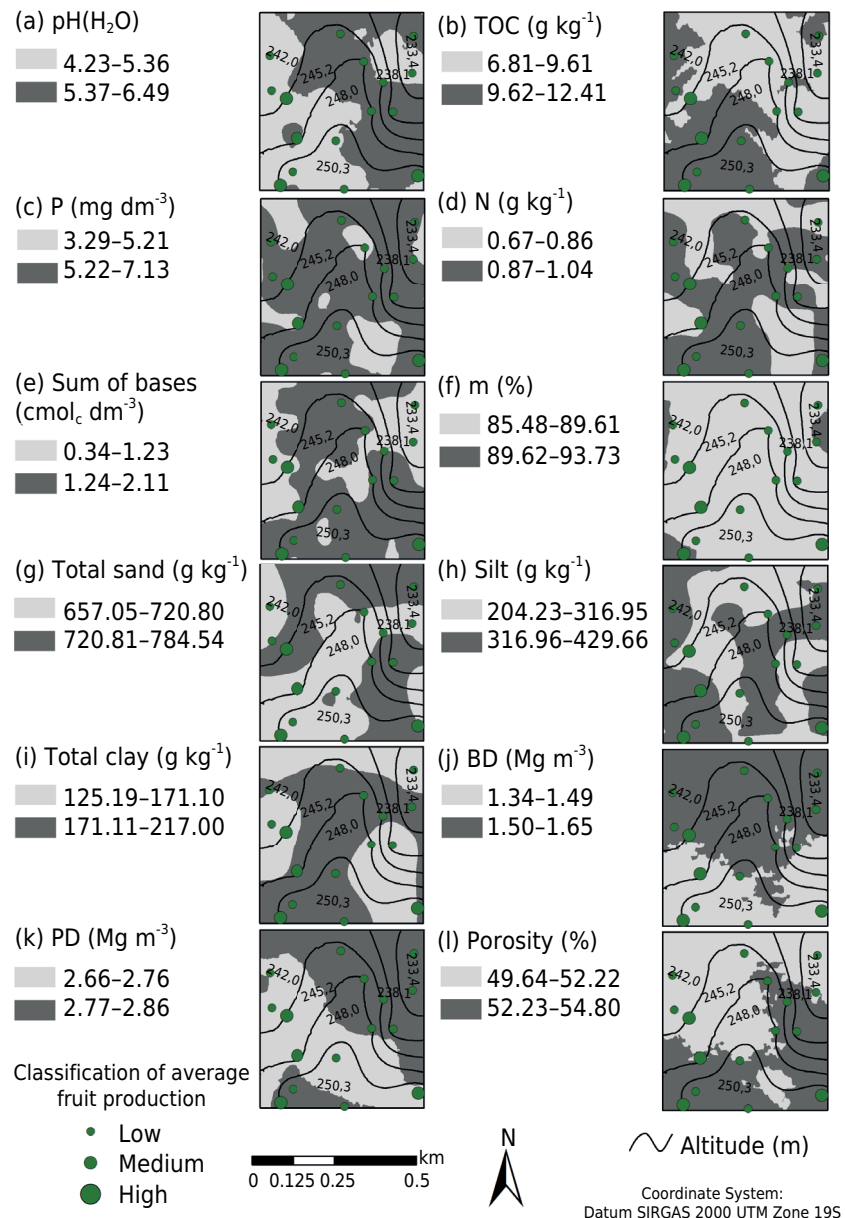


Figure 7. Spatial distribution of soil physical and chemical properties in Filipinas - Plot 2, in the state of Acre, Brazil. Lines and values in the maps correspond to the altitude of the area, circles correspond to the average fruit production between the years 2010 and 2020, and values presented in the legends are the soil properties.

(Spera et al., 2019); however, it was observed in this study that Brazil nut trees also occur in *Latossolos Vermelhos*, showing high fruit production. In the Amazon, in general, *Latossolos Vermelho-Amarelos*, *Latossolos Amarelos*, and *Argissolos Vermelho-Amarelos* commonly occur in plateau areas (Lepsch, 2010), which may explain the occurrence of Brazil nut trees in these areas.

The absence or scarcity of Brazil nut trees with high fruit production in the areas of *Argissolo Vermelho-Amarelo Distrófico latossólico*, *Argissolo Vermelho-Amarelo Distrófico petroplíntico*, and in *Argissolo Vermelho-Amarelo Distrófico plintossólico* is probably due to the low natural fertility and presence of plinthite and petroplinthite. The presence of plinthite in the soil leads to imperfect drainage and prevents root penetration, causing low absorption of water and nutrients. Brazil nut trees with low and medium fruit production were found in the area of *Argissolo Vermelho Distrófico abruptico*. This result is probably due to the presence of abrupt textural change, which can limit the internal flow of water and favor the formation of a suspended water table, causing oxygen deficiency

in the period of higher rainfall. Analyzing the distribution of soil classes aiming at the stratification of environments, management, and correlation with *B. excelsa* productivity in Filipinas, Bardales et al. (2011) found that the *Argissolos Vermelho-Amarelos* that occur in this Brazil nut stand are more susceptible to instability, with a predisposition to erosion. The slope of the area (6 to 14 %) and the soil depths (varying from shallow to deep) may have favored the appearance of concretions and processes of moderate to strong erosion in this soil class (Bardales et al., 2011). The authors observed that, although Brazil nut trees have low production in this type of pedoenvironment, there is a large number of trees.

Through cluster analysis, it was found that there is a difference in the number of Brazil nut trees and fruit production between Cachoeira and Filipinas (Figure 1). This pattern was reflected in the clusters of soil profiles, in which *Argissolo Vermelho Distrófico latossólico*, *Argissolo Vermelho-Amarelo Distrófico petroplíntico*, and *Argissolo Vermelho Distrófico abruptico* were grouped because they did not have any Brazil nut tree with high fruit production and also because they occur only in Filipinas (Figure 3). The soil classes *Argissolo Vermelho-Amarelo Distrófico plintossólico* and *Latossolo Vermelho Distrófico argissólico* were probably grouped because they had Brazil nut trees with high fruit production. However, in the *Argissolo Vermelho-Amarelo Distrófico plintossólico*, there were only three Brazil nut trees, one in each production class. The area of *Argissolo Vermelho-Amarelo Distrófico típico* was probably isolated because it had Brazil nut trees with high and low fruit production. In addition, this soil class occurred in both stands, but Cachoeira had a higher number of trees with high production, and Filipinas had low fruit production.

In general, the CV observed in this study was low to moderate, evidenced especially by geostatistics, which indicated moderate to high spatial dependence for most variables. It is common soil properties have moderate to high data variability since environmental factors can interfere with these variables (Carvalho et al., 2003). Regarding the spatial dependence of soil physical and chemical properties, for SB, a random distribution was observed in the FP01 plot, due to the spacing adopted in the soil sampling, larger than necessary to detect spatial dependence. In this study, approximately 60 % of the variables showed moderate spatial dependence. According to Cambardella et al. (1994), moderate spatial dependence occurs when there is a homogenization of soil. This may occur due to the use and management adopted in these areas (Cavalcante et al., 2007).

When evaluating the semivariograms of the soil properties, we observed that some variables (pH, COT, and N) of the FP02 plot had lower range values (114.87 m) compared to the CP01, CP02, and FP01 areas, indicating greater variability and less spatial continuity, and consequently, less fruit production when compared to Cachoeira. This variability may be due to the strong tendency to erosion and the predisposition to instability, in addition to the variation in the declivity of this area (Bardales et al., 2011). According to Wanderley et al. (2012), the range (a) is the distance at which the samples are spatially correlated; that is, it represents the maximum distance of influence of the evaluated property, and after this distance, the samples are spatially independent, showing no spatial dependence. This pattern indicates that the smaller the range, the greater the variability, as samples located in an area of radius equal to the range are more homogeneous (Marques Júnior et al., 2008).

Regarding the spatial distribution of soil properties in the stands, the predominance of Brazil nut trees in areas with lower pH values was also observed by Locatelli et al. (2002). These authors verified a good development in diameter and height in Brazil nut trees in areas with low pH, CEC, and high levels of Al saturation. This indicates that the vegetative development of the species does not necessarily occur in more acidic soils, but favors the process of soil acidification due to the absorption of nutrients by Brazil nut trees and understory plants, according to Costa et al. (2017). The authors

also state that the most productive individuals absorb more nutrients, resulting in lower values of SB, favoring acidification and, consequently, reduction of soil fertility. This pattern may explain the occurrence of Brazil nut trees in sites with low values of SB and regions with higher levels of m % in the plots of Cachoeira. However, the occurrence of low pH values and high levels of m % is common in soils of the state of Acre (Wadt, 2002; Bernini, 2010). The high content of m % does not cause phytotoxicity because the extractor used to determine the levels of Al^{3+} (KCl) causes the dissolution of structural aluminum, which is a non-exchangeable form, increasing the results of analytical values, but without reflecting the true contents of exchangeable aluminum in the soil, which are lower (Wadt, 2002).

In general, for TOC, similar patterns were verified in the plots of the two Brazil nut stands. In plots CP02, FP01, and FP02, it was observed that the variables TOC and SB favored a higher fruit production, except in FP01 for SB, which had a pure nugget effect. In CP01, there was no pattern in the distribution of TOC in relation to fruit production. The association between TOC and fruit production occurred because the accumulation of plant residues improves soil properties, providing a more favorable edaphic environment for plant development. The same pattern was not found for P distribution in the Brazil nut stands. Different results were found for the relationship between P and fruit production in the study conducted by Kainer et al. (2007). These authors verified that there were individuals with higher fruit production in sites with low P content, indicating the high demand of the specie for this nutrient.

In general, in the studied plots, there was no distribution pattern for the variables sand, silt, and clay as a function of the fruit production of Brazil nut. According to Guerreiro et al. (2017), Brazil nut has better adaptation and, consequently, better production in soils with texture ranging from clayey to very clayey. According to the same authors, soils with sandy texture are not suitable to maximize the development potential of the species, probably due to low nutrient content and moisture retention. However, Ivanov et al. (2018) verified that the individuals produce a lower quantity of seeds in soils with clayey texture when compared to those growing in soils with clay loam and sandy clay texture, that is, soils with lower nutrient adsorption and mainly lower moisture retention, since the regular distribution of rainfall in the region favors water supply throughout the year. The pattern established by Locatelli et al. (2002) was observed in this study since virtually all plots with high production and higher number of individuals were verified in higher regions. Spera et al. (2019) point out in their study that the Brazil nut tree has a preference for areas with this characteristic.

The Brazil nut stands Cachoeira and Filipinas showed a similar pattern regarding the variables BD and PD. Regions with lower values of these properties had high fruit production and/or a higher number of trees. This pattern is possibly due to the low adaptation of the species to areas with imperfect drainage in overly compacted or dense soils (Locatelli et al., 2005). Analyzing the soil properties that influence the development of Brazil nut trees in bauxite mining restoration areas in the Amazon, Melo et al. (2018) found that higher values of BD cause a negative effect on the growth of *B. excelsa*. The observed pattern corroborates the results found in the plots FP01 and FP02, because the highest occurrence of Brazil nut tree was verified in areas with higher porosity, that is, in soils with lower water retention.

The values of range (a) and maps with the spatial distribution of soil properties in Brazil nut stands indicated greater spatial variability for pH, COT, SB, P, N, total sand, silt, total clay, and porosity. A greater number of properties with high variability was observed in FP02 compared to the other areas. These properties may be associated with the low fruit production in Filipinas. According to Gandah et al. (2000), the heterogeneity of soil properties can interfere with the production of some species. This variability can be explained by the source material of the soil or the different landforms found in Brazil nut stands (Cambardella et al., 1994).

The species *B. excelsa* was observed in different soil types and, consequently, showed distinct fruit production between the stands. Naturally, the association of the soil class with altitude and distribution of soil chemical and physical properties determined part of the fruit production capacity. Therefore, the absence of high fruit production in Filipinas, compared to Cachoeira, can be attributed, in part, to the soil classes that occur in this area, mainly associated with the soil physical properties and altitude of the area. The maps generated through geostatistics can provide support for guiding the management of the species, with the objective of increasing fruit production in this Brazil nut stand, because they show the locations of soil classes, nutrient content, and the occurrence of Brazil nut trees with low, medium and high fruit production. In addition, this study can stimulate the development of other research, aiming to better understand the productive potential of native cultures, better soil properties, and strategically plan management. Therefore, this research results can assist in local agricultural development.

The cutting of lianas associated with individuals of *B. excelsa*, top-dressing fertilization with phosphorus, and the increase in the number of trees from which extractivists collect have already been suggested for increasing productivity by Kainer et al. (2007), who analyzed the variation in fruit production of *B. excelsa* in Filipinas. Relating the variations in Brazil nut fruit production and nutritional status with soil properties, Costa et al. (2017) proposed, as a way to replace the nutrients, to deposit pruning residues and the nutshells on the soil, since the fruit has high levels of calcium, magnesium, and potassium. Based on this study, together with these management recommendations, Brazil nut seedlings should be planted in clearings where soils compatible with high fruit production occur.


CONCLUSIONS

Although the occurrence of plants and the production of Brazil nut fruits (*Bertholletia excelsa*) were associated with the classes and the physical and chemical soil properties, pyxidium production differed between areas. In general, soil physical properties were limiting factors for the Brazil nut presented high fruit production and/or higher occurrence of trees. Filipinas environment showed a low fruit production and greater spatial variability of soil properties compared to Cachoeira.






ACKNOWLEDGMENTS






This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001. We thank the Brazilian Agricultural Research Corporation (Embrapa) for the data collection and the Kamukaia Network projects.



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REFERENCES

- Alvares CA, Stape JL, Sentelhas PC, Gonçalves JLM, Sparovek G. Köppen's climate classification map for Brazil. *Meteorol Z.* 2013;22:711-28. <https://doi.org/10.1127/0941-2948/2013/0507>
- Americas Regional Workshop (Conservation & Sustainable Management of Trees, Costa Rica, November 1996). *Bertholletia excelsa*. The IUCN Red List of Threatened Species. 1998:e.T32986A9741363. <https://doi.org/10.2305/IUCN.UK.1998.RLTS.T32986A9741363.en>
- Bardales NG, Moura DCS, Silva LM, Wadt LHO. Levantamento semi-detalhado e classificação de solos no Seringal Filipinas, Epitaciolândia, Acre. In: XXXIII Congresso Brasileiro de Ciência do Solo - Solos nos biomas brasileiros: sustentabilidade e mudanças climáticas; julho - agosto 2011; Uberlândia, Minas Gerais. Uberlândia: Sociedade Brasileira de Ciência do Solo; 2011. p. 1-4.
- Bernini TA. Caracterização mineralógica, identificação das substâncias húmicas e quantificação do alumínio em solos da formação Solimões - Acre [dissertação]. Seropédica: Universidade Federal Rural do Rio de Janeiro; 2010.
- Bertwell TD, Kainer KA, Cropper Junior WP, Staudhammer CL, Wadt LHO. Are Brazil nut populations threatened by fruit harvest? *Biotropica.* 2018;50:50-9. <https://doi.org/10.1111/btp.12505>
- Cambardella CA, Moorman TB, Novak JM, Parkin TB, Karlen DL, Turco RF, Konopka AE. Field scale variability of soil properties in central Iowa soils. *Soil Sci Soc Am J.* 1994;58:1501-11. <https://doi.org/10.2136/sssaj1994.03615995005800050033x>
- Carvalho MP, Takeda EY, Freddi OS. Variabilidade espacial de atributos de um solo sob videira em Vitória Brasil (SP). *Rev Bras Cienc Solo.* 2003;27:695-703. <https://doi.org/10.1590/S0100-06832003000400014>
- Cavalcante EGS, Alves MC, Souza ZM, Pereira GT. Variabilidade espacial de atributos químicos do solo sob diferentes usos e manejos. *Rev Bras Cienc Solo.* 2007;31:1329-39. <https://doi.org/10.1590/S0100-06832007000600012>
- Coopeagro. Plano de desenvolvimento sustentável do projeto de assentamento Chico Mendes. Acre: Município de Epitaciolândia; 2001.
- Costa JR, Castro ABC, Wandelli EV, Coral SCT, Souza SAG. Aspectos silviculturais da castanha-do-brasil (*Bertholletia excelsa*) em sistemas agroflorestais na Amazônia Central. *Acta Amazon.* 2009;39:843-50. <https://doi.org/10.1590/S0044-59672009000400013>

- Costa MG, Tonini H, Mendes Filho P. Atributos do solo relacionados com a produção da castanha-do-brasil (*Bertholletia excelsa*). *Flor@m*. 2017;24:e20150042. <https://doi.org/10.1590/2179-8087.004215>
- Elias GA, Santos R. Produtos florestais não madeireiros e valor potencial de exploração sustentável da floresta atlântica no sul de Santa Catarina. *Cienc Florest*. 2016;26:249-62. <https://doi.org/10.5902/1980509821117>
- Ferreira RRM, Bardales NG, Silva LM, Miqueloni DP, Wadt LHO. Levantamento de solos semidetalhado sob crescimento de castanhal nativo na região leste do Acre. Rio Branco: Embrapa Acre; 2017.
- Gandah M, Stein A, Brouwer J, Bouma J. Dynamics of spatial variability of millet growth and yields at three sites in Niger, West Africa and implications for precision agriculture research. *Agr Syst*. 2000;63:123-40. [https://doi.org/10.1016/S0308-521X\(99\)00076-1](https://doi.org/10.1016/S0308-521X(99)00076-1)
- Guerreiro QLM, Oliveira Júnior RC, Santos GR, Ruivo MLP, Beldini TP, Carvalho EJM, Silva KE, Guedes MC, Santos PRB. Spatial variability of soil physical and chemical aspects in a Brazil nut tree stand in the Brazilian Amazon. *Afr J Agric Res*. 2017;12:237-50. <https://doi.org/10.5897/AJAR2016.11766>
- Holdridge LR. *Ecología basada en zonas de vida*. San José: Instituto Interamericano de Ciencias Agrícolas; 1978.
- Homma AKO. Extrativismo vegetal ou plantio: qual a opção para a Amazônia? In: Homma AKO, editor. *Extrativismo vegetal na Amazônia: história, ecologia, economia e domesticação*. Brasília: Embrapa; 2014. p. 17-43.
- Instituto Brasileiro de Geografia e Estatística - IBGE. *Produção da extração vegetal e da silvicultura 2019*. Rio de Janeiro: IBGE; 2020.
- Ivanov GB, Fleig FD, Tonini H. Fatores edafoclimáticos relacionados à produção de sementes em castanhais nativos de Roraima. *Pesq Flor Bras*. 2018;38:e201701553. <https://doi.org/10.4336/2018.pfb.38e201701553>
- Kainer KA, Wadt LHO, Staudhammer CL. Explaining variation in Brazil nut fruit production. *Forest Ecol Manag*. 2007;250:244-55. <https://doi.org/10.1016/j.foreco.2007.05.024>
- Lepsch IF. *Formação e conservação dos solos*. São Paulo: Oficina de Textos; 2010.
- Locatelli M, Martins EP, Vieira AH, Pequeno PLL, Silva Filho EP, Ramalho AR. *Plantio de castanha-do-brasil: uma opção para reflorestamento em Rondônia*. Porto Velho: Embrapa, CPAF-Rondônia; 2002.
- Locatelli M, Vieira AH, Martins EP, Souza VF, Macedo RS. *Crescimento em diâmetro de castanha-do-brasil (Bertholletia excelsa H.B.K.) cultivada em solo de baixa fertilidade*. Porto Velho: Embrapa Rondônia; 2005.
- Marques Júnior J, Souza ZM, Pereira GT, Barbieri DM. Variabilidade espacial de matéria orgânica, P, K e CTC de um Latossolo cultivado com cana-de-açúcar por longo período. *Rev Biol Cienc Terra*. 2008;8:143-52.
- Mello YR, Oliveira TMN. Análise estatística e geoestatística da precipitação média para o município de Joinville (SC). *Rev Bras Meteorol*. 2016;31:229-39. <https://doi.org/10.1590/0102-778631220150040>
- Melo VF, Batista AH, Barbosa JZ, Barbeiro L, Gomes R, Dultra MTM. Soil quality and reforestation of the Brazil nut tree (*Bertholletia excelsa* Bonpl.) after laterite-type bauxite mining in the Brazilian Amazon forest. *Ecol Eng*. 2018;125:111-8. <https://doi.org/10.1016/j.ecoleng.2018.10.016>
- MMA - Ministério do Meio Ambiente, SEDR - Secretaria de Extrativismo e Desenvolvimento Rural Sustentável, Departamento de Extrativismo. *Castanha-do-Brasil: boas práticas para o extrativismo sustentável orgânico*. Brasília: MMA; 2017.
- Muller CH. *Castanha-do-brasil: estudos agrônômicos*. Belém: Embrapa CPATU; 1981.
- Myers GP, Newton AC, Melgarejo O. The influence of canopy gap size on natural regeneration of Brazil nut (*Bertholletia excelsa*) in Bolivia. *Forest Ecol Manag*. 2000;127:119-28. [https://doi.org/10.1016/S0378-1127\(99\)00124-3](https://doi.org/10.1016/S0378-1127(99)00124-3)

- Neves CA. A castanheira do Pará. *Revista de Agricultura*. 1938;13:462-76.
- Neves ES, Wadt LHO, Guedes MC. Estrutura populacional e potencial para o manejo de *Bertholletia excelsa* (Bonpl.) em castanhais nativos do Acre e Amapá. *Sci For*. 2016;44:19-31. <https://doi.org/10.18671/scifor.v44n109.02>
- Oliveira PCG, Farias PRS, Lima HV, Fernandes AR, Oliveira FA, Pita JD. Variabilidade espacial de propriedades químicas do solo e da produtividade de citros na Amazônia Oriental. *Rev Bras Eng Agr Amb*. 2009;13:708-15. <https://doi.org/10.1590/S1415-43662009000600007>
- Ortiz EG. Brazil nut (*Bertholletia excelsa*). In: Shanley P, Pierce AR, Laird SA, Guillen A, editors. *Tapping the green market: certification & management of non-timber forest products*. London: Earthscan Publications Ltd.; 2002. p. 61-74.
- Pelissari AL, Roveda M, Caldeira SF, Sanquetta CR, Corte APD, Rodrigues CK. Geostatistical modeling of timber volume spatial variability for *Tectona grandis* L.F. precision forestry. *Cerne*. 2017;23:115-22. <https://doi.org/10.1590/01047760201723012291>
- Peres CA, Baider C. Seed dispersal, spatial distribution and population structure of Brazil nut trees (*Bertholletia excelsa*) in southeastern Amazonia. *J Trop Ecol*. 1997;13:595-616.
- R Development Core Team. R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria; 2020. Available from: <http://www.R-project.org/>.
- Santos HG, Jacomine PKT, Anjos LHC, Oliveira VA, Lumbrreras JF, Coelho MR, Almeida JA, Araújo Filho JC, Oliveira JB, Cunha TJF. Sistema brasileiro de classificação de solos. 5. ed. rev. ampl. Brasília, DF: Embrapa; 2018.
- Santos RD, Lemos RC, Santos HG, Ker JC, Anjos LHC, Shimizu SH. Manual de descrição e coleta de solo no campo. 7. ed. rev. e ampl. Viçosa, MG: Sociedade Brasileira de Ciência do Solo; 2015.
- Secretaria de Estado de Meio Ambiente do Governo do Estado do Acre - SEMA. Diagnóstico socioeconômico e cadastro da Reserva Extrativista Chico Mendes - Plano Resex sustentável. Rio Branco: SEMA; 2010.
- Seidel EJ, Oliveira MS. Novo índice geoestatístico para a mensuração da dependência espacial. *Rev Bras Cienc do Solo*. 2014;38:699-705. <https://doi.org/10.1590/S0100-06832014000300002>
- Serrano ROP. Regeneração e estrutura populacional de *Bertholletia excelsa* H. B. K. em áreas com diferentes históricos de ocupação, no vale do Rio Acre (Brasil) [dissertação]. Rio Branco: Universidade Federal do Acre; 2005.
- Silva CS, Mendonça BAF, Pereira MG, Araújo EJG, Castellani DC. Spatial dependency and correlation of properties of soil cultivated with oil palm, *Elaeis guineensis*, in agroforestry systems in the eastern Brazilian Amazon. *Acta Amazon*. 2018;48:280-9. <https://doi.org/10.1590/1809-4392201704423>
- Silva DW, Claudino LS, Oliveira CD, Matei AP, Kubo RR. Extrativismo e desenvolvimento no contexto da Amazônia brasileira. *Desenvolv Meio Ambiente*. 2016;38:557-77. <https://doi.org/10.5380/dma.v38i0.44455>
- Silva LS, Marques Júnior J, Barrón V, Gomes RP, Teixeira DDB, Siqueira DS, Vasconcelos V. Spatial variability of iron oxides in soils from Brazilian sandstone and basalt. *Catena*. 2020;185:104258. <https://doi.org/10.1016/j.catena.2019.104258>
- Soil Survey Staff. Keys to soil taxonomy. 12th ed. Washington, DC: United States Department of Agriculture, Natural Resources Conservation Service; 2014.
- Spera ST, Magalhães CAS, Baldoni AB, Calderano SB. Caracterização pedológica de locais de estudo de populações naturais de castanheira-do-brasil no estado de Mato Grosso. *Nativa*. 2019;7:145-61. <https://doi.org/10.31413/nativa.v7i2.6502>
- Staudhammer CL, Wadt LHO, Kainer KA, Cunha TA. Comparative models disentangle drivers of fruit production variability of an economically and ecologically important long-lived Amazonian tree. *Sci Rep*. 2021;11:2563. <https://doi.org/10.1038/s41598-021-81948-4>
- Stone SS. From tapping to cutting trees: participation and agency in two community-based timber management projects in Acre, Brazil [dissertation]. Gainesville: University of Florida; 2003.

- Teixeira PC, Donagemma GK, Fontana A, Teixeira WG. Manual de métodos de análise de solo. 3. ed. rev e ampl. Brasília, DF: Embrapa; 2017.
- Vieira SR. Geoestatística em estudos de variabilidade espacial do solo. In: Novais RF, Alvarez VH, Schaefer GR, editores. Tópicos em ciência do solo. Viçosa: Sociedade Brasileira de Ciência do solo; 2000. v. 1. p. 1-54.
- Vilhena MR. Ciência, tecnologia e desenvolvimento na economia da castanha-do-Brasil: a transformação industrial da castanha-do-brasil na COMARU - Região Sul do Amapá [dissertação]. Campinas: Universidade Estadual de Campinas; 2004.
- Wadt LHO, Kainer KA, Staudhammer CL, Serrano ROP. Sustainable forest use in Brazilian extractive reserves: natural regeneration of Brazil nut in exploited populations. *Biol Conserv.* 2008;141:332-46. <https://doi.org/10.1016/j.biocon.2007.10.007>
- Wadt PGS. Manejo de solos ácidos do estado do Acre. Rio Branco: Embrapa Acre; 2002.
- Wanderley HS, Amorim RFC, Carvalho FO. Variabilidade espacial e preenchimento de falhas de dados pluviométricos para o estado de Alagoas. *Rev Bras Meteorol.* 2012;27:347-54. <https://doi.org/10.1590/S0102-77862012000300009>
- Warrick AW, Nielsen DR. Spatial variability of soil physical properties in the field. In: Hillel D, editor. *Applications of soil physics*. Cambridge: Academic press; 1980. p. 319-44.
- Zoneamento Ecológico-Econômico do Acre - ZEE. Recursos Naturais e Meio Ambiente. Rio Branco: Secretaria de Estado de Ciência, Tecnologia e Meio Ambiente; 2000. v. 1.