Turcios, M. M.; Jaramillo, M. M. A., V.B.; Vale Jr., J. F.; Fearnside, P.M.; Barbosa, R.I. 2015. Soil charcoal as long-term pyrogenic carbon storage in Amazonian seasonal forests. Global Change Biology, doi: 10.1111/gcb.13049.

Title: Soil charcoal as long-term pyrogenic carbon storage in Amazonian seasonal forests

Running head: Pyrogenic carbon stocks

Authors: Maryory M. Turcios[1], Margarita M. A. Jaramillo[1], José F. do Vale Jr. [1], Philip M. Fearnside[2], Reinaldo Imbrozio Barbosa[3(*)]

Author affiliations:

1. Federal University of Roraima (UFRR), Post-graduate Program in Natural Resources (PRONAT), Av. Cap. Ene Garcez 2413 - Bairro Aeroporto, 69304-000 Boa Vista, Roraima, Brazil

2. Department of Environmental Dynamics, National Institute for Research in Amazonia (INPA), Av. André Araújo no 2936, CEP 69067-375, Manaus, Amazonas, Brazil

3. Department of Environmental Dynamics, National Institute for Research in Amazonia (INPA), Roraima's Office (NPRR), Rua Coronel Pinto 315 – Centro, 69301-150 Boa Vista, Roraima, Brazil

(*) Corresponding Author: Reinaldo Imbrozio Barbosa **-** Tel.: + 55 95 3623 9433;
e-mail: reinaldo@inpa.gov.br

Keywords: Charcoal stocks, forest fires, global carbon cycle, seasonal forest, soil charcoal

Paper type: Primary Research Article

Word count: abstract = 247; main text = 3333 (excluding abstract and references)

Reference count: 73; **Number of Figures and Tables:** 4 (+ 4 Supp. Material)

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Abstract

Forest fires (paleo + modern) have caused charcoal particles to accumulate in the soil vertical profile in Amazonia. This forest compartment is a long-term carbon reservoir with an important role in global carbon balance. Estimates of stocks remain uncertain in forests that have not been altered by deforestation but that have been impacted by understory fires and selective logging. We estimated the stock of pyrogenic carbon derived from charcoal accumulated in the soil profile of seasonal forest fragments impacted by fire and selective logging in the northern portion of Brazilian Amazonia. Sixty-nine soil cores to 1-m depth were collected in 12 forest fragments of different sizes. Charcoal stocks averaged 3.45±2.17 Mg ha^{-1} (2.24±1.41 Mg C ha^{-1}). Pyrogenic carbon was not directly related to the size of the forest fragments. This carbon is equivalent to 1.40% (0.25% to 4.04%) of the carbon stocked in aboveground live tree biomass in these fragments. The vertical distribution of pyrogenic carbon indicates an exponential model, where the 0-30 cm depth range has 60% of the total stored. The total area of Brazil's Amazonian seasonal forests and ecotones not altered by deforestation implies 65-286 Tg of pyrogenic carbon accumulated along the soil vertical profile. This is 1.2-2.3 times the total amount of residual pyrogenic carbon formed by biomass burning worldwide in one year. Our analysis suggests that the accumulated charcoal in the soil vertical profile in Amazonian forests is a substantial pyrogenic carbon pool that needs to be considered in global carbon models.

Keywords: Charcoal stocks, forest fires, global carbon cycle, seasonal forest, soil charcoal

Introduction

Charcoal stored in terrestrial soils represents one of the ways by which carbon is positioned in the environment in relatively inert form and hence acts as a long-term reservoir because it does not easily recombine with the oxygen to form CO_2 (Druffel, 2004, Fearnside *et al.*, 2001, Schmidt, 2004, Seiler & Crutzen, 1980). The charcoal is also transferred to ocean sediments by processes of erosion and river transport, adding to another long-term carbon pool (Suman, 1984). This charcoal is derived from incomplete pyrolysis of biomass and it is characterized by a high concentration of carbon and high resistance to natural degradation processes (Foereid *et al.*, 2011, Forbes *et al.*, 2006, Kuhlbusch & Crutzen, 1995).

Despite their importance as a “missing carbon sink”, these deposits are not counted in the IPCC Guidelines for the balance of global emissions and sinks of atmospheric CO_2 (IPCC, 2006, Lehmann *et al.*, 2006, Santin *et al.*, 2015). This omission is mainly because of uncertainty stemming from high variability in the spatial distribution and in the nature of biomass exposed to fire in different ecosystems (Glaser *et al.*, 2002, Preston & Schmidt, 2006, Simpson & Hatcher, 2004). Environmental conditions (e.g., soil, vegetation type and climate) are also determinants affecting the frequency of surface soil charcoal formation, consumption of charcoal in subsequent fires and the quality of the charcoal formed (Bird *et al.*, 2015). Irregularity in charcoal deposition rates directly influences vertical accumulation and spatial distribution of pyrogenic carbon (Forbes *et al.*, 2006, IPCC, 2006).

In contrast to studies in temperate and boreal regions (DeLuca & Aplet, 2008, Licata & Sanford, 2012), uncertainty regarding charcoal in the Amazon lies mainly in the fact that most studies involving charcoal distribution in the soil profile were designed to answer other questions: (i) paleo-environmental dynamics (Cordeiro *et al.*, 2014, Meneses *et al.*, 2013, Toledo & Bush, 2007), (ii) arqueological evidence for indigenous land uses (Levis *et al.*, 2012), (iii) formation of anthropogenic black soils (Glaser *et al.*, 2002, Lehmann *et al.*, 2003, Roosevelt, 2013) and (iv) soil charcoal formation by clearing and biomass burning associated with deforestation (Fearnside *et al.*, 2007, Graça *et al.*, 1999). However, the Brazilian Amazon still has a vast area of intact forests (> 3.0 × 10^6 km^2 not disturbed by recent deforestation), where realistic estimates of carbon stocks in different compartments are needed to improve understanding of the region's role in regulating global climate (Nogueira *et al.*, 2015, Saatchi *et al.*, 2007).

In general, charcoal dispersed along the soil vertical profile under forests that have not been perturbed by recent deforestation comes from biomass burning following two process: (i) paleo-fires that occurred throughout the Holocene in Amazonia (Meggers, 1994, Saldarriaga & West, 1986, Sanford *et al.*, 1985) associated with human disturbances and/or climatic anomalies (Bassini & Becker, 1990, Hermanowski *et al.*, 2015, Santos *et al.*, 2000) and, (ii) modern forest fires in the post-1970 period, where severe droughts and feedbacks associated with forest selective logging increase risk of understory fires (Laurance & Williamson, 2001, Morton *et al.*, 2013, Nepstad *et al.*, 2004). Charcoal formed by paleo-fires is relatively stable in the deeper soil layers, while modern forest fires have an additive effect on pyrogenic carbon in the surface layers. This effect is most dramatic in the set of seasonal forests and ecotones that represent much of the forest area in the southern and northern "arcs of deforestation" in Amazonia (Barni *et al.*, 2015, Brazil-INPE, 2013, Fearnside *et al.*, 2009). Since these forest types have often been subjected to selective logging and are very sensitive to severe droughts, there is a higher incidence of forest fires in these regions (Alencar *et al.*, 2015, Aragão *et al.*, 2008, Brienen *et al.*, 2015). In this case, the charcoal formed will depend on the size of the affected area and on the degree of impact of selective logging on forest structure, as these factors determine the amount of necromass exposed to fire (Alencar *et al.*, 2011, Barbosa & Fearnside, 1999). Estimates of charcoal stock in these forests reduce uncertainty and improve understanding of carbon sources and sinks in Amazonia.

The aim of this study was to estimate the carbon stock derived from soil charcoal accumulated in the vertical profile of seasonal forests affected by fire and selective logging in the Brazilian Amazon's northern "arc of deforestation". These remnants are natural paleoclimatic forest fragments that have a history of both Holocene fires (Desjardins *et al.*, 1996) and modern forest fires (Santos *et al.*, 2013), which can provide important clues to the spatial and vertical variability of charcoal carbon deposits (fossil + modern). Our objectives were to (i) determine charcoal carbon stocks using the size of forest fragments as a spatial predictor and (ii) determine the pattern of distribution of charcoal carbon along the soil vertical profile. The results extend knowledge of pyrogenic carbon stocks in Amazonia and provide information for inclusion of this forest compartment in national estimates of greenhouse-gas emissions.

Materials and Methods

Study Area

The study was conducted in the Nova Amazônia I Settlement Project (PANA-I) in an area of ~440 km^2 located ~35 km northwest of the city of Boa Vista, capital of the state of Roraima (Fig. 1). This area is situated in the ecotone zone of forest-savanna of the Branco River-Rupununi River region, on the border with Venezuela and Guyana (Barbosa *et al.*, 2007, Huber *et al.*, 2006). We mapped 34 remnants (forest fragments or forest islands) of semideciduous seasonal forests with paleoclimatic origin. The fragments were naturally dispersed over a landscape with low relief and altitude (~90 m a.s.l.). Forest fragments in the forest-savanna ecotone in Roraima have been exposed to frequent impact of selective logging and understory forest fire but have been relatively resilient in maintaining their size despite constant disturbances (Couto-Santos *et al.*, 2014). Fabaceae and Sapotaceae are the most abundant plant families in these fragments, while *Pouteria surumuensis* Baehni (Sapotaceae), the main tree species, is a pioneer (Jaramillo, 2015, Santos *et al.*, 2013).

All forest fragments in this region are on Oxisol with sandy clay-loam texture, moderate acidity, low fertility and organic matter content generally decreasing with increasing depth (Fig. S1, Supplementary Material). Data from the Brazilian National Institute of Meteorology (INMET) station for the city of Boa Vista indicate that the driest months are between December and March, annual rainfall varies from 1500 to1700 mm and average annual temperature is 27.8 ± 0.6 °C; all of these values are consistent with the Aw climate according to the Köppen classification (Barbosa *et al.*, 2012).

Experimental Design

Twelve fragments (sample units or sample sites) were randomly sampled. In each fragment, two or three equidistant transects were laid out in the north-south direction, where soil samples (subsamples) were collected with a "bipartite root auger" (Eijkelkamp, Giesbeek, The Netherlands). The sampler is a cylindrical tube 8 cm in diameter. Each core was taken from a profile to 100 cm depth, divided into six intervals (0-10, 10-20, 20-30, 30-40, 40-50 and 90-100 cm). The subsamples were arranged equidistantly along the transects in order to capture the variability in charcoal stocks between the edges and the interior of each fragment. Using several subsamples rather than a single soil core has been found to be a suitable tool for describing the spatial and vertical distribution of soil charcoal at each sample site (McMichael *et al.*, 2012). Fire (paleo + modern) produces charcoal that is randomly and non-uniformly dispersed (Sanford & Horn, 2000). A single core for a sample site would, therefore, be inadequate for estimating soil-carbon stocks. In total, 69 soil cores (each divided into six depth ranges) were collected in the12 forest fragments between December 2013 and February 2014, which is the dry period in this region (Table S1, Supplementary Material).

Charcoal Triage

Various direct and indirect methods exist for quantifying the different fractions of charcoal particles (Buma *et al.*, 2014, Hammes *et al.*, 2007, Skjernstad *et al.*, 1999). We adopted a direct method to quantify macroscopic charcoal particles (≥ 1 mm in diameter), which were manually collected in each 10-cm depth interval. Coarse particles (≥ 2 mm in diameter) were directly separated from the air-dried (24 h) soil by sieving, while smaller particles (≥ 1 mm and <2 mm) were collected by the flotation method. The flotation method (Carcaillet, 2001) consisted of placing air-dried soil in a recipient with water to collect the floating charcoal pieces. Smaller particles (<1 mm) were discarded. Pieces of soil charcoal saturated with water were considered to be insignificant because soil samples were collected in the regional dry period. Voucher specimens of the soil samples were deposited at the National Institute for Research in Amazonia base in Boa Vista, Roraima (INPA-NPRR). Finally, all collected pieces were dried in an electric oven (± 102 °C) to constant weight.

Data Transformation

Charcoal quantities was converted to mass per unit area (Mg ha^{-1}) for each depth range (0-10, 10-20, 20-30, 30-40, 40-50 and 90-100 cm). All values were adjusted for soil bulk density along the 1-m vertical profile, as suggested by Carcaillet & Talon (2001). Bulk density was estimated by Feitosa (2009) using a horizontal collection of undeformed samples obtained by the Kopecky Method (Embrapa, 1997) (Fig. S2, Supplementary Material). The charcoal mass in each depth interval not sampled directly (50-60, 60-70, 70-80 and 80-90 cm) was estimated indirectly using the exponential regression model with the highest coefficient of determination (R^2) for each forest fragment. We used the final range of 90-100 cm as a proxy to calibrate the curve of the models obtained in each fragment following an exponential decay pattern similar to that observed for micro charcoal flux in lake sediments in Roraima (Cordeiro *et al.*, 2014). Finally, charcoal stock for each forest fragment was calculated as an arithmetic mean of the set of sub-samples for each depth interval.

To transform charcoal mass values (Mg ha^{-1}) into pyrogenic carbon stock (Mg C ha^{-1}) we used the average carbon concentration of 64.95% estimated for charcoal pieces formed by biomass burning in the ecotone of Roraima (Barbosa & Fearnside, 1996). After this procedure, a single regression model for the carbon stock derived from charcoal mass was derived in order to determine the general vertical distribution pattern for the 1-m profile.

Data Analysis

The data set was subjected to normality tests. Pyrogenic carbon stock (dependent variable) was related to the area of each forest fragment (independent variable) for the purpose of checking general spatial patterns of carbon deposits on the basis of the current size of these fragments. The relation between total pyrogenic carbon stock (to 1-m depth) and the aboveground live biomass of trees with diameter at breast height (DBH) ≥ 10 cm was calculated as a percentage. Tree biomass in each fragment was obtained from Jaramillo (2015). Carbon concentration in live tree biomass was considered to be 48.5% (Silva, 2007). The purpose of this calculation was to create a reference value for seasonal forests affected by fire and selective logging, which is easy to integrate into general models of carbon flux, as suggested by Forbes *et al.* (2006). Finally, a one-way analysis of variance ($\text{ANOVA}_{0.05}$; Bartlett's $\text{test}_{0.05}$) was used to verify differences in the means and variances of the carbon stocks along the soil vertical profile of all fragments (vertical variability). All analyses were performed with R software (R Core Team, 2014).

Results

Charcoal and Pyrogenic Carbon

All forest fragments (sample units) contained charcoal particles along the soil vertical profile to 1-m depth, indicating that fire (paleo + modern) disturbances have been relatively recurrent in these seasonal ecosystems. Only nine sub-samples (13%) contained no carbon particles ($\geq$ 1 mm) along the soil vertical profile. There were no particles larger than 15 mm in diameter in any of the sub-samples assessed. Estimated soil charcoal stock considering all fragments analyzed was 3.45±2.17 Mg ha^{-1} while pyrogenic carbon (2.24±1.41 Mg C ha^{-1}) was equivalent to 1.40% (range 0.25% to 4.04%) of the carbon stock in aboveground live biomass of trees with DBH $\geq$ 10 cm (Table 1). High variability was found among the charcoal stocks in the 12 forest fragments (Bartlett's $test_{0.05}$, $p < 0.0001$). Forest-fragment size was a weak predictor of pyrogenic carbon stock due to high variability within each fragment (Fig. 2).

Vertical Variability

Estimates of carbon stock in soil charcoal differed along the vertical profile (one-way ANOVA; $F_{0.05} = 4.1719$; $p < 0.0001$), with the largest single carbon concentration (26.5%) occurring in the 10-20 cm range (Fig. 3a,b; Table S2 in Supplementary Material). The first soil layers (0-30 cm) held 60.5% of the total carbon stock while the deepest layer (90-100 cm) held the lowest percentage (4.2%). The distribution of pyrogenic carbon along the soil vertical profile was calculated as an exponential decay pattern with high heterogeneity of variances in the values observed at different depths (Bartlett's test$_{0.05}$, $p < 0.00001$). The general decay pattern for pyrogenic carbon followed the model below:

$$Y = 0.5299 \times e^{-0.022 \times X} \quad (R^2 = 0.8618)$$

Where Y = pyrogenic carbon stock (Mg C ha^{-1}) and X = midpoint of the depth interval (cm).

Discussion

The soil charcoal stock observed along the 1-m profile shows that incidence of fires (paleo + modern) over space and time have been determining the accumulation of pyrogenic carbon in seasonal forest soils in this area of the Amazon region. Values for charcoal stocks found under these forest fragments in Roraima (range 0.79-7.22 Mg ha^{-1}) are close to the means found under forests near San Carlos de Rio Negro, Venezuela (4.6-13.9 Mg ha^{-1}) (Sanford *et al.*, 1985). Although our values do not include small charcoal particles (<1 mm in diameter) along the soil vertical profile, and therefore can be considered as conservative, their order of magnitude indicates that this forest compartment cannot be neglected in regional estimates of carbon stocks and flows.

Pyrogenic carbon stock (range 0.46-4.69 Mg C ha^{-1}) found along the soil vertical profile is also of the same order of magnitude as charcoal carbon formed by modern biomass burning following deforestation at a variety of locations throughout Brazilian Amazonia (1.6-6.0 Mg C ha^{-1}) (Fearnside *et al.*, 1999, Fearnside *et al.*, 2001, Graça *et al.*, 1999, Righi *et al.*, 2009). In this case, pyrogenic carbon represents 2.2% of the total carbon affected by fire, but, since it is derived from burning primary forests for agricultural purposes, the larger amounts of necromass exposed to fire make combustion more intense (Fearnside, 2002). This reference value for deforestation in primary forests should not be confused with the soil pyrogenic carbon stocks (1-m depth) for forests that were not recently cleared but have been impacted by understory fires and selective logging in the modern period (e.g., 1.40% of the aboveground live carbon in trees in this study). Modern accumulation contributes a smaller amount (0.01-0.26 Mg C ha^{-1} for each understory fire) and is regulated by different processes and rates of charcoal formation and consumption (Barbosa & Fearnside, 1999). Therefore, our value for pyrogenic carbon stock represents a substantial fossilized charcoal deposit, in addition to the smaller quantity of pyrogenic carbon produced in the modern age and infrequently deposited in the topsoil.

The values given here show that accumulation of pyrogenic carbon (fossil + modern) in this type of forest is not related to the area of the forest fragments but indicates high spatial variability among their individual carbon stocks. This is suggested as a pattern for tropical soils indicating that the history of paleo-fires and the availability and distribution of biomass exposed to fire are the most important factors (Bird *et al.*, 2015, Power *et al.*, 2008, Titiz & Sanford Jr., 2007). These factors are also consistent with what has been observed in uncontrolled savanna fires in the areas adjacent to the fragments we studied in Roraima. Modern uncontrolled fires in the Roraima savanna are frequent, of low intensity and occur at random (Barbosa & Fearnside, 2005), spreading in the understory of the forest fragments and producing soil charcoal at different temporal and spatial scales. This charcoal source is in addition to that from sporadic deforestation of small portions of the fragments for subsistence farming (both modern and ancient). However, independent of the mix of processes (paleo-fires, swidden agriculture and modern understory fires), the soil charcoal formed may be considered as a proportion of the biomass affected by fire in the depositional environment (Power *et al.*, 2008). We therefore suggest using the reference range (0.25% to 4.04% of aboveground carbon in live trees) to estimate pyrogenic carbon stocks in the soil vertical profile (1-m depth) under seasonal forests with a history of Holocene fires and with frequent impacts from selective logging and understory fires. Although uncertainties are still substantial, aboveground carbon in live trees is easiest to estimate and provides a realistic alternative basis for estimation that avoids subjective values that are far from the reality of observed carbon stocks.

Differences in the distribution charcoal deposits along the soil vertical profile are consistent with Amazonian paleoclimate studies in ecotone areas in Roraima (Cordeiro *et al.*, 2014, Desjardins *et al.*, 1996), where the highest charcoal concentration was found in the layers closest to the soil surface. This is a relatively steady pattern in ecotones in the northern and southern “arcs of deforestation” in Brazilian Amazonia, and a relation of this pattern to modern climate stability has been suggested (Bush *et al.*, 2008). On the other hand, the vertical model of soil charcoal distribution found in our study does not have the same decay pattern as that observed in other Amazon sites. For example, in forests in Guyana (Hammond *et al.*, 2007) and in ombrophilous forest close to Manaus in central Amazonia (Piperno & Becker, 1996, Santos *et al.*, 2000), soil charcoal presence was highest in intermediate layers (30-60 cm). These comparisons indicate that vertical patterns will vary in accord with regional historical factors such as fire frequency, climate change, bio-pedoturbation and land use at each location. Therefore, the vertical decay model (to 1-m depth) described in this study cannot be considered to be a standard for the whole of Amazonia, but it indicates that the distribution of charcoal deposits in the soil profile of the seasonal forest studied supports the largest concentration of pyrogenic carbon in the layers closest to the surface.

Based on our results, we conclude that carbon stocks (fossil + modern) derived from soil charcoal in seasonal forest fragments affected by fires and selective logging in Brazil’s state of Roraima show high spatial variability and an exponential decay pattern with depth in the soil profile. The largest pyrogenic carbon concentrations are associated with the layers closest to the surface. Our results imply that the remaining area of seasonal forests and ecotones that have not been altered by deforestation in Brazilian Amazonia as a whole (783.8 × 10^3 km^2: (FUNCATE, 2006) have a storage potential of 65-286 Tg of pyrogenic carbon to 1-m depth. This is 1.2-2.3 times the total residual pyrogenic carbon produced by biomass burning worldwide in one year (56-123 Tg: Bird *et al.*, 2015), indicating the order of magnitude of this forest carbon compartment. Despite the uncertainty involved in estimates of this magnitude, our analysis suggests that the substantial amount of pyrogenic carbon found in Amazon forest soils must be considered a matter of priority for incorporation into global carbon models.

Acknowledgments

This study was supported by the "Ecology and Management of Natural Resources of the Roraima Savanna" project (PPI-INPA 015/122) and the National Council for Scientific and Technological Development of Brazil (CNPq 303081/2011-2), under a fellowship for R.I. Barbosa. M.M. Turcios was supported by a post-graduate fellowship provided by the Organization of American States (OAS). We thank Karine Dias Batista (Soil Laboratory, EMBRAPA-Roraima), Valdinar Melo (CCA - UFRR) and Semiramys Moreira (CCA - UFRR) for their collaboration in the soil analysis. Urias Santana (EAGRO - UFRR), Williamar Silva (PRONAT - UFRR) and Heleno Parente (INPA - Núcleo Roraima) collaborated in the field work. P.E. Barni (UERR) produced the map. Tad Bennicoff (Smithsonian Tropical Research Institute, Center for Tropical Forest Science Program Records) helped in bibliographic queries. Referee comments were very helpful.

References

Alencar A, Asner GP, Knapp D, Zarin D (2011) Temporal variability of forest fires in eastern Amazonia. Ecological Applications, **21**, 2397–2412.

Alencar AA, Brando PM, Asner GP, Putz FE (2015) Landscape fragmentation, severe drought and the new Amazon forest fire regime. Ecological Applications, (http://dx.doi.org/10.1890/1814-1528.1891).

Aragão LE, Malhi Y, Barbier N, Lima A, Shimabukuro Y, Anderson L, Saatchi S (2008) Interactions between rainfall, deforestation and fires during recent years in the Brazilian Amazonia. Philosophical transactions of the Royal Society of London. Series B, Biological sciences, **363**, 1779-1785.

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, Fearnside PM (1996) Pasture burning in Amazonia: Dynamics of residual biomass and the storage and release of aboveground carbon. Journal of Geophysical Research-Atmospheres, **101**, 25847-25857.

Barbosa RI, Fearnside PM (1999) Incêndios na Amazônia brasileira: estimativa da emissão de gases de efeito estufa pela queima de diferentes ecossistemas de Roraima na passagem do evento “El-Niño” (1997/1998). Acta Amazonica, **29**, 513-534.

Barbosa RI, Fearnside PM (2005) Fire frequency and area burned in the Roraima savannas of Brazilian Amazonia. Forest Ecology and Management, **204**, 371-384.

Barbosa RI, Mourão Jr. M, Casadio GML, Da Silva SJR (2012) Reproductive phenology of the main tree species in the Roraima savanna, Brazilian Amazon. Ecotropica, **18**, 81-91.

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-INPE (2013) Projeto PRODES: Monitoramento da Floresta Amazônica Brasileira por Satélite. São José dos Campos, São Paulo, Brazil, Instituto Nacional de Pesquisas Espaciais (INPE). Available at: http://www.obt.inpe.br/prodes/index.html. (accessed 25 02 2014).

Brienen RJ, Phillips OL, Feldpausch TR *et al.* (2015) Long-term decline of the Amazon carbon sink. Nature, **519**, 344-348.

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, Silman MR, Mcmichael C, Saatchi S (2008) Fire, climate change, and biodiversity in Amazonia: a late-Holocene perspective. Philosophical Transactions of the Royal Society B: Biological Sciences, **363**, 1795–1802.

Carcaillet C (2001) Are Holocene wood-charcoal fragments stratified in alpine and subalpine soils? Evidence from the Alps based on AMS ^{14}C dates. The Holocene, **11**, 231-242.

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.

Cordeiro RC, Turcq BJ, Moreira LS *et al.* (2014) Palaeofires in Amazon: interplay between land use change and palaeoclimatic events. Palaeogeography, Palaeoclimatology, Palaeoecology, **415**, 137–151.

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.

Deluca TH, Aplet GH (2008) Charcoal and carbon storage in forest soils of the Rocky Mountain West. Frontiers in Ecology and the Environment, **6**, 18-24.

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.

Druffel ERM (2004) Comments on the importance of black carbon in the global carbon cycle. Marine Chemistry, **92**, 197-200.

Embrapa (1997) *Manual de métodos de análise de solo,* Rio de Janeiro, RJ, Empresa Brasileira de Pesquisa Agropecuária (Embrapa), Centro Nacional de Pesquisa de Solos. Available at: http://www.obt.inpe.br/prodes/index.html. (accessed 25 02 2014).

Fearnside PM (2002) Fogo e emissão de gases de efeito estufa dos ecossistemas florestais da Amazônia brasileira. Estudos Avançados, **16**, 99-123.

Fearnside PM, Barbosa RI, Graça PMLA (2007) Burning of secondary forest in Amazonia: Biomass, burning efficiency and charcoal formation during land preparation for agriculture in Apiau, Roraima, Brazil. Forest Ecology and Management, **242**, 678-687.

Fearnside PM, Graça PMLA, Leal-Filho N, Rodrigues FJA, Robinson JM (1999) Tropical forest burning in Brazilian Amazonia: measurement of biomass loading, burning efficiency and charcoal formation at Altamira, Pará. Forest Ecology and Management, **123**, 65-79.

Fearnside PM, Graça PMLA, Rodrigues FJA (2001) Burning of Amazonian rainforest: burning efficiency and charcoal formation in forest cleared for cattle pasture near Manaus, Brazil. Forest Ecology and Management, **146**, 115-128.

Fearnside PM, Righi CA, Graça PMLA, Keizer EWH, Cerri CC, Nogueira EM, Barbosa RI (2009) Biomass and greenhouse-gas emissions from land-use change in Brazil's Amazonian "arc of deforestation": The states of Mato Grosso and Rondonia. Forest Ecology and Management, **258**, 1968-1978.

Feitosa KKA (2009) Caracterização e classificação de solos em "ilhas florestais" e savanas associadas no nordeste de Roraima. Unpublished MSc. Universidade Federal de Roraima, Boa Vista, Roraima, Brazil, 75 pp.

Foereid B, Lehmann J, Major J (2011) Modeling black carbon degradation and movement in soil. Plant and Soil, **345**, 223-236.

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.

FUNCATE (2006) *Uso e cobertura da terra na Floresta Amazônica: Subprojeto 106/2004 PROBIO (Projeto de Conservação e Utilização Sustentável da Diversidade Biológica Brasileira),* Brasília, DF, Fundação de Ciência, Aplicações e Tecnologia Espaciais (FUNCATE), Secretaria de Biodiversidade e Florestas do Ministério de Meio Ambiente, Conselho Nacional de Desenvolvimento Científico e Tecnológico, Global Environment Fund (GEF) and World Bank.

Glaser B, Lehmann J, Zech W (2002) Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal - a review. Biology and Fertility of Soils, **35**, 219-230.

Graça PMLA, Fearnside PM, Cerri CC (1999) Burning of Amazonian forest in Ariquemes, Rondônia, Brazil: biomass, charcoal formation and burning efficiency. Forest Ecology and Management*,* **120**, 179-191.

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 (http://dx.doi.org/3010.1029/2006gb002914).

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, Da 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.

Huber O, Stefano RD, Aymard G, Riina R (2006) Flora and vegetation of the Venezuelan Llanos: a review. In: *Neotropical Savannas and Seasonally Dry Forests: Plant Diversity, Biogeography, and Conservation.* (eds Pennington RT, Lewis GP, Ratter JA) pp 95-120. Boca Raton, FL, Taylor & Francis Group.

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.

Jaramillo MMA (2015) Estrutura, biomassa arbórea e composição florística de ilhas de mata da savana de Roraima, Norte da Amazônia Brasileira. Unpublished MSc. Universidade Federal de Roraima, Boa Vista, Roraima, Brazil, 57 pp.

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.

Laurance WF, Williamson GB (2001) Positive feedbacks among forest fragmentation, drought, and climate change in the Amazon. Conservation Biology, **15**, 1529-1535.

Lehmann J, Gaunt J, Rondon M (2006) Bio-char sequestration in terrestrial ecosystems: A Review. Mitigation and Adaptation Strategies for Global Change, **11**, 395-419.

Lehmann J, Silva Jr. JP, Steiner C, Nehls T, Zech W, Glaser B (2003) Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. Plant and Soil, **249**, 343–357.

Levis C, De Souza PF, Schietti J, Emilio T, Pinto JL, Clement CR, Costa FR (2012) Historical human footprint on modern tree species composition in the Purus-Madeira interfluve, Central Amazonia. PloS one, **7**, e48559.

Licata C, Sanford R (2012) Charcoal and total carbon in soils from foothills shrublands to subalpine forests in the Colorado Front Range. Forests, **3**, 944-958.

McMichael CH, Correa-Metrio A, Bush MB (2012) Pre-Columbian fire regimes in lowland tropical rainforests of southeastern Peru. Palaeogeography, Palaeoclimatology, Palaeoecology, **342-343**, 73-83.

Meggers BJ (1994) Archeological evidence for the impact of mega-niño events on Amazonia during the past two millennia. Climatic Change, **28**, 321–338.

Meneses MENS, Costa ML, Behling H (2013) Late Holocene vegetation and fire dynamics from a savanna-forest ecotone in Roraima state, northern Brazilian Amazon. Journal of South American Earth Sciences, **42**, 17-26.

Morton D, Le Page Y, Defries R, Collatz G, Hurtt G (2013) Understorey fire frequency and the fate of burned forests in southern Amazonia. Philosophical Transactions of the Royal Society B: Biological Sciences, **368**, 20120163.

Nepstad D, Lefebvre P, Lopes Da Silva U *et al.* (2004) Amazon drought and its implications for forest flammability and tree growth: a basin-wide analysis. Global Change Biology, **10**, 704-717.

Nogueira EM, Yanai AM, Fonseca FO, Fearnside PM (2015) Carbon stock loss from deforestation through 2013 in Brazilian Amazonia. Global Change Biology, **21**, 1271–1292.

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.

Power MJ, Marlon J, Ortiz N *et al.* (2008) Changes in fire regimes since the Last Glacial Maximum: an assessment based on a global synthesis and analysis of charcoal data. Climate Dynamics, **30**, 887-907.

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.

R Core Team (2014) *R: A language and environment for statistical computing,* Viena, Austria, R Foundation for Statistical Computing.

Righi CA, Graça PMLA, Cerri CC, Feigl BJ, Fearnside PM (2009) Biomass burning in Brazil's Amazonian “arc of deforestation”: burning efficiency and charcoal formation in a fire after mechanized clearing at Feliz Natal, Mato Grosso. Forest Ecology and Management, **258**, 2535-2546.

Roosevelt AC (2013) The Amazon and the Anthropocene: 13,000 years of human influence in a tropical rainforest. Anthropocene, **4**, 69-87.

Saatchi S, Houghton R, Alvalá R, Soares J, Yu Y (2007) Distribution of aboveground live biomass in the Amazon basin. Global Change Biology, **13**, 816-837.

Saldarriaga JG, West DC (1986) Holocene fires in the Northern Amazon Basin. Quaternary Research, **26**, 358-366.

Sanford RL, Horn SP (2000) Holocene rain-forest wilderness: A Neotropical perspective on humans as an exotic, invasive species. USDA Forest Service Proceedings, **3**, 168-173.

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.

Santos GM, Gomes PRS, Anjos RM *et al.* (2000) ^{14}C AMS dating of fires in the central Amazon rain forest. Nuclear Instruments and Methods in Physics Research B, **172**, 761-766.

Santos NMC, Vale Júnior JF, Barbosa RI (2013) Florística e estrutura arbórea de ilhas de mata em áreas de savana do norte da Amazônia brasileira. Boletim do Museu Paraense Emílio Goeldi (Ciências Naturais), **8**, 205-221.

Schmidt MWI (2004) Carbon budget in the black. Nature, **427**, 305-306.

Seiler W, Crutzen PJ (1980) Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere from biomass burning. Climatic Change, **2**, 207-247.

Silva RP (2007) Alometria, estoque e dinâmica da biomassa de florestas primárias e secundárias na região de Manaus (AM). Unpublished PhD Universidade Federal do

Amazonas (UFAM) / Instituto Nacional de Pesquisas da Amazônia (INPA), Manaus, AM, 152 pp.

Simpson MJ, Hatcher PG (2004) Overestimates of black carbon in soils and sediments. Die Naturwissenschaften*,* **91**, 436-440.

Skjernstad JO, Taylor JA, Smernik RJ (1999) Estimation of charcoal (char) in soils. Communications in Soil Science and Plant Analysis*,* **30**, 2283-2298.

Suman DO (1984) The production and transport of charcoal formed during agricultural burning in central Panama. Interciencia*,* **9**, 311-313.

Titiz B, Sanford Jr. RL (2007) Soil charcoal in old-growth rain forests from sea level to the Continental Divide. Biotropica*,* **39**, 673 - 682.

Toledo MB, Bush MB (2007) A mid-Holocene environmental change in Amazonian savannas. Journal of Biogeography*,* **34**, 1313-1326.

SUPPORTING INFORMATION CAPTIONS

Table S1- Geographical location, number of sub-samples and size of seasonal forest fragments (sampling units) in the forest-savanna ecotone of Roraima.

Table S2. Pyrogenic carbon derived from soil charcoal found along the 1-m vertical profile in seasonal forest fragments of different sizes. Values in italics were estimated by regressions (exponential model) for each fragment individually. Numbers in bold are outliers that were normalized by the mean of all values for the respective depth ranges: 10-20 cm (39.34 Mg ha^{-1}, fragment area = 1.252 ha) and 90-100 cm (9.19 Mg ha^{-1}; fragment area = 44.685 ha).

Figure S1. Physical and chemical characteristics of soils of forest fragments dispersed in the forest-savanna contact zone in Roraima. Where: sand, clay and silt in (%); SOM = Soil Organic Matter (g kg^{-1}), SB = Sum of Bases ($cmol_c$ dm^{-3}) and Al^{+3} = Aluminum ($cmol_c$ dm^{-3}). The gray dots are estimates to show the behavior of these properties along the 1-m depth soil profile. Vertical bars are standard deviation (SD).

Figure S2 – Estimation of soil bulk density (g cm^{-3}) in the 1-m vertical profile observed in forest fragments dispersed in the forest-savanna ecotone of Roraima, northern Brazilian Amazon. Bulk density was calculated as the ratio between the dry soil weight (g) of the samples and the Kopecky´s ring volume (cm^3), following Embrapa (1997). The exponential model was derived from data by Feitosa (2009): $Y = 1.2582 + 0.0437 \times \ln(X)$ ($R^2 = 0.9943$); where Y = soil bulk density (g cm^{-3}) and X = midpoint of the depth interval (cm).

TABLES

Table 1. Charcoal, pyrogenic carbon and pyrogenic carbon fraction (1-m depth) as a function of carbon derived from the aboveground live biomass in trees with DBH ≥ 10 cm. Tree biomass was estimated by Jaramillo (2015). Carbon concentration in tree biomass assumed to be 48.5% (Silva, 2007). Standard deviation (SD) in parentheses.

Sample unit	Fragment area (ha)	Tree biomass (Mg ha^{-1})	Tree carbon (Mg ha^{-1})	Soil charcoal (Mg ha^{-1})	Pyrogenic carbon (Mg ha^{-1})	Charcoal mass as % of tree biomass (%)	Charcoal carbon as % of tree carbon (%)
1	1.252	164.8	79.9	4.98	3.23	3.02	4.04
2	2.693	257.4	124.8	2.29	1.49	0.89	1.19
3	5.285	202.1	98.0	1.26	0.82	0.62	0.84
4	7.307	201.3	97.6	1.69	1.10	0.84	1.13
5	11.589	196.7	95.4	4.50	2.92	2.29	3.06
6	11.641	432.0	209.5	2.94	1.91	0.68	0.91
7	12.125	260.9	126.5	4.88	3.17	1.87	2.51
8	15.798	376.9	182.8	0.79	0.46	0.21	0.25
9	30.598	380.6	184.6	2.83	1.84	0.74	1.00
10	44.685	540.7	262.2	7.22	4.69	1.34	1.79
11	50.282	491.2	238.2	6.70	4.35	1.36	1.83
12	57.230	447.7	217.1	1.33	0.86	0.30	0.40
Mean	-	329.4	159.7	3.45 (2.17)	2.24 (1.41)	1.05 (0.84)	1.40 (1.13)

FIGURE CAPTIONS

Figure 1. Study area location indicating the boundaries of PANA-I and the spatial distribution of the sampled forest fragments (black) in the state of Roraima, Brazil.

Figure 2. Relationship between pyrogenic carbon stock (Mg C ha^{-1}) and area (ha) of seasonal forest fragments in Roraima: $Y = 1.76278 + 0.02254 \times X$ ($n = 12$; $F_{0.05} = 1.114$; $p < 0.3161$; $R^2 = 0.1002$).

Figure 3. Vertical distribution of (a) charcoal stocks and (b) pyrogenic carbon sampled in the soil profile (1-m depth) in forest fragments in the forest-savanna ecotone of Roraima. Box-plots indicate median values of the first and third quartiles, and bars indicate ranges (maximum and minimum) for data from the 12 sampling units divided among all 10-cm soil intervals in the profile to 1-m depth. Points outside the maximum and minimum interval bars represent outliers. Values for 50-90 cm depth were estimated by regression (charcoal stocks and pyrogenic carbon), assuming the observed exponential decay pattern. Soil charcoal outliers for 10-20 cm (39.34 Mg ha^{-1}; fragment area = 1.25 ha) and 90-100 cm (9.19 Mg ha^{-1}; fragment area = 44.68 ha) were normalized by the average of all values in their respective depth ranges.

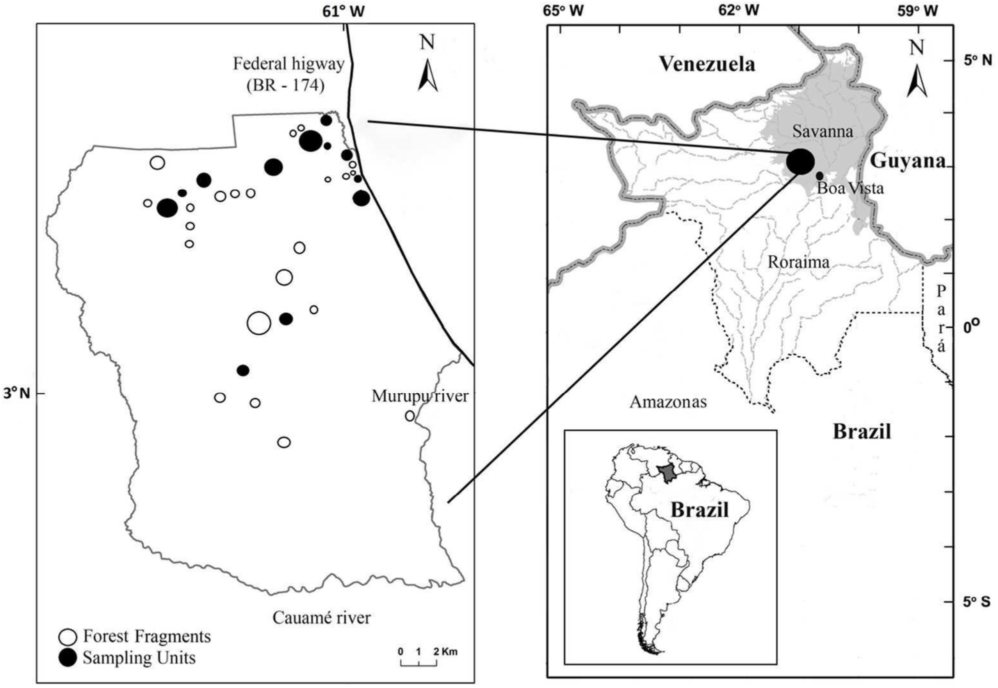

Figure 1. Study area location indicating the boundaries of PANA-I and the spatial distribution of the sampled forest fragments (black) in the state of Roraima, Brazil.
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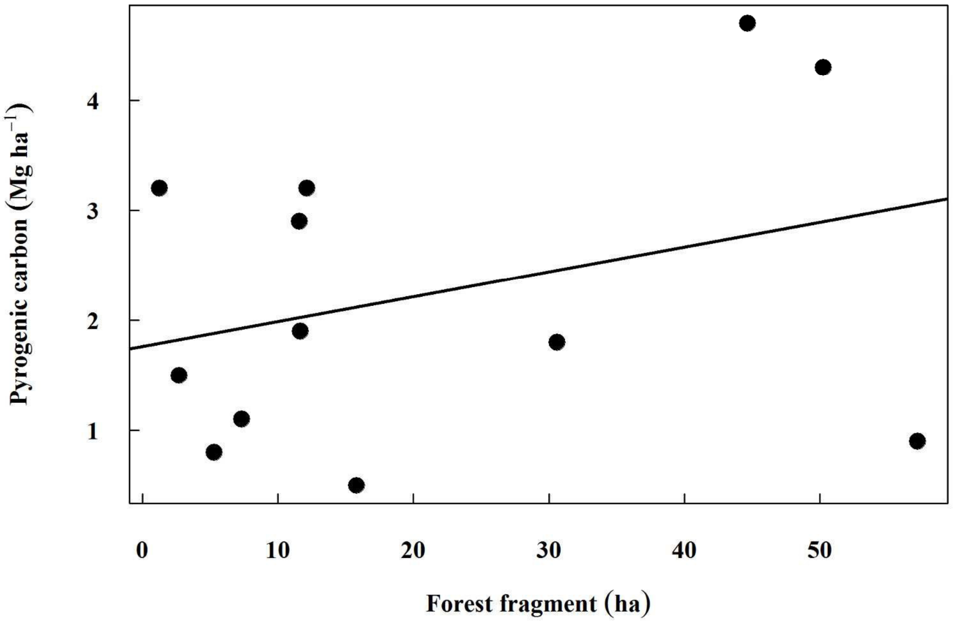

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168x119mm (300 x 300 DPI)

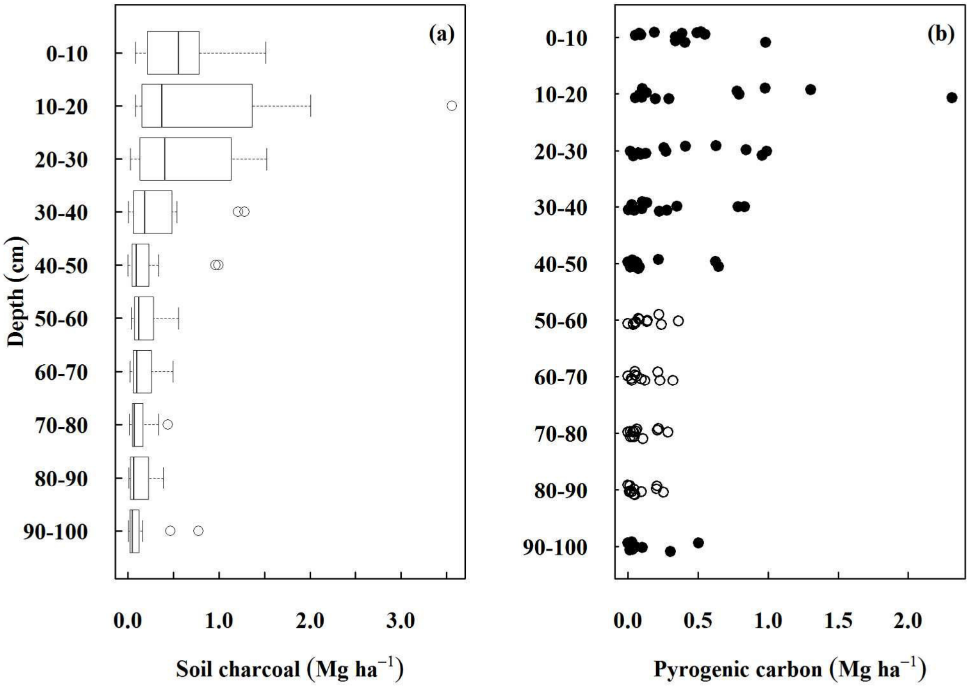


Figure 3. Vertical distribution of (a) charcoal stocks and (b) pyrogenic carbon sampled in the soil profile (1-m depth) in forest fragments in the forest-savanna ecotone of Roraima. Box-plots indicate median values of the first and third quartiles, and bars indicate ranges (maximum and minimum) for data from the 12 sampling units divided among all 10-cm soil intervals in the profile to 1-m depth. Points outside the maximum and minimum interval bars represent outliers. Values for 50-90 cm depth were estimated by regression (charcoal stocks and pyrogenic carbon), assuming the observed exponential decay pattern. Soil charcoal outliers for 10-20 cm (39.34 Mg ha-1; fragment area = 1.25 ha) and 90-100 cm (9.19 Mg ha-1; fragment area = 44.68 ha) were normalized by the average of all values in their respective depth ranges.
168x119mm (300 x 300 DPI)

SUPPLEMENTARY MATERIAL

Soil charcoal as long-term pyrogenic carbon storage in Amazonian seasonal forests

Maryory M. Turcios[1], Margarita M. A. Jaramillo[1], José Frutuoso do Vale Jr. [1], Philip M. Fearnside[2], Reinaldo Imbrozio Barbosa[3(*)]

1. Federal University of Roraima (UFRR), Post-graduate Program in Natural Resources (PRONAT), Av. Cap. Ene Garcez 2413 - Bairro Aeroporto, 69304-000 Boa Vista, Roraima, Brazil

2. Department of Environmental Dynamics, National Institute for Research in Amazonia (INPA), Av. André Araújo no 2936, CEP 69 067-375, Manaus, Amazonas, Brazil

3. Department of Environmental Dynamics, National Institute for Research in Amazonia (INPA) – Roraima's Office (NPRR), Rua Coronel Pinto 315 – Centro, 69301-150 Boa Vista, Roraima, Brazil

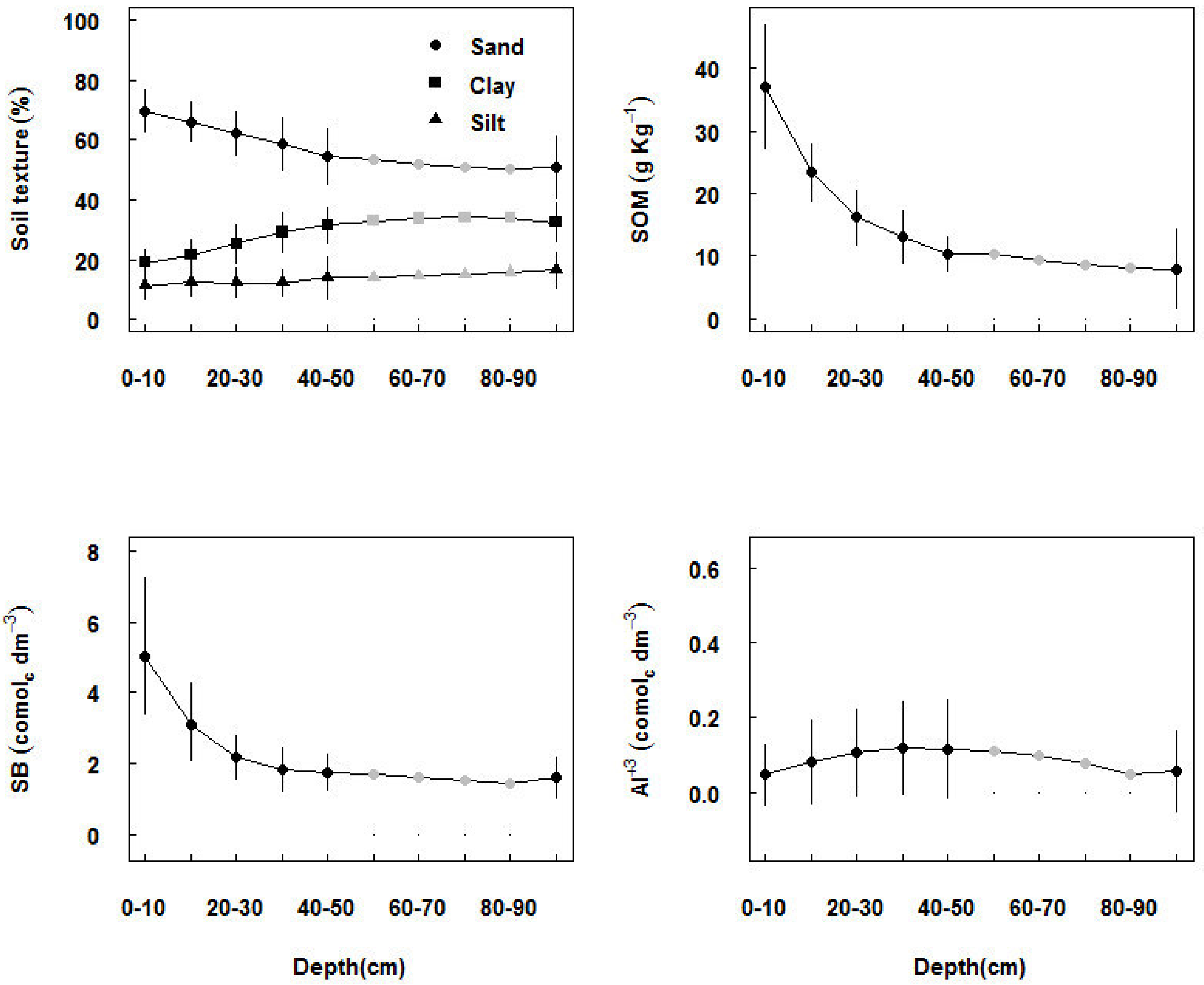
(*) Corresponding Author: Reinaldo Imbrozio Barbosa **-** Tel.: + 55 95 3623 9433;
e-mail: reinaldo@inpa.gov.br

Table S1- Geographical location, number of sub-samples and size of seasonal forest fragments (sampling units) in the forest-savanna ecotone of Roraima.

Sample Unit	Area (ha)	Sub-samples	Latitude (N)	Longitude (W)
1	1.25	2	03°06.06	60°55.60
2	2.70	4	03°07.45	60°50.57
3	5.28	4	03°00.60	60°53.09
4	7.31	6	03°06.39	60°49.40
5	11.59	8	03°08.15	60°50.60
6	11.64	8	03°02.18	60°51.81
7	12.12	6	03°13.25	60°49.57
8	15.80	4	03°06.66	60°54.41
9	30.60	8	03°06.56	60°53.23
10	44.69	3	03°05.84	60°49.54
11	50.28	8	03°05.32	60°55.41
12	57.23	8	03°07.37	60°51.23
Total	250.49	69	-	-

Table S2. Pyrogenic carbon derived from soil charcoal found along the 1-m vertical profile in seasonal forest fragments of different sizes. Values in italics were estimated by regressions (exponential model) for each fragment individually. Numbers in bold are outliers that were normalized by the mean of all values for the respective depth ranges: 10-20 cm (39.34 Mg ha^{-1}, fragment area = 1.252 ha) and 90-100 cm (9.19 Mg ha^{-1}; fragment area = 44.685 ha).

Fragment Size (ha)	0-10	20-30	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	Total (Mg ha^{-1})
1.252	0.4059	**0.9790**	0.4096	0.0281	0.0638	*0.2211*	*0.2146*	*0.2083*	*0.2021*	0.5024	3.23
2.693	0.0532	0.0520	0.8431	0.2255	0.0450	*0.0725*	*0.0630*	*0.0548*	*0.0476*	0.0291	1.49
5.285	0.0815	0.0984	0.0175	0.3509	0.0535	*0.0545*	*0.0493*	*0.0446*	*0.0404*	0.0296	0.82
7.307	0.5203	0.1324	0.2713	0.0456	0.0221	*0.0387*	*0.0262*	*0.0177*	*0.0120*	0.0138	1.10
11.589	0.0910	0.2915	0.6274	0.2777	0.6460	*0.2381*	*0.2265*	*0.2155*	*0.2050*	0.1029	2.92
11.641	0.3368	1.3038	0.0396	0.1020	0.0292	*0.0390*	*0.0248*	*0.0158*	*0.0101*	0.0101	1.91
12.125	0.9816	0.7926	0.9590	0.0306	0.2167	*0.0800*	*0.0485*	*0.0294*	*0.0179*	0.0130	3.17
15.798	0.1869	0.1958	0.0751	0.0022	0.0000	*0.0003*	*0.0001*	*0.00002*	*0.0000*	0.000001	0.46
30.598	0.3385	0.1024	0.1288	0.1355	0.6230	*0.1343*	*0.1191*	*0.1057*	*0.0937*	0.0547	1.84
44.685	0.4933	0.7786	0.9882	0.8312	0.0796	*0.3600*	*0.3193*	*0.2832*	*0.2512*	**0.3022**	4.69
50.282	0.5507	2.3129	0.2545	0.7858	0.0736	*0.1398*	*0.0937*	*0.0628*	*0.0421*	0.0337	4.35
57.230	0.3834	0.0794	0.0922	0.0976	0.0168	*0.0509*	*0.0412*	*0.0334*	*0.0271*	0.0392	0.86
Mean (Mg ha^{-1})	0.37	0.59	0.39	0.24	0.16	*0.12*	*0.10*	*0.09*	*0.08*	0.09	2.24



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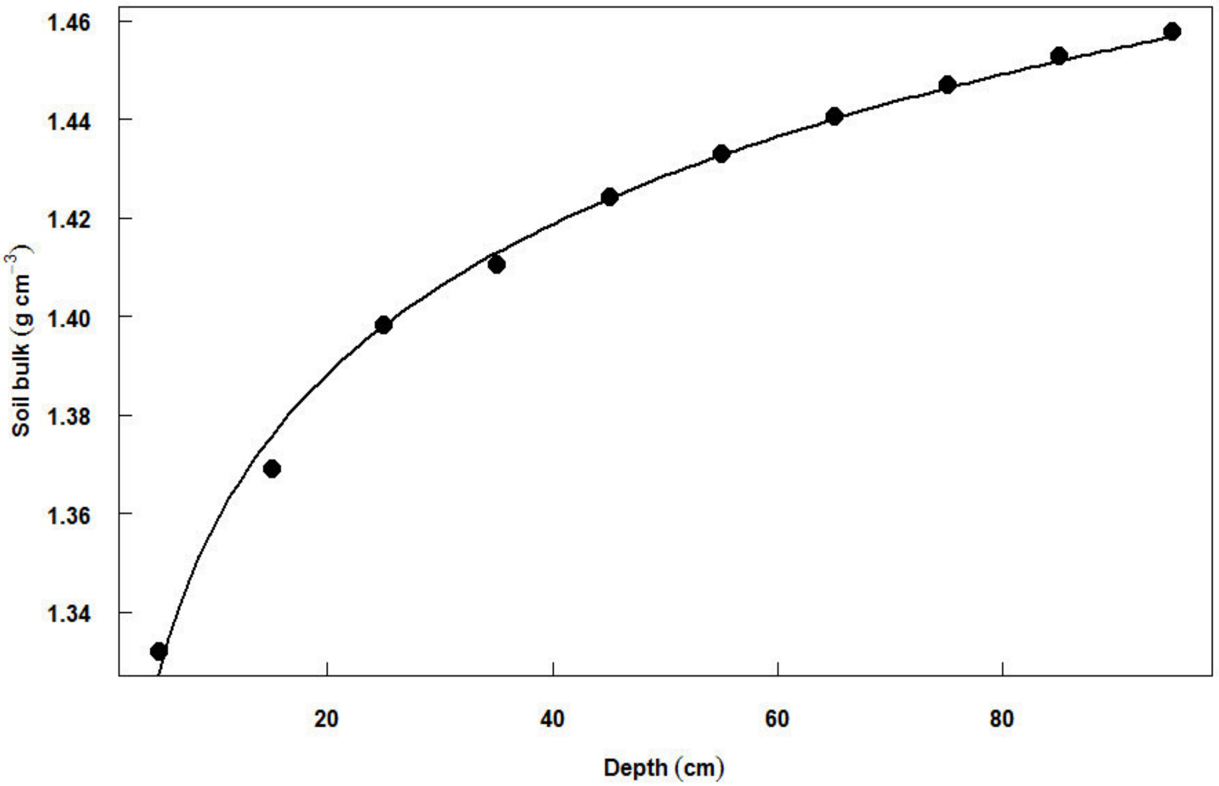

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Reference

Feitosa KKA (2009) Caracterização e classificação de solos em "ilhas florestais" e savanas associadas no nordeste de Roraima. Unpublished MSc. Universidade Federal de Roraima, Boa Vista, Roraima, Brazil, 75 pp.