Carvalho, Lidiany Camila da S.; Philip M. Fearnside, Marcelo T. Nascimento, Reinaldo I. Barbosa. 2018. Amazon soil charcoal: Pyrogenic carbon stock depends of ignition source distance and forest type in Roraima, Brazil. ***Global Change Biology*** **24(9): 4122-4130. https://doi.org/10.1111/gcb.14277**

ISSN: 1365-2486

Title: Amazon soil charcoal: Pyrogenic carbon stock depends of ignition source distance and forest type in Roraima, Brazil

Running head: Amazon soil charcoal

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Keywords: Carbon sequestration, Charcoal stock, Global carbon cycle, Pyrogenic carbon, Seasonal forest, Soil charcoal.

Type of Paper: Primary Research Article

Word count: abstract = 261; main text = 3928 (excluding abstract, tables, figures and references)

Reference count: 53; **Number of Figures and Tables:** 2 tables and 3 figures

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Abstract

Pyrogenic carbon (PyC) derived from charcoal particles (paleo + modern) deposited in the soil column has been little studied in the Amazon, and our understanding of the factors that control the spatial and vertical distribution of these materials in the region's forest soils is still unclear. The objective of this study was to test the effect of forest type and distance from the ignition source on the PyC stocks contained in macroscopic particles of soil charcoal (≥ 2 mm; 1-m depth) dispersed in ecotone forests of the northern Brazilian Amazon. Thirty permanent plots were set up near a site that had been occupied by pre-Columbian and by modern populations until the late 1970s. The sampled plots represent seasonal and ombrophilous forests that occur under different hydro-edaphic restrictions. Our results indicate that the largest PyC stock was spatially dependent on distance to the ignition source (< 3 km), occurring mainly in flood-free ombrophilous forests (3.46±5.22 Mg PyC ha^{-1}). The vertical distribution of PyC in the deeper layers of the soil (> 50 cm) in seasonal forests was limited by hydro-edaphic impediments that restricted the occurrence of charcoal. These results suggest that PyC stocks derived from macroscopic charcoal particles in the soil of this Brazilian Amazon ecotone region are controlled by the distance from the ignition source of the fire, and that forest types with higher hydro-edaphic restrictions can inhibit formation and accumulation of charcoal. Making use of these distinctions reduces uncertainty and improves our ability to understand the variability of PyC stocks in forests with a history of fire in the Amazon.

Keywords: Carbon sequestration, Charcoal stock, Global carbon cycle, Pyrogenic carbon, Seasonal forest, Soil charcoal.

Introduction

Charcoal fragments are commonly found in forest soils in many parts of the Amazon, indicating that the region contains a large pool of pyrogenic carbon (PyC) formed over a great number of fire episodes by paleoclimatic anomalies and/or modern human activities (Bush *et al.*, 2007, Hermanowski *et al.*, 2015, Sanford *et al.*, 1985). These deposits are considered to be long-term carbon forms that are very important for the global carbon balance (100-1000 yr; Singh *et al.*, 2012, Spokas, 2013) because their production is an efficient mechanism for carbon sequestration (Santin *et al.*, 2015), and because the magnitude of these terrestrial reservoirs can be very large (Bird *et al.*, 2015, Landry & Matthews, 2017). However, these reservoirs of stable carbon have not been accounted by IPCC Guidelines (IPCC, 2006) because regional and global estimates still have large uncertainties related to spatial distribution, consumption rates, fuel quality, and factors affecting the rates of vertical accumulation and degradation (Forbes *et al.*, 2006, Reisser *et al.*, 2016).

In the Amazon there is already a clear qualitative understanding that much of the charcoal found in the soil column in mature forests originated from the historical interaction between humans and the environment, which was almost always linked to a high frequency of fires in the Holocene (Goulart *et al.*, 2017, McMichael *et al.*, 2017). Recent studies have suggested that the occurrence of charcoal is dependent on the distance from the ignition source because the spread of fire in the forest understory would tend to have both lower intensity and lower speed of propagation as distance from the source increases (Bush *et al.*, 2015, McMichael *et al.*, 2011). In this case, the probability of charcoal occurrence would also be associated with the environmental conditions that determine the occurrence of different forest types around the ignition sources.

Improved quantitative estimates of the PyC reservoir associated with the charcoal produced by these interactions is a priority due to the global importance of the Amazon region, and better spatial representation is needed of these carbon stocks (Turcios *et al.*, 2016). The scarcity of quantitative information on PyC stocks stems from the lack of real understanding of the effect of factors controlling the spatial and vertical distributions of charcoal among the different forest types in the Amazon (Koele *et al.*, 2017). Pedogenic variations and distinct hydro-edaphic restrictions can influence the formation and/or accumulation of both "paleo" carbon (deeper layers) produced by paleofires (Piperno & Becker, 1996) and the "modern" (post-Columbian) charcoal derived from surface fires that burn forest biomass deposited on the soil (Barbosa & Fearnside, 1999, Barni *et al.*, 2015, Fonseca *et al.*, 2017).

Although there are problems with the standardization of sampling methods and with analysis and spatialization (Zimmerman & Mitra, 2017), there is no doubt that improving understanding of the aspects that determine the spatial and vertical distribution of soil-charcoal stocks is an important part of the effort to reduce uncertainties and refining our estimates of PyC deposits in this forest compartment. The objective of the present study was to estimate PyC stocks derived from charcoal (paleo + modern) dispersed in the soil column of an ecotone forest area in the northern Brazilian Amazon, inferring its spatial and vertical distribution as a function of distance from the ignition source and as a function of the dominant forest types, which are closely associated with different hydro-edaphic characteristics.

Materials and Methods

Study area

The study was carried out at the Maracá Ecological Station, a federal conservation unit formed by Maracá Island and small islets in the Uraricoera River in the central-northern portion of Brazil's state of Roraima (3°15' – 3°35' N e 61°22'- 61°58' W) (Fig. 1). The climate of the region is seasonal and marked by the transition between savanna (Aw) and monsoon (Am) subtypes according to the Köppen classification. Based on data from the Maracá Meteorological Station (1984-2005), the average annual rainfall in the region is 2086±428 mm, where the driest months (<100 mm $month^{-1}$) are from December to March, and the wettest months (>300 mm $month^{-1}$) from May to August (Barbosa, 1997, Couto-Santos *et al.*, 2014). The predominant wind direction in the study region is northeast to southwest mainly in the driest months (Brazil-MME, 1975). The vegetation of Maracá is characterized by an ecotone zone formed by contact of the continuous forest formations with the large savanna area located in the northern part of the Brazilian Amazon, between the Rupununi and Branco River basins (Barbosa *et al.*, 2007, Milliken & Ratter, 1998). The continuous forest is characterized by a mosaic of ombrophilous and seasonal forests that occur on different soil and drainage types (Nortcliff & Robison, 1998, Robison & Nortcliff, 1991).

Experimental design and data collection

Data collection was carried out between July and October 2015 in a set of 30 permanent plots established by the Brazilian Program for Biodiversity Research (PPBio) in

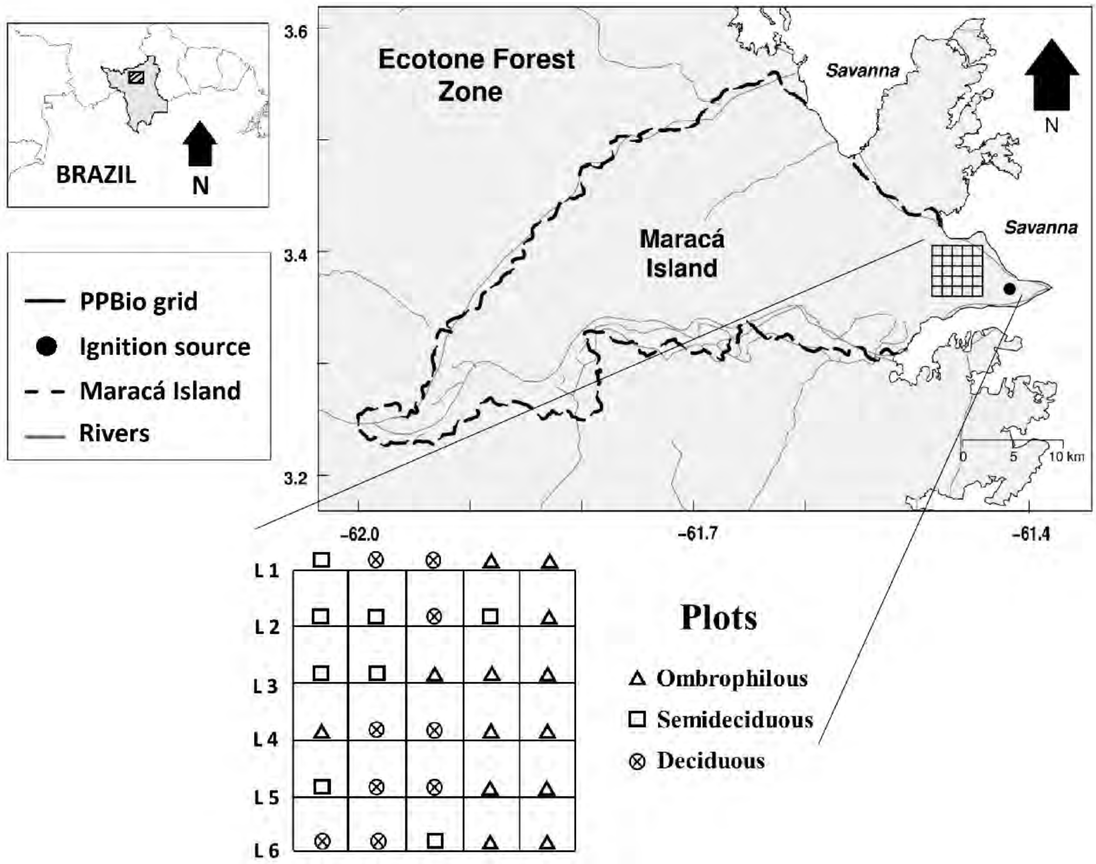

Figure 1. Study area indicating the sample grid and the set of permanent plots located in the eastern sector of Maracá Island, state of Roraima, northern Brazilian Amazonia.

the eastern portion of Maracá Island (Fig. 1). These plots follow the RAPELD standard and are arranged systematically along six trails, each 5 km in length, which follow an east-west orientation and form a 25-km² sampling grid (Pezzini *et al.*, 2012). The central line of each plot is defined by a transect 250 m in length that strictly follows the elevation contours in order to reduce environmental variability (Magnusson *et al.*, 2005). To estimate the charcoal stock, two subsamples were collected along this central line of each plot: one at 80 m and another at 160 m distance from the starting point of the plot. The subsamples were collected using a "bipartite root auger" (Eijkelkamp, Giesbeek, The Netherlands). Each subsample was obtained from vertical collections (0-100 cm in depth) divided into 10-cm sections. Each sample value represents the average of two subsamples obtained for each depth section, totaling 30 composite samples, each with 10 depth sections.

Classification of the forest type of each permanent plot was carried out based on the Brazilian vegetation classification system (Brazil-IBGE, 2012), taking advantage of the preliminary forest inventory (structure and species composition) carried out by Nascimento *et al.* (2017) in the 30 permanent plots (Table 1; Supplementary Material, Table S1). The plots in seasonal deciduous forests (n = 9) occupy the bottoms of valleys at low altitude (60±6 m a.s.l.) where poorly drained soils (seasonally flooded) occur and are characterized by high percentages of silt, in addition to high Al^{+3} and Fe^{+2} content. Seasonal semideciduous forests (n = 8) occupy slopes (75±5 m a.s.l.) formed by red and dark-red Ultisols without seasonal flooding, which are occasionally covered by rocky fragments (petroplintites or quartzites). The ombrophilous forests (n = 13) occupy flooding-free areas located on flat relief (75±4 m a.s.l.), where yellow and red-yellow Ultisols are predominant and Fe^{+2} levels are low.

Soil charcoal triage

In this study "soil charcoal" was defined as solid visible residual pieces (macroscopic particles ≥ 2 mm in diameter) derived from the carbonization of biomass by fire (paleo + modern), where “pyrogenic carbon” (PyC) is stored and dispersed through the vertical soil column (Buma *et al.*, 2014, Kuhlbusch & Crutzen, 1995, Preston & Schmidt, 2006). The soil collected (0-100 cm) was air dried, sifted and the charcoal particles were separated manually for each 10-cm interval. Particles < 2 mm in diameter were not collected due to the degree of uncertainty involved in the collection of very small fractions by the direct method. After separation, the charcoal particles were dried at 100±2°C in an electric oven until reaching constant weight (±0.0001 g). Soil samples from each collection section are deposited in the

Table 1. Environmental description of the main forest types that occur in the eastern portion of Maracá Island based on their hydro-edaphic characteristics.

Forest Type (1)	Drainage type (2)	Soil Class (2)	Relief (2)	Altitude (m)	Sand (%)	Silt (%)	Clay (%)	Al^{+3} (meq%)	Fe^{+2} (mg kg^{-1})
Ombrophilous (n=13)	Well	Ultisol (yellow and red-yellow)	flat and high	75.3	81.8	9.6	8.7	0.258	54.53
Seasonal - semideciduous (n=8)	Well	Ultisol (red and dark-red)	slope and high	75.5	78.7	11.4	9.9	0.200	74.91
Seasonal - deciduous (n=9)	Poor	Gray hydromorphic associated with Ultisol (yellow)	flat and low	60.2	78.6	14.2	7.2	0.316	131.51

(1) Forest types defined by the Brazilian vegetation classification system (Brazil-IBGE, 2012), together with the study by Nascimento *et al.* (2017). Numbers in parentheses represent the total of permanent plots sampled;

(2) Soil, drainage and relief classes were derived from field observations in association with the studies by Robison & Nortcliff (1991) and Villacorta (2017);

Soil analyses (0-20 cm) were performed by Pimentel & Baccaro (2011).

National Institute for Research in Amazonia's office in Boa Vista, Roraima (INPA/NAPRR). Chemical and physical soil data for each plot can be found in the PPBio data repository (Pimentel & Baccaro, 2011).

Geographical information on primary ignition source

Maracá Island is a valuable study area for this type of investigation due to the control that the Uraricoera River exerts both on the spread and penetration of fire from ignition sources external to the island, since the river functions as a natural geographical barrier. This geographical feature ensures that most forest fires originated from within the island and, presumably, the burned areas are near locations that were occupied by humans at the time. The eastern sector of Maracá Island was historically occupied by pre-Columbian (indigenous) populations and later by family farmers until the late 1970s. The island was used as an area for shifting cultivation and selective logging. In this part of the island it is possible to observe residual ceramics (Proctor & Miller, 1998) associated with trees with scars provoked by forest fires that occurred up to the late 1970s (Barlow *et al.*, 2010). The central and the western sectors of Maracá have no record of any human occupation site, presumably due to the fact that the soils are characterized by rocky outcrops with no possibility of long-term agriculture.

Although the existing preliminary surveys at Maracá are not entirely conclusive due to the lack of a greater number of observations reporting the presence/absence of ceramic material or of vestiges of seasonal/temporary pre-Columbian communities in the central and western sectors of Maracá, evidence is sufficiently strong to indicate that the eastern portion of the island was intensely occupied. All these geographical and human occupation features are present in the eastern portion of Maracá Island and allow inferences about the spatial footprint of most fire occurred in Maracá, considering a single geographical area of human use. Despite uncertainties, the approximate location of the archaeological site in the eastern portion of the island (UTM / Zone 20 - 372697.8 N; 673724.0 W) was defined as the primary ignition source, since this site was the main center of human habitation of Maracá (Proctor & Miller, 1998).

Data analysis

The soil-charcoal stock (0-100 cm) in each permanent plot was estimated as the arithmetic mean of the two subsamples and their subsequent conversion to units of mass per unit area (Mg ha^{-1}), considering soil density (g cm^{-3}) as a correction factor as suggested by Carcaillet & Talon (2001). Soil density was obtained by the Kopecky's Ring method (Embrapa, 2011), and the results are available in the PPBio data repository (Barbosa *et al.*, 2017). Pyrogenic carbon stock (Mg PyC ha^{-1}) was obtained using the carbon concentration (64.95%) determined from charcoal derived from tree biomass burned in ecotone forest areas in Roraima (Barbosa & Fearnside, 1996).

A normality test was applied to charcoal and PyC stock data in ombrophilous (well-drained) and seasonal (poorly and well-drained) forests. Non-parametric analysis of variance (Kruskal-Wallis; $\alpha = 0.05$) was applied to detect differences among the three forest types. The homogeneity of variance for PyC stock distributed along the soil profile in the three forest types was tested (Barlett's test, $\alpha = 0.05$). The effect of the distance to the primary ignition source on the spatial distribution of PyC stocks was determined by regression analysis. All analyses were performed with R software (R Core Team, 2016).

Results

Stock and spatial variability

Charcoal fragments (≥ 2 mm) were found in 67% (20) of the soil samples analyzed (Supplementary Material, Table S2). The size of the fragments was very variable, but rarely exceeded 1 cm in length. In the 10 plots without charcoal, eight were in seasonal forests: five in poorly drained soils (deciduous forest) and three in well-drained soils (semideciduous forest). The mean charcoal stock varied from 0 to 28.70 Mg ha^{-1} (2.44±5.78 Mg ha^{-1}; mean±SD), equivalent to 1.59±3.76 Mg PyC ha^{-1} (Table 2). The disaggregation of this value among the analyzed forest types indicates that the PyC stock of ombrophilous forest (3.46±5.22 Mg PyC ha^{-1}) was higher than that of semideciduous and deciduous seasonal forests ($H = 18.209$, $p = 0.0001$).

Table 2. Variation in stocks of charcoal and pyrogenic carbon (Mg ha^{-1}, mean ± SD, 1-m depth) in relation to the forest types on Maracá Island. Standard deviation in parentheses. Different lowercase letters indicate significant differences between the means (Kruskal-Wallis, α=0.05).

Forest type	Charcoal stock (Mg ha^{-1})	PyC (Mg ha^{-1})
Ombrophilous	5.33 (8.04) b	3.46 (5.22) b
Seasonal – semideciduous	0.30 (0.48) a	0.19 (0.31) a
Seasonal – deciduous	0.18 (0.31) a	0.12 (0.20) a
Total	2.44 (5.78)	1.59 (3.76)

Vertical variability

Macroscopic charcoal fragments were found along the entire vertical column (0-100 cm) of the ombrophilous forests (well-drained), but this pattern did not occur in seasonal forest types. The vertical distribution of the PyC derived from charcoal particles varied heterogeneously (Barlett's test; $p = 0.0013$) between the ombrophilous forest and the other two seasonal types (Fig. 2). Most PyC found in ombrophilous forests was concentrated in the upper soil layers, especially between 10 and 50 cm depth (75.5%). In contrast, PyC in the semideciduous seasonal forest (well-drained) was only found between 0 and 60 cm depth. Some samples in the deepest sections (60-100 cm) could not be collected in this forest type because of physical impediments (layers of rocks). In the deciduous seasonal forest (poorly drained), the PyC stock was limited to the first 50 cm of soil because the deeper layers (50-100 cm) were almost always weathered due to contact with the groundwater.

Ignition-source distance

Distance from the primary ignition source was significantly related to PyC stock ($F = 36.59$, $p < 0.0001$; $R^2 = 0.6703$). The relationship is represented by a decay model (Equation 1), which is linearized to obtain the homoscedasticity. The PyC stock increases with proximity to the primary ignition source (Fig. 3):

$$ln(Y) = 4.9964 - 3.7705 \times ln(X) \qquad \text{(Eq. 1)}$$

Where Y is the pyrogenic carbon stock (Mg PyC ha^{-1}) estimated for each permanent plot and X is the distance (km) from the primary ignition source.

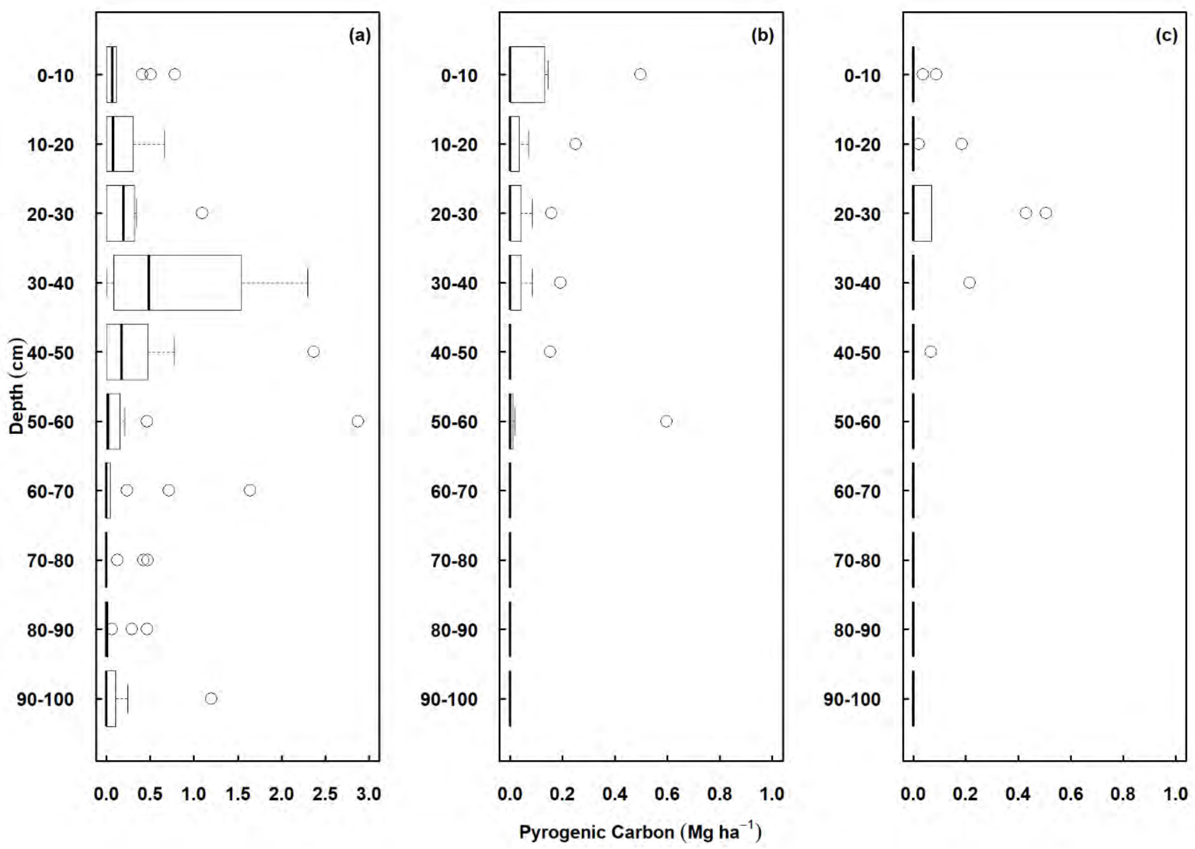

Figure 2. Vertical distribution of the PyC stock (Mg PyC ha^{-1}; 1-m depth) in different forest types of Maracá Island: (a) Ombrophilous, (b) Seasonal - semideciduous and (c) Seasonal - deciduous. Box plots indicate the 75% (upper limit) and 25% (lower limit) percentiles of the data, and the values of the medians (center line). The center bars indicate the range (maximum and minimum) of the average soil PyC stocks in each depth section. Hollow circles represent outliers.

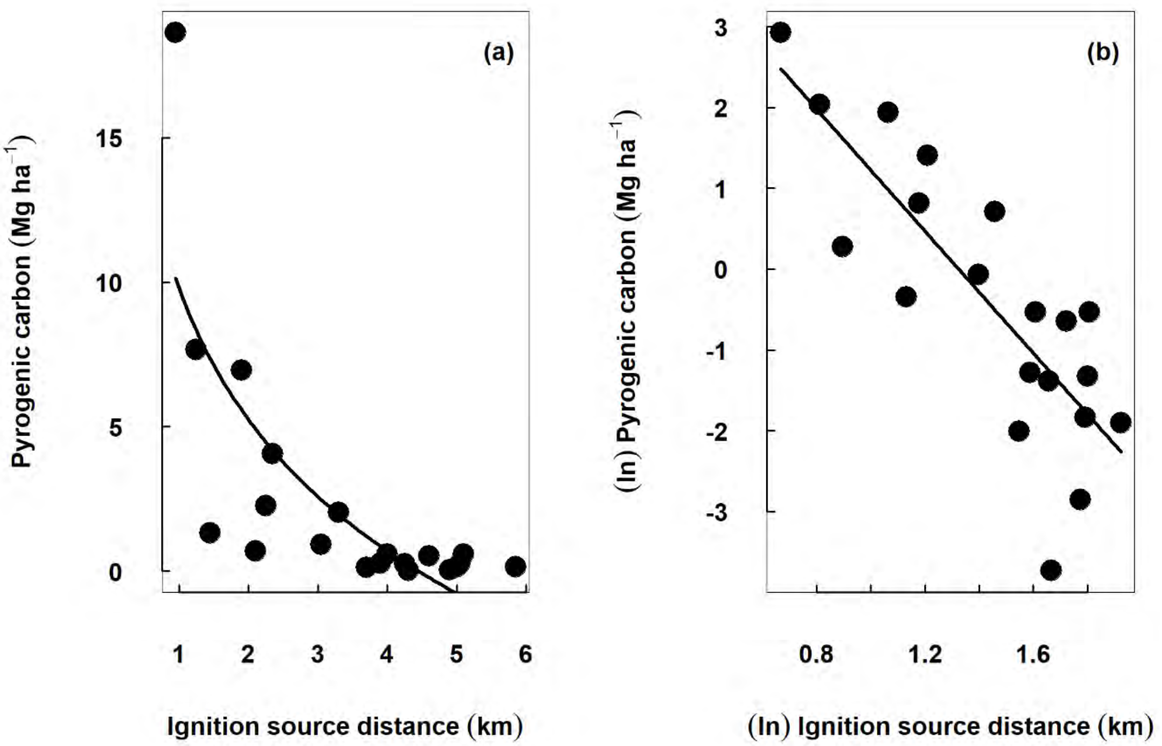

Figure 3. Relationship between distance from primary ignition source (km) and pyrogenic carbon stock (Mg PyC ha^{-1}) for ecotone forests in the northern portion of Brazil's state of Roraima. Panel (a) represents a non-linear function and (b) a linearized function to obtain homoscedasticity. Ten permanent plots without charcoal in the soil column were not recorded in the graphs to avoid distortion in the models.

Discussion

Stock and spatial variability

Our findings are the first for the mosaic of forests in the ecotone zone of the northern Brazilian Amazon, indicating that different hydro-edaphic conditions support different PyC stocks derived from the charcoal dispersed in the soil column. These findings are consistent with paleoclimatic studies carried out in the savanna-forest transition zone of Roraima (Desjardins *et al.*, 1996), indicating a strong association between recent periods of human activity (modern: surface layers) and drier past phases (paleo: deeper layers) that provide variation in the accumulation of charcoal along the soil column.

Our general mean values for charcoal stock (2.44 Mg ha^{-1}) can be considered conservative according to both the particle triage criterion (≥ 2 mm diameter) and sample depth (1 m). For example, when compared to different types of mature forests in the upper Rio Negro (4.6-13.9 Mg ha^{-1}; Sanford *et al.*, 1985), our result is 1.9-5.7 times lower. Similarly, PyC mean values in Maracá (1.59 Mg PyC ha^{-1}) represent only ~70% of the PyC values estimated by Turcios *et al.* (2016) for seasonal forest fragments dispersed in savanna areas in Roraima (2.24 Mg PyC ha^{-1}), and they are only half those estimated by Koele *et al.* (2017) as a general mean for the entire Amazon (3.62 Mg PyC ha^{-1}). These distinctions indicate that, in addition to the observed differences between the criteria for inclusion/exclusion of particles and sampling depth, the environmental conditions that define the forest type (e.g. hydro-edaphic conditions) and the fire history (e.g., areas with greater or lesser anthropogenic pressure) must also be considered as factors controlling PyC stocks in this forest compartment. In any case, the evidence from this study indicates (together with the other studies in the region) that soil charcoal represents an important long-term PyC reservoir that has been neglected in the estimates of carbon flow and stock in the Amazon.

Our sampling also indicates that there is great spatial variability in PyC stocks derived from the charcoal deposited in the soil under the different forest types that form the ecotone zone. These distinctions are important because they have a direct influence on regional estimates. For example, not all samples collected had charcoal fragments in the soil column. This variation is common in investigations of this nature and has been credited mainly to the quantity and high spatial variation of the combustible material that is burned. However, most samples without charcoal were in the seasonal forests, which are associated with some type of environmental impediment. At Maracá, the hydro-edaphic gradient that conditions each forest type determined the spatial variation of its soil-charcoal stocks, indicating that forests free of periodic flooding may contain greater amounts of PyC as compared to forests on poorly drained soil (seasonally flooding) or on slopes with rocky material in the deeper soil layers (> 50 cm). This result is in agreement with the observations of Bassini & Becker (1990), indicating a low frequency of charcoal occurrence in ravines and stream beds in forest sites near Manaus in central Amazonia. Thus, considering that the structure and above-ground tree biomass (fuel material) of the three forest types at Maracá are equivalent (363-434 Mg ha^{-1}; Nascimento *et al.*, 2014), it is possible to infer that the effect of fire (paleo + modern) on charcoal formation was enhanced in ombrophilous forests (~1.5% charcoal stored in soil in terms of above ground biomass), and inhibited or masked in seasonal forests (0.04-0.07%) due to distinct hydro-edaphic traits that define these forest types (Supplementary Material, Table S3).

Although our data are not intended to assess the possible causes of the observed patterns, various hypotheses are possible. The greater amount of charcoal in well-drained upland forests could be produced either by more char production in the upland forests (since they are most suitable for shifting cultivation) or by more char loss in the lowland forests, or by both effects. Seasonal fluctuations in water table may well have led to the comparatively rapid degradation of charcoal in the lowland soils (at least to particles < 2 mm in diameter). It is also possible that seasonal flooding in low areas causes charcoal, being buoyant, to simply float away in the next wet season.

Vertical variability

The hydro-edaphic conditions associated with the forest types investigated at Maracá also had a substantial effect on the distribution and the vertical accumulation of macroscopic charcoal particles in the soil column (1-m depth). Individually, ombrophilous forest accumulated more charcoal and PyC in the sub-surface layers (10-40 cm) than did other forest types, with an irregular decay pattern consistent with the findings of Hammond *et al.* (2007) in forests with low fire frequency in Guyana. These irregular decay patterns among the forest types studied at Maracá indicate that other factors have been acting on the vertical distribution of soil charcoal (paleo + modern), such as land use (mainly in places that are more suitable for shifting cultivation, such as ombrophilous forests), climate change (environmental change involving severe past fires between glacial and interglacial phases) or pedoturbations such as windthrows and migration of charcoal by burning of thick roots. These factors are intrinsic characteristics of each forest type and, therefore, they are part of the environmental and structural representation which is contextualized by different hydro-edaphic conditions that define the vertical distribution of soil charcoal stocks at Maracá.

The lack of a firm decay pattern in the PyC pool in the ombrophilous forest at Maracá differs from the exponential pattern found by Turcios *et al.* (2016), and that was assumed by Koele *et al.* (2017) as a general model for the whole Amazon region. In the case of seasonal forests that are periodically flooded, both the flow and the presence of water in the soil column are likely to be important factors limiting the occurrence of macroscopic charcoal particles in the soil. Under conditions of high humidity, the soil can work as an inhibitor of fire input (i.e., less production of charcoal) or as an accelerator of the fragmentation of any macroscopic charcoal particles that are produced, modifying the form and the fate of the PyC, as was also suggested by Foereid *et al.* (2011) and Kasin & Ohlson (2013).

This inference is consistent and indicates that over time the periodically flooded forests of Maracá act to favor the hydrological transport and/or degradation of macroscopic charcoal particles. PyC derived from macroscopic particles would therefore tend to be partially lost through remineralization and partially reduced to chemical and physical forms with higher recalcitrance in the environment and that can only be detected by analytical methods (Bird *et al.*, 2015, Hammes *et al.*, 2007). On the other hand, seasonal forests without periodic flooding also have low charcoal stocks, especially in the deeper soil, in cases where layers of rocks are present that act as physical barriers. Forests on shallow soils associated with slopes are not uncommon in Amazonia, especially in the contact zones (ecotones) at the edges of the plateaus of central Brazil (on the southern edge of the Amazon forest) and the Guianas (on the northern edge), as in the case of the ecotone in Maracá. However, these soil conditions also limit the accumulation of charcoal particles due to pedogenic barriers (rock layers), which can act as a physical factor removing charcoal through erosive transport on steep slopes. Understanding these pedogenic determinants is critical to efforts to associate different forest types in the Amazon with vertical soil charcoal and PyC stocks. Therefore, we suggest that the exponential decay model must be used parsimoniously for PyC pools in regional estimates because this model is not suitable for all soil types in the region. Disregarding these attributes may lead to substantial bias in estimates of Amazonian PyC stocks.

Ignition source distance

Our results imply that distance from the fire ignition source (e.g. human occupation sites) is also an important controlling factor for the occurrence of charcoal in the forests in the northern forests of Roraima. Similar results were also observed in African tropical forests (Vleminckx *et al.*, 2014) and ancient sites of human occupation across the Amazon basin (McMichael *et al.*, 2011). The proposed model for Maracá is consistent with previous studies and implies that fire does not follow homogeneous patterns of frequency and spread, resulting in larger PyC stocks (~4.63 Mg ha^{-1}) near of the areas of use (< 3 km) and lower (~0.28 Mg ha^{-1}) or non-existent stocks at greater distances from these areas (3-6.5 km). This result does not imply that areas distant from the ancient or present occupation sites in the Amazon are fire-free or have no soil-charcoal stocks, but it does show that the probability of fire occurrence is much lower. Thus, for modeling the PyC stocks derived from soil charcoal throughout Amazon region, estimates for charcoal and PyC must include the effect of known sites of past and present human occupation. These sites represent environmental, paleoclimatic and occupation contexts that are directly related to charcoal occurrence in the soil column. Although information on past fire-spread patterns in association with charcoal stocks does not exist at the regional scale in Amazonia, models that take advantage of distance relationships with charcoal occurrence will produce more realistic estimates of PyC stocks in the region.

Based on our results, we conclude that variation in the PyC stock derived from soil charcoal in the study region seems to be controlled by distance from the ignition source. The hydro-edaphic conditions that define each forest type can either inhibit or favor the formation and/or the accumulation of macroscopic charcoal particles dispersed in the soil column.

Independent of the chronology of the accumulation of charcoal fragments, our findings indicate that the pedogenesis of the forest types in our study area is also a determining factor for the macroscopic charcoal stocks, especially in the deeper soil layers in seasonal forest types. Making use of these distinctions reduces uncertainty and improves our ability to understand the variability of PyC stocks throughout the soil profile of forest ecosystems with a history of fire (paleo + modern) in the Amazon.

Acknowledgments

This study was supported by INPA's institutional project ''Ecology and Management of Natural Resources of the Roraima Savanna" (PPI-INPA 015/122). The Brazilian Coordination for the Improvement of Higher Education Personnel (CAPES) provided a fellowship for L.C.S. Carvalho, and the National Council for Scientific and Technological Development of Brazil (CNPq) provided fellowships for R.I. Barbosa (CNPq 303081/2011-2), P.M. Fearnside (CNPq 304020/2010-9) and M.T. Nascimento (CNPq 308352/2015-7). The Chico Mendes Institute for Biodiversity Conservation (ICMBio) provided infrastructure and authorization for the study (Authorization 46537-1). Two anonymous reviewers provided helpful comments.

References

Barbosa RI (1997) Distribuição das chuvas em Roraima. In: *Homem, Ambiente e Ecologia no Estado de Roraima.* (eds Barbosa RI, Ferreira EFG, Castellon EG) pp 325-335. Manaus, Amazonas, Brazil, Instituto Nacional de Pesquisas da Amazônia (INPA).

Barbosa RI, Campos C, Pinto F, Fearnside PM (2007) The "Lavrados" of Roraima: Biodiversity and Conservation of Brazil's Amazonian Savannas. Functional Ecosystems and Communities, **1**, 29-41.

Barbosa RI, Carvalho LCS, Melo VF (2017) Soil bulk density in nine permanent plots of the PPBio grid at Maracá Ecological Station, Roraima. Manaus, Amazonas (Brazil) <https://ppbiodata.inpa.gov.br/metacatui/#view/PPBioAmOc.114.5>, Programa de Pesquisas em Biodiversidade (PPBio).

Barbosa RI, Fearnside PM (1996) Pasture burning in Amazonia: dynamics of residual biomass and the storage ande realease of aboveground carbon. Journal of Geophysical Research, **101**, 25847-25857.

Barbosa RI, Fearnside PM (1999) Incêndios na Amazônia brasileira: estimativa da emissão de gases do efeito estufa pela queima de diferentes ecossistemas de Roraima na passagem do evento "El Niño" (1997/98). Acta Amazonica, **29**, 513-534.

Barlow J, Silveira JM, Cochrane MA (2010) Fire scars on Amazonian trees: exploring the cryptic fire history of the Ilha de Maraca. Biotropica, **42**, 405-409.

Barni PE, Pereira VB, Manzi AO, Barbosa RI (2015) Deforestation and forest fires in Roraima and their relationship with phytoclimatic regions in the Northern Brazilian Amazon. Environmental Management, **55**, 1124-1138.

Bassini F, Becker P (1990) Charcoal's occurrence in soil depends on topography in *terra firme* forest near Manaus, Brazil. Biotropica, **22**, 420-422.

Bird MI, Wynn JG, Saiz G, Wurster CM, McBeath A (2015) The pyrogenic carbon cycle. Annual Review of Earth and Planetary Sciences, **43**, 273-298.

Brazil-IBGE (2012) Manual técnico da vegetação brasileira: sistema fitogeográfico, inventário das formações florestais e campestres, técnicas e manejo de coleções botânicas, procedimentos para mapeamentos. In: *Manuais Técnicos em Geociências 1.* pp 275, Rio de Janeiro, Brazil, Instituto Brasileiro de Geografia e Estatística (IBGE).

Brazil-MME (1975) Projeto RADAMBRASIL - Levantamento de Recursos Naturais. Rio de Janeiro, Ministério das Minas e Energia, Departamento Nacional de Produção Mineral.

Buma B, Poore RE, Wessman CA (2014) Disturbances, their interactions, and cumulative effects on carbon and charcoal stocks in a forested ecosystem. Ecosystems, **17**, 947-959.

Bush MB, McMichael CH, Piperno DR *et al.* (2015) Anthropogenic influence on Amazonian forests in pre-history: An ecological perspective. Journal of Biogeography, **42**, 2277-2288.

Bush MB, Silman MR, De Toledo MB *et al.* (2007) Holocene fire and occupation in Amazonia: records from two lake districts. Philosophical transactions of the Royal Society of London. Series B, Biological sciences, **362**, 209-218.

Carcaillet C, Talon B (2001) Soil carbon sequestration by Holocene fires inferred from soil charcoal in dry French Alps. Artic, Antartic, and Alpine Research, **33**, 282-288.

Couto-Santos FR, Luizão FJ, Carneiro-Filho A (2014) The influence of the conservation status and changes in the rainfall regime on forest-savanna mosaic dynamics in Northern Brazilian Amazonia. Acta Amazonica, **44**, 197-206.

Desjardins T, Carneiro-Filho A, Mariotti A, Chauvel A, Girardin C (1996) Changes of the forest-savanna boundary in Brazilian Amazonia during the Holocene revealed by stable isotope ratios of soil organic carbon. Oecologia, **108**, 749-756.
Embrapa (2011) Manual de Métodos de Análise de Solo. In: *Documentos 132.* (eds Donagema GK, Campos DVBD, Calderano SB, Teixeira WG, Viana JHM) pp 230, Rio de Janeiro, RJ, Embrapa Solos.
Foereid B, Lehmann J, Major J (2011) Modeling black carbon degradation and movement in soil. Plant and Soil, **345**, 223-236.
Fonseca MG, Anderson LO, Arai E *et al.* (2017) Climatic and anthropogenic drivers of northern Amazon fires during the 2015/2016 El Niño event. Ecological Applications, **27**, 2514-2527.
Forbes MS, Raison RJ, Skjemstad JO (2006) Formation, transformation and transport of black carbon (charcoal) in terrestrial and aquatic ecosystems. Science of the Total Environment, **370**, 190-206.
Goulart AC, Macario KD, Scheel-Ybert R *et al.* (2017) Charcoal chronology of the Amazon forest: A record of biodiversity preserved by ancient fires. Quaternary Geochronology, **41**, 180-186.
Hammes K, Schmidt MWI, Smernik RJ *et al.* (2007) Comparison of quantification methods to measure fire-derived (black/elemental) carbon in soils and sediments using reference materials from soil, water, sediment and the atmosphere. Global Biogeochemical Cycles, **21**, GB3016.
Hammond DS, Ter Steege H, Van Der Borg K (2007) Upland soil charcoal in the wet tropical forests of Central Guyana. Biotropica, **39**, 153–160.
Hermanowski B, Costa ML, Behling H (2015) Possible linkages of palaeofires in southeast Amazonia to a changing climate since the Last Glacial Maximum. Vegetation History and Archaeobotany, **24**, 279-292.
IPCC (2006) 2006 IPCC (Intergovernmental Panel on Climate Change) Guidelines for National Greenhouse Gas Inventories - Appendix 1: CO_2 Removals in Residual Combustion Products (charcoal): Basis for Future Methodological Development. In: Eggleston HS, Buendia L, Miwa K, Ngara T and Tanabe K (Eds.), National Greenhouse Gas Inventories Programme, IGES. pp Ap 1.1 - Ap 1.2.
Kasin I, Ohlson M (2013) An experimental study of charcoal degradation in a boreal forest. Soil Biology and Biochemistry, **65**, 39-49.
Koele N, Bird M, Haig J *et al.* (2017) Amazon Basin forest pyrogenic carbon stocks: First estimate of deep storage. Geoderma, **306**, 237-243.
Kuhlbusch TaJ, Crutzen PJ (1995) Toward a global estimate of black carbon in residues of vegetation fires representing a sink of atmospheric CO_2 and a source of O_2. Global Biogeochemical Cycles, **9**, 491-501.
Landry J-S, Matthews HD (2017) The global pyrogenic carbon cycle and its impact on the level of atmospheric CO2 over past and future centuries. Global Change Biology, **23**, 3205–3218.
Magnusson WE, Lima AP, Luizão R, Luizão F, Costa FRC, Castilho CV, Kinupp VF (2005) RAPELD: A modification of the Gentry Method for biodiversity surveys in long-term ecological research sites. Biota Neotropica, **5**, 19-24.
McMichael CH, Bush MB, Piperno DR, Silman MR, Zimmerman AR, Anderson C (2011) Spatial and temporal scales of pre-Columbian disturbance associated with western Amazonian lakes. The Holocene, **22**, 131-141.
McMichael CN, Matthews-Bird F, Farfan-Rios W, Feeley KJ (2017) Ancient human disturbances may be skewing our understanding of Amazonian forests. Proceedings of the National Academy of Sciences of the United States of America, **114**, 522-527.

Milliken W, Ratter JA (1998) The vegetation of the Ilha de Maracá. In: *Maracá: the biodiversity and environment of an Amazonian rainforest.* (eds Milliken W, Ratter JA) pp 71-112. Chichester, UK, Wiley.
Nascimento MT, Barbosa RI, Dexter KG, Castilho CV, Silva Carvalho LC, Villela DM (2017) Is the Peltogyne gracilipes monodominant forest characterised by distinct soils? Acta Oecologica, **85**, 104-107.
Nascimento MT, Carvalho LCS, Barbosa RI, Villela DM (2014) Variation in floristic composition, demography and above-ground biomass over a 20-year period in an Amazonian monodominant forest. Plant Ecology & Diversity, **7**, 293-303.
Nortcliff S, Robison D (1998) The soils of the Ilha de Maracá. In: *Maracá: the biodiversity and environment of an Amazonian rainforest.* (eds Milliken W, Ratter JA) pp 47-69. Chichester, UK, Wiley.
Pezzini F, Melo PHA, Oliveira DMS *et al.* (2012) The Brazilian Program for Biodiversity Research (PPBio) Information System. Biodiversity & Ecology, **4**, 265-274.
Pimentel TP, Baccaro FB (2011) Coletas e análises físico-químicas do solo de 30 parcelas permanentes instaladas na Estação Ecológica Maracá - RR (ESEC Maracá / ICMBio). Boa Vista, Roraima <https://ppbiodata.inpa.gov.br/metacatui/#view/menger.194.2>, PPBio.
Piperno DR, Becker P (1996) Vegetational history of a site in the Central Amazon Basin derived from phytolith and charcoal records from natural soils. Quaternary Research, **45**, 202–209.
Preston CM, Schmidt MWI (2006) Black (pyrogenic) carbon: a synthesis of current knowledge and uncertainties with special consideration of boreal regions. Biogeosciences, **3**, 397–420.
Proctor J, Miller RP (1998) Human occupation on the Ilha de Maracá: preliminary notes. In: *Maracá: the biodiversity and environment of an Amazonian rainforest.* (eds Milliken W, Ratter JA) pp 431-442. Chichester, UK, Wiley.
R Core Team (2016) *R: A language and environment for statistical computing,* Vienna, Austria <http://www.R-project.org/>, R Foundation for Statistical Computing.
Reisser M, Purves RS, Schmidt MWI, Abiven S (2016) Pyrogenic carbon in soils: a literature-based inventory and a global estimation of its content in soil organic carbon and stocks. Frontiers in Earth Science, **4**, 80.
Robison DM, Nortcliff S (1991) Os solos da reserva de Maracá, Roraima: segunda aproximação. Acta Amazonica, **21**, 409-424.
Sanford RL, Saldarriaga J, Clarck KE, Uhl C, Herrera R (1985) Amazon rain-forest fires. Science, **227**, 53-55.
Santin C, Doerr SH, Preston CM, Gonzalez-Rodriguez G (2015) Pyrogenic organic matter production from wildfires: a missing sink in the global carbon cycle. Global Change Biology, **21**, 1621-1633.
Singh BP, Cowie AL, Smernik RJ (2012) Biochar carbon stability in a clayey soil as a function of feedstock and pyrolysis temperature. Environmental Science & Technology, **46**, 11770-11778.
Spokas KA (2013) Impact of biochar field aging on laboratory greenhouse gas production potentials. GCB Bioenergy, **5**, 165-176.
Turcios MM, Jaramillo MM, Vale Jr. JF, Fearnside PM, Barbosa RI (2016) Soil charcoal as long-term pyrogenic carbon storage in Amazonian seasonal forests. Global Change Biology, **22**, 190-197.
Villacorta CDA (2017) Condicionantes edáficas para a monodominância do gênero Peltogyne (Fabaceae) na Ilha de Maracá, Roraima, norte da Amazônia brasileira. Unpublished Master Degree UFRR, Boa Vista (RR), 46 pp.

Vleminckx J, Morin-Rivat J, Biwole AB *et al.* (2014) Soil charcoal to assess the impacts of past human disturbances on tropical forests. PloS one, **9**, e108121.
Zimmerman AR, Mitra S (2017) Trial by fire: on the terminology and methods used in pyrogenic organic carbon research. Frontiers in Earth Science, **5**, 95.

SUPPLEMENTARY MATERIAL

Amazon soil charcoal: Pyrogenic carbon stock depends on ignition-source distance and forest type in Roraima, Brazil

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Figure S1. Fire scars observed at the base of trees located near (< 3 km) the ignition source in the eastern portion of Maracá Island.

Table S1 – Hydro-edaphic characterization of the 30 permanent plots (PPBio Maracá) used in soil-charcoal sampling in an ecotone zone (Roraima, Maracá Island) in the northern Brazilian Amazon. Data from chemical and physical soil analyses were derived from Pimentel & Baccaro (2011). Drainage was defined by field observation associated with a study by Villacorta (2017). Forest types were redefined from the study by Nascimento *et al*. (2017).

Permanent Plot (PPBio-Code)	Forest Type (1)	Drainage (2)	Coverage Index % (3)	Altitude (m a.s.l.)	Sand %	Silt %	Clay %	pH (H_2O)	Al (meq%)	Mg (cmolc kg^{-1})	Fe (mg kg^{-1})
L1_0500	Ombrophilous	Well	0	71.9	78.1	13.5	8.5	4.15	0.56	0.08	50.0
L1_1500	Ombrophilous	Well	0	77.8	84.8	9.3	6.0	4.25	0.31	0.08	45.0
L1_2500	Seasonal	Poor	40	57.7	87.2	9.8	3.0	4.88	0.25	0.24	128.0
L1_3500	Seasonal	Poor	33	54.9	47.1	36.0	17.0	4.26	0.35	0.25	145.4
L1_4500	Seasonal	Well	20.6	77.9	74.0	14.5	11.5	4.84	0.04	0.44	63.5
L2_0500	Ombrophilous	Well	0	69.8	82.7	6.4	11.0	4.35	0.10	0.10	47.5
L2_1500	Seasonal	Well	9.5	74.5	72.4	13.6	14.0	4.14	0.40	0.19	72.0
L2_2500	Seasonal	Poor	31.6	61.2	82.4	10.6	7.0	4.32	0.25	0.20	101.5
L2_3500	Seasonal	Well	6.3	79.8	77.0	13.5	9.5	4.71	0.05	0.18	49.0
L2_4500	Seasonal	Well	11.1	81.2	74.3	13.2	12.5	4.77	0.07	0.37	56.8
L3_0500	Ombrophilous	Well	0	78.5	83.2	7.8	9.0	4.04	0.35	0.10	60.5
L3_1500	Ombrophilous	Well	0	75.7	85.3	9.2	5.5	4.64	0.20	0.15	85.5
L3_2500	Ombrophilous	Well	0	78.5	86.9	10.1	3.0	4.56	0.15	0.05	32.5
L3_3500	Seasonal	Well	11.9	72.6	82.4	8.1	9.5	4.26	0.30	0.13	145.5
L3_4500	Seasonal	Well	5.9	81.2	87.0	6.0	7.0	4.38	0.25	0.06	76.5
L4_0500	Ombrophilous	Well	0	72.6	79.1	12.4	8.5	4.29	0.50	0.09	63.0
L4_1500	Ombrophilous	Well	0	79.2	77.1	13.9	9.0	4.08	0.30	0.04	78.0
L4_2500	Seasonal	Poor	24.2	64.8	88.4	7.2	4.5	4.62	0.25	0.28	180.5
L4_3500	Seasonal	Poor	24.1	63.1	81.6	13.5	5.0	4.69	0.30	0.12	117.0
L4_4500	Ombrophilous	Well	0	82.9	82.9	9.1	8.0	4.60	0.10	0.10	40.5
L5_0500	Ombrophilous	Well	0	72.9	76.6	8.9	14.5	5.08	0.04	0.28	27.4
L5_1500	Ombrophilous	Well	0	73.8	82.2	9.3	8.5	4.21	0.30	0.06	73.0
L5_2500	Seasonal	Poor	(*)	62.8	79.7	13.3	7.0	4.45	0.35	0.42	148.0
L5_3500	Seasonal	Poor	44.4	59.5	81.9	12.6	5.5	4.60	0.40	0.19	182.5
L5_4500	Seasonal	Well	15.9	67.4	83.2	10.3	6.5	4.68	0.15	0.17	64.0

L6_0500	Ombrophilous	Well	0	72.7	84.0	6.5	9.5	4.66	0.30	0.06	57.5
L6_1500	Ombrophilous	Well	0	72.9	80.1	8.4	11.5	4.65	0.15	0.18	48.5
L6_2500	Seasonal	Well	8.5	69.3	79.1	11.9	9.0	4.25	0.34	0.27	72.0
L6_3500	Seasonal	Poor	24.7	59.9	78.4	13.1	8.5	4.60	0.25	0.29	48.0
L6_4500	Seasonal	Poor	58.4	58.2	80.6	11.9	7.5	4.60	0.44	0.33	132.7

1. Forest types defined by the Brazilian vegetation classification system (Brazil-IBGE, 2012) in addition to the study by Nascimento *et al*. (2017). Numbers in parentheses represent the total numbers of permanent plots sampled;

2. Soil classes, drainage and relief were derived from field observations from the studies by Robison & Nortcliff (1991) and Villacorta (2017);

3. Coverage index of deciduous species. Calculated as the mean of the sum of the percentage of the basal area and the percentage of the number of deciduous individuals in relation to the total number of individual trees with diameter at the breast height (DBH) ≥ 10 cm. The species *Peltogyne gracilipes* (Fabaceae) was used as a deciduous descriptor in all plots, following the study by Nascimento *et al*. (2017). *Not calculated;

4. Soil analysis (0-20 cm) performed by Pimentel & Baccaro (2011).

Table S2. Charcoal stock (Mg ha^{-1}) quantified along the soil column (0-100 cm) and the distance of each sample (permanent plot) from the ignition source (UTM / Zone 20 - 372697.8 N; 673724.0 W) in an ecotone forest zone in the eastern portion of Maracá Island. Where "ns" = soil section not sampled because of (i) friable edaphic material formed by constant contact with the water table in the deeper layers or (ii) contact with rock layers.

Permanent Plot (PPBio Code)	Ignition source distance (km)	Soil Depth (cm)										
		00_10	10_20	20_30	30_40	40_50	50_60	60_70	70_80	80_90	90_100	Total
L1_0500	4.25	0.0000	0.0739	0.0000	0.3125	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3864
L1_1500	4.60	0.4082	0.0949	0.2211	0.0407	0.0238	0.0177	0.0000	0.0000	0.0000	0.0000	0.8064
L1_2500	5.10	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
L1_3500	5.75	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
L1_4500	6.45	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	ns	ns	ns	ns	0.0000
L2_0500	3.30	0.0690	0.1989	0.1375	2.2134	0.1922	0.0000	0.0158	0.0000	0.0614	0.2431	3.1314
L2_1500	3.70	0.1226	0.0000	0.0849	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.2076
L2_2500	4.30	0.0370	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0370
L2_3500	5.05	0.0000	0.2508	0.1575	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.4083
L2_4500	5.85	0.1447	0.0000	0.0000	0.0853	0.0000	0.0000	0.0000	0.0000	ns	ns	0.2300
L3_0500	2.35	0.7786	0.0000	0.3358	2.2973	2.3701	0.0830	0.0372	0.1256	0.0136	0.2299	6.2711
L3_1500	2.85	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
L3_2500	3.65	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
L3_3500	4.50	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	ns	ns	ns	ns	0.0000
L3_4500	5.40	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	ns	ns	0.0000
L4_0500	1.45	0.5055	0.3043	0.3180	0.1258	0.7781	0.0000	0.0000	0.0000	0.0000	0.0000	2.0317
L4_1500	2.25	0.0890	0.0000	1.0955	0.4415	0.2262	0.4631	0.2315	0.4733	0.4657	0.0000	3.4858
L4_2500	3.15	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	ns	0.0000
L4_3500	4.10	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
L4_4500	5.10	0.0000	0.0781	0.1913	0.0000	0.4836	0.0442	0.0000	0.0000	0.0000	0.1044	0.9016
L5_0500	0.95	0.0674	4.3729	19.5572	0.8662	0.0797	0.2074	1.6432	0.4185	0.2867	1.1994	28.6987
L5_1500	1.90	0.1069	9.7684	0.0000	0.4844	0.1727	0.1481	0.0369	0.0000	0.0000	0.0000	10.7173
L5_2500	2.95	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
L5_3500	3.90	0.0000	0.0000	0.4291	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.4291
L5_4500	4.90	0.0000	0.0697	0.0000	0.0000	0.0000	0.0193	0.0000	0.0000	0.0000	0.0000	0.0890
L6_0500	1.25	0.0000	0.6644	0.2700	7.2858	0.0000	2.8718	0.7154	0.0000	0.0000	0.0000	11.8074

L6_1500	2.10	0.0000	0.0000	0.1032	0.5120	0.4716	0.0000	0.0000	0.0000	0.0000	0.0000	1.0868
L6_2500	3.05	0.4977	0.0000	0.0000	0.1922	0.1542	0.5966	0.0000	0.0000	ns	ns	1.4408
L6_3500	4.00	0.0000	0.1840	0.5069	0.2140	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9048
L6_4500	5.00	0.0875	0.0210	0.0694	0.0000	0.0677	0.0000	0.0000	0.0000	0.0000	0.0000	0.2457

Table S3. Reference values (%) considering the soil charcoal (1-m depth) as a percentage of total above-ground tree biomass estimated for the three forest types.

Forest type	Above ground biomass (*) ($Mg\ ha^{-1}$)	Charcoal stock ($Mg\ ha^{-1}$)	Reference Value (%)
Ombrophilous	363	5.33	1.45
Seasonal – semideciduous	434	0.30	0.07
Seasonal – deciduous	440	0.18	0.04

(*) Estimated by Nascimento *et al.* (2014).

References

Brazil-IBGE (2012) Manual técnico da vegetação brasileira: sistema fitogeográfico, inventário das formações florestais e campestres, técnicas e manejo de coleções botânicas, procedimentos para mapeamentos. In: *Manuais Técnicos em Geociências 1*. pp 275, Rio de Janeiro, Brazil, Instituto Brasileiro de Geografia e Estatística (IBGE).

Nascimento MT, Barbosa RI, Dexter KG, Castilho CV, Silva Carvalho LC, Villela DM (2017) Is the Peltogyne gracilipes monodominant forest characterised by distinct soils? Acta Oecologica, **85**, 104-107.

Nascimento MT, Carvalho LCS, Barbosa RI, Villela DM (2014) Variation in floristic composition, demography and above-ground biomass over a 20-year period in an Amazonian monodominant forest. Plant Ecology & Diversity, **7**, 293-303.

Pimentel TP, Baccaro FB (2011) Coletas e análises físico-químicas do solo de 30 parcelas permanentes instaladas na Estação Ecológica Maracá - RR (ESEC Maracá / ICMBio). Boa Vista, Roraima <https://ppbiodata.inpa.gov.br/metacatui/#view/menger.194.2>, PPBio.

Robison DM, Nortcliff S (1991) Os solos da reserva de Maracá, Roraima: segunda aproximação. Acta Amazonica, **21**, 409-424.

Villacorta CDA (2017) Condicionantes edáficas para a monodominância do gênero Peltogyne (Fabaceae) na Ilha de Maracá, Roraima, norte da Amazônia brasileira. Unpublished Master Degree UFRR, Boa Vista (RR), 46 pp.