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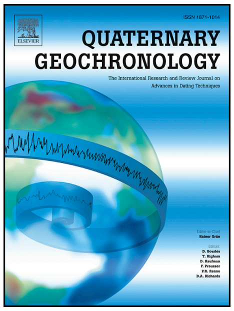

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Charcoal chronology of the Amazon forest:
a record of biodiversity preserved by ancient fires

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Abstract

The Amazon region holds a wide variety of ethnic groups and microclimates, enabling different interactions between humans and environment. To better understand the evolution of this region, ancient remains need to be analysed by all possible means. In this context, the study of natural and/or anthropogenic fires through the analysis of carbonized remains can give information on past climate, species diversity, and human intervention in forests and landscapes. In the present work, we undertook an anthracological analysis along with the ^{14}C dating of charcoal fragments using accelerator mass spectrometry (AMS). Charcoal samples from forest soils collected from seven different locations in the Amazon Basin were taxonomically classified and dated. Out of the 16 groups of charcoal fragments identified, five contained more than one taxonomic type, with the Fabaceae, Combretaceae and Sapotaceae families having the highest frequencies. ^{14}C charcoal dates span ~6000 years (from 6876 to 365 yr BP) among different families, with the most significant variation observed for two fragments from the same sampling location (spanning 4000 ^{14}C yr). Some sample sets resulted in up to five different families. These findings demonstrate the importance of the association between anthracological identification and radiocarbon dating in the reconstruction of paleo-forest composition and fire history.

Keywords: Radiocarbon; AMS; Anthracology; ancient fires; charcoal; biodiversity

Introduction

The rainforests of South America present unique environmental features and their central role in the regulation of Earth's climate is currently widely recognized (e.g. Lenton et al. 2008). A complex set of physical, chemical, and environmental characteristics in Amazonia has allowed some of the most diverse forms of life to flourish. The Amazon Basin has undergone climate variation that has affected forest extent and composition (Wang et al. 2017).

For many years, it was thought that Amazonia was relatively unaffected by humans prior to the arrival of Europeans (Denevan 1992). However, evidence has emerged pointing to the existence of complex and sedentary societies in some regions of Amazonia (Neves 2005). This has led to debate into the onset, extent, and timescale of the early impact of humans in the area, including the frequency of fire, both as a tool and applied accidentally (Willis et al. 2004; Heckenberger et al. 2007; Denevan et al. 2011; Levis et al. 2012). In some areas, populations modified their surrounding environment according to their needs, leaving behind testimonies to their occupation, such as domesticated species, artefacts, and Anthropogenic Dark Earth soils (*Terra Preta de Índio*) (e.g. Clement 1999; Petersen et al. 2001; Neves et al. 2003; 2004).

Fire was the main tool used by indigenous people to transform and manage landscapes (Erikson 2008). Hence, fire regimes are linked with past human disturbance during the Holocene and charcoal records have been used to identify such activities (Bush et al. 2008; Mayle and Power 2008). Wildfires may also occur in Amazonian forests in extremely dry periods (Piperno and Becker 1996; Wang et al. 2017). During fire episodes, either from natural or anthropogenic origin, common tree species suffer the greatest total mortality, but rare species are most likely to be locally extirpated (Cochrane and Schulze 1999; Slik et al. 2002). Wetter forests burn less frequently than drier forests but are more vulnerable to fire, as trees have thinner protective layers of bark (Uhl and Kauffman 1990), resulting in higher mortality rates, especially during drought years.

According to Cochrane (2003), fire susceptibility in tropical forests depends mostly on moisture stress, with forests becoming potentially flammable during periods of extensive drought. Transitional deciduous and semi-deciduous forests have longer dry seasons, greater water stress, more open canopies and greater leaf litter that affect fire characteristics. Closed-canopy evergreen rainforests, in turn, have short, or no seasonal moisture deficits, with higher humidity levels preventing sustained combustion, even after months without precipitation (Uhl et al. 1988). However, both natural and anthropogenic disturbances of forest canopies increase ground irradiance, leading to drier necromass and greater vulnerable to fire (Cochrane 2003). Independently of the cause of the fires in these ecosystems, fire frequency is related to climate, with return intervals of hundreds or thousands of years (Sanford et al. 1985).

The study of ancient fires relies on the analysis of charcoal remains. AMS radiocarbon dating of charcoal can be used to determine the date that carbon was incorporated into wood, and for young wood, an approximate date of burning (McFadgen 1982). Over millennia, charcoal fragments retain the age record of each component of the original tree.

Even if the death of the plant is related to the time of burning, growth layers formed over the life of the tree can add years to age determination (McFadgen 1982). McFadgen (1982) defines the time lapse between the death of a tree and the date of an event as ‘inbuilt age’, introducing the concepts of growth and storage ages. Growth age is due to the heartwood of living trees being composed of old cells that have lost most of their functions and ceased taking up ^{1}4C. Although important to provide structural strength, this part of the wood is considered dead and may be hundreds of years old when the tree dies. The idea of a storage age, in turn, arises from wood being stored for long periods before decomposing. Thus, inbuilt age is the sum of growth and storage ages. It follows that the effect of the inbuilt age in the dating of the sample is greater when analyzing long-lived trees (McFadgen 1982). In the case of natural fires, the inbuilt age of trees may frequently be small due to fire preferentially killing young, small diameter trees (Cochrane et al. 1999). Therefore, different charcoal fragments can reflect the ages of different parts of the same tree, different trees in a single fire, or even different fire episodes.

For these reasons, before radiocarbon dating charcoal, a careful structural analysis must be performed. The present study makes use of cellular wood structures preserved after carbonization, using anthracological analysis to taxonomically classify charcoal remains. Such analysis enables the recognition of bark and twigs, which are the younger parts of the trees and can be therefore more closely associated with time of death.

Anthracological analysis involves conducting microscopic observation of preserved anatomical structures to determine tree taxonomic identity through a comparison between unknown charcoal fragments against well-identified samples from an anatomical database. Ideally, after anthracological analysis, each charcoal fragment should be individually dated so that more precise results can be related to the initial characteristics of the fragment.

In this study, we performed both anthracological analysis and radiocarbon dating in sets of charcoal samples collected in mature forests with no known history of fire and no evidence of recent anthropogenic disturbance in several locations within the Amazon Basin, Our aim was to reconstruct past biodiversity and fire chronology.

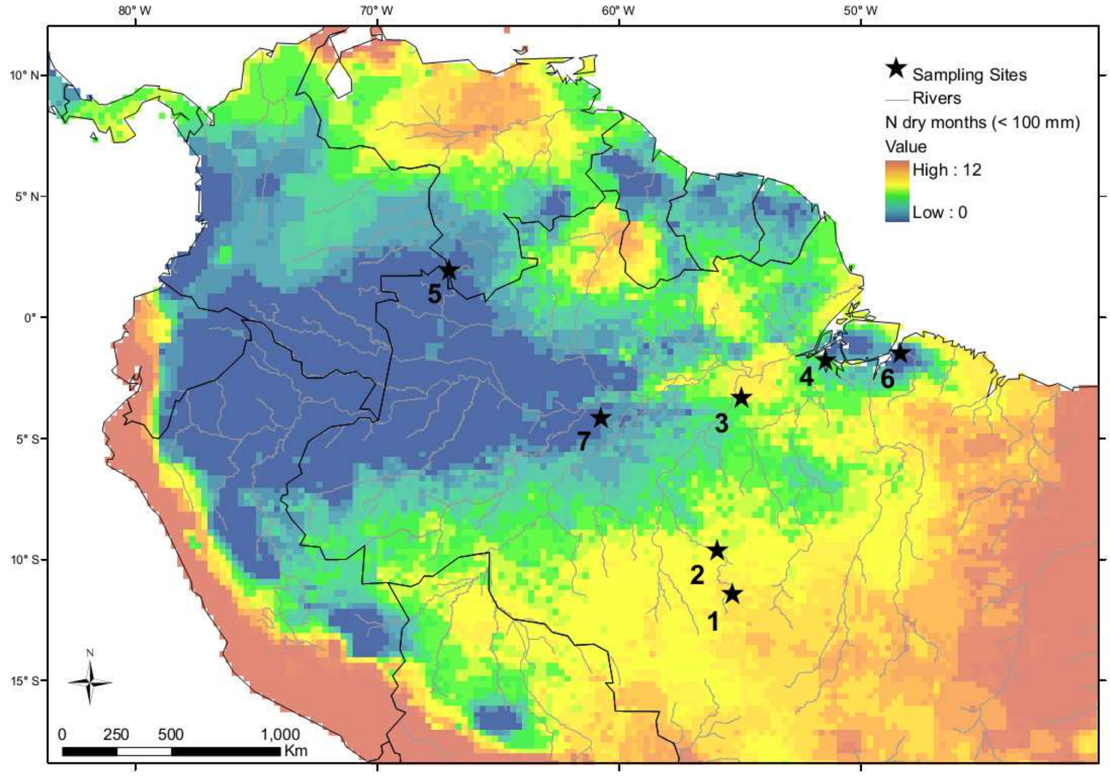


Figure 1: Distribution of sampling sites in the Amazon Basin. These sites were selected across a gradient of rainfall seasonality. Number of dry months were calculated by maximum cumulative number of months with < 100 mm using data of the Tropical Rainfall Measuring Mission (TRMM) satellite product 3B43 V6 at a 0.25° resolution (Kummerow et al. 1998). The river network was obtained from the HydroSHEDS dataset (Lehner et al. 2008).

Materials and Methods

The Amazon Basin study sites span a large precipitation seasonality gradient, encompassing Southern Venezuela and the Brazilian states of Amazonas, Pará, and Mato Grosso (Figure 1). The soils of a total of 7 research areas were sampled. In six areas, eight soil pits were excavated to 2 m depth in representative locations for the dominant soil and topographic positions. Charcoal found in each soil pit was collected, dried, and stored. At one location, two small pits were excavated to 50 cm in depth at intervals of 10 cm. Using a Kopecky cylinder (100 cm^3), horizontal undisturbed soil samples were collected at each 10 cm depth. The soil was dried and charcoal samples visible to the naked eye were removed and stored. We define a sample set as a group of charcoal fragments collected from a single soil pit at a given depth.

Anthracological analysis was performed at the National Museum of the Rio de Janeiro Federal University (UFRJ). To allow wood anatomical investigation, charcoal pieces were manually broken, exposing transverse, longitudinal-tangential and longitudinal-radial sections. Each section was examined under a reflected light brightfield/darkfield microscope and identification was achieved through the comparison to a reference collection (Charcoal collection from the National Museum, UFRJ – Scheel-Ybert, 2016) and the use of specialized literature (e.g. Metcalfe and Chalke 1950; Détienne and Jacquet 1983).

Following this analysis, charcoal fragments were prepared and analyzed at the Radiocarbon Laboratory of the Universidade Federal Fluminense (LAC-UFF). Standard acid-base-acid (ABA) pretreatment chemistry was employed to decontaminate the samples before dating. This was undertaken using 1.0M hydrochloric acid (HCl) (2 hr at 90°C) and 1.0M sodium hydroxide (NaOH) (1 hr at 90°C). After pre-treatment, the samples were combusted in prebaked quartz tubes containing silver powder and cupric oxide at 900°C for 3 hr in a muffle oven. Carbon dioxide was then purified with dry ice/ethanol traps in the graphitization line and converted to graphite using the zinc/titanium hydrate method with an iron catalyst (Xu et al. 2007; Macario et al. 2015). Individual torch-sealed tubes were heated at 520°C for 7 hr in a muffle oven. Graphite samples were pressed in aluminum cathodes and measured in a NEC 250kV Single Stage Accelerator System (SSAMS). The results were corrected for isotopic fractionation by measuring the $\delta^{13}C$ online in the accelerator. Background was measured using processed Alfa Aesar graphite with an average $^{14}C/^{13}C$ ratio of 6×10^{-13}. Average machine background was 10^{-13} for unprocessed graphite. For quality control both International Atomic Energy Agency (IAEA) reference materials and an internal charcoal secondary standard were measured. Calibration was performed with the OxCal v 4.2.4 (Bronk Ramsey 1995) software using the SHCal13 atmospheric curve (Hogg et al. 2013) for negative latitudes and the IntCal13 curve for positive latitudes (Reimer at al. 2013).

Results and discussion

Most of the radiocarbon results are concentrated between 2700 and 500 yr BP (Table 1 and Figure 2). The high density of ^{14}C dates during this period is consistent with other datasets from the Amazonian region and with most dates of archaeological charcoal (e.g. McMichael et al. 2012; Bush et al. 2008; Nevle and Bird 2008). Only 3 of 27 dates were <500 cal BP and those youngest dates were from the same soil depth (15 cm) at one study location, suggesting the dates were from the same fire event. Recent fire, therefore, was rare and geographically restricted in our dataset from mature forests. This contrasts with McMichael et al. (2017) based on a geospatial analysis of archaeological evidence, suggesting that mature forest plots such as those of our study may have been affected by early European settlers.

The calibrated dates show varied and asynchronous fire episodes over greater time periods spanning the >1000 km sampled area and large precipitation seasonality gradient (Figure 1). For example, the chronology indicates that fire occurred in the intervals 2700-2400 cal yr BP (positions 1 and 7), 1900-1500 (positions 3,4, 5 and 6), 1400-1000 (positions 1, 4 and 6) and 700-500 cal yr BP (positions 3, 4, 5, 6 and 7) (Figure 3). Coeval episodes in different places may be a sign of a climatic event, possibly a drier period. The oldest dated ages were in eastern Amazonia (Belterra, Pará) and the most recent in central Amazonia (Careiro, Amazonas) (Table 1).

The fire history of Amazonian forests may be linked with global climate change records. One important factor related to global climatic changes which should be considered is the production of cosmogenic nuclides such as ^{14}C and ^{10}Be. Since the formation of these nuclides depends on the arrival of galactic cosmic rays in the atmosphere, the effect of solar activity deflecting such particles would decrease their production rate. Therefore, this anti-correlation with ^{14}C and ^{10}Be production is used as a proxy of solar activity, and potentially also an indicator of drought episodes (Stuiver and Braziunas 1993; Mayeski et al. 2004). According to Stuiver and Braziunas (1993), variation in Δ^{14}C over time (Fig 3) is tied to either ocean circulation change or solar modulation of atmospheric ^{14}C production with the possibility of a simultaneous contribution by both factors, where presumably solar forcing results in climatic change which, in turn, causes ocean circulation change. In addition, other factors can be related to climatic changes such as the presence of greenhouse gases CO_2 and CH_4 or increases in volcanic aerosols. All these factors will contribute to the complex pattern of thermohaline circulation as its intensity determines poleward heat transport, and influences global climate (Stuiver and Braziunas, 1993). Climatic changes during the Holocene were investigated by Mayeski et al. (2004), who identified Rapid Climatic Changes (RCC) in different parts of the world. The first RCC was recorded between 9000 and 8000 cal yr BP and was considered the last major deglaciating stage affecting the Northern Hemisphere. It was attributed mainly to reduced oceanic ventilation, since there was no clear change in cosmogenic isotopes production. Volcanic SO_4 production was unusually high in the Northern Hemisphere, which could be evidence of intense volcanic activity, while biogenic CH_4 declined - probably in response to aridity in the low- to mid-latitudes (Blunier et al. 1995; Mayeski et al. 2004). Fire episodes recorded in this study may be associated with past climatic changes. Our oldest dated charcoal (7759-7585 cal yr BP) from Belterra, for instance, corroborates the idea of tropical aridity at that time. Although severe droughts were documented in Amazonia between 8000 and 4000 cal. yr BP (Mayle and Power 2008), only one charcoal fragment was dated within this period.

In the period from 3500 to 2500 cal yr BP, pronounced aridity was recorded in East Africa, the Amazon basin, Ecuador and the Caribean/Bermuda region (Haug et al. 2001). Mayeski et al. (2004) have suggested that solar variability is responsible for such an event since it coincides with maxima in $\Delta^{14}C$ and ^{10}Be. The period from 1200 to 1000 cal yr BP includes generally dry conditions in Tropical Africa, monsoonal Pakistan and Ecuador, when there is a slight increase in atmospheric CO_2, while drought was linked to solar output in Yucatan (Hodell et al. 1991, 2001). The more recent episode, starting at 600 cal yr BP, would be related to the fastest and strongest climatic changes in the Holocene. At this time, there was a drop in CO_2 and a rise in CH_4, suggestive of wet conditions. However, this period features a more variable response in humidity at low latitudes.

Fire episodes that happened from 1900 to 1600 cal yr BP do not coincide with those reported by Bush et al. (2006) or with RRC events described by Mayeski et al. (2004), and may not be significant in a global scale. The occurrence of fires in positions 3, 4 and 6 may be related to human occupation, since these locations follow the course of the Amazon River that was densely occupied in pre-Columbian times. From 2500 years BP, these societies started to settle along the major river bluffs with a significant population growth and the development of a sedentary lifestyle (Neves et al. 2003; Heckenberger and Neves 2009; Denevan 1996). A peak in pre-Columbian population occurred from 1300 to 500 BP in different regions of Amazonia, associated with the development of sedentary and complex societies (Heckenberger and Neves 2009; Arroyo-Kalin 2011; Moraes and Neves 2012; Stenborg 2016). By the shore of the Solimões river, in Central Amazonia, three main periods of human occupation have been observed (1400-1300 yr BP, 1200-930 yr BP and 600-350 yr BP), with 1400-1300 yr BP being the less intense period and 1400-1300 BP the most (Machado 2005). Our results include dates from these three periods, leading to the possibility of anthropogenic influence in the occurrence of such fires because of fire management, disturbance, and gap formation due to human activity.

A total of 13 families were identified from the anthracological analysis (Table 1). Fabaceae, Sapotaceae and Combretaceae families were the most frequent among the identified fragments. Families identified in four of the seven locations are also abundant in the present-day. For instance, Fabaceace, which we identified at four of the seven regions, was also the most abundant and most diverse family of the largest dataset of Amazonian forest plots representing present-day contemporary forest composition (Steege et al. 2013). The Goupiaceae family is abundant and has species considered hyperdominant in the Amazonian tree flora, but has very low diversity (Steege et al. 2013). However, we only identified one charred species of Goupiaceace.

Some of the charcoal fragments could not be identified; some were unidentifiable because they were too damaged (53D and E, 66B, 77C, 79A, B and C), and others remain indeterminate because they were too small and contained few visible diagnostic features (52A, 53C, 87B). Most of the reference material is from the Atlantic Forest and the studied material comes from the Amazon forest. A comparison between these two forested ecosystems reveals that for the same families, ecosystem-specific characteristics can be distinguished, e.g., vessel diameter was larger in Amazon samples of the same family due to greater water availability (Alves and Angyalossy 2000). In tropical forests with high species diversity, identification is often difficult as the anatomy of many species is still unknown (Wheeler and Baas 1998). Expansion of charred reference material is therefore a priority to aid identification.

Table 1. Sample identification, present abundant families, and calibrated radiocarbon ages. Families in bold were both identified through anthracological analysis and are abundant in present-day composition for the region.

Location (Point)	Abundant families at present day	Source	Identified families	Sample	Lab Id	Depth (cm)	^{14}C age (yr BP)	Calibrated age (cal BP) 95.4%	
Claudia - MT (1)	Melastomataceae	(KUNZ et al., 2010; IVANAUSKAS, 2002)	Calophyllaceae	14P09A58	LACUFF150361	110	1120±33	1058	928
Novo Mundo - MT (2)	Burseraceae, Moraceae and **Fabaceae**	(SASAKI et al., 2008)	**Fabaceae**	14P09A65	LACUFF150319	30	2480±30	2703	2355
			Fabaceae Caesalpinoideae	14P09A66A	LACUFF150330	30	2728±30	2854	2749
			unidentifiable	14P09A66B	LACUFF150321		2685±39	2851	2721
Belterra - PA (3)	Fabaceae, Lecythidaceae and Moraceae	(GUALBERTO et al., 2014; ALMEIDA et al., 2012; ANDRADE, 2011)	Sapotaceae	14P09A51	LACUFF150360	96	637±27	647	541
			indeterminate	14P09A52A	LACUFF150308	30	6876±41	7759	7585
			Combretaceae	14P09A52B	LACUFF150309		1950±31	1927	1747
Melgaço - PA (4)	Fabaceae, Flacourtiaceae, Arecaceae, **Goupiaceae** and Lecythidaceae.	(ICMBio, 2012; FERREIRA et al., 2015).	Chrysobalanaceae	14P09A53A	LACUFF150310	25	1686±28	1609	1430
			Anacardiaceae	14P09A53B	LACUFF150311		1236±30	1185	985
			indeterminate	14P09A53C	LACUFF150312		1611±31	1534	1377
			unidentifiable	14P09A53D	LACUFF150313		1690±31	1692	1430
			unidentifiable	14P09A53E	LACUFF150314		1748±31	1702	1544
			Goupiaceae	14P09A55	LACUFF150315	15	1134±30	1058	934
			Combretaceae	14P09A56	LACUFF150316	40	1620±32	1539	1378
			Lauraceae	14P09A87A	LACUFF150327	25	783±30	730	577
			indeterminate	14P09A87B	LACUFF150328		1347±29	1294	1180
Rio Negro - AM/VE (5)	Lecythidaceae	(OLIVEIRA et al., 2001)	Melastomataceae	14P09A67	LACUFF150369	54	776±32	729	572
			Combretaceae	14P09A68	LACUFF150364	37	641±29	649	542
			Anacardiaceae	14P09A71	LACUFF150365	78	1975±31	1995	1755
Marituba - PA (6)	**Fabaceae** and Lecythidaceae	(ALMEIDA et al., 2011; AMARAL et al., 2009; MELO, 2004)	**Fabaceae** *Lonchocarpus*	14P09A60	LACUFF150362	-	1604±31	1530	1375
			Myrtaceae	14P09A61	LACUFF150317	-	662±34	655	550
Careiro - AM /BR (7)	Lecythidaceae, **Fabaceae** and Sapotaceae	(SILVA et al., 2008; OLIVEIRA et al., 2008; OLIVEIRA e AMARAL, 2004)	Melastomataceae	14P09A73	LACUFF150367	5	523±34	548	495
			Rubiaceae	14P09A75A	LACUFF150369	15	758±37	725	566
			Lauraceae	14P09A77B	LACUFF150372	15	480±29	533	456
			unidentifiable	14P09A77C	LACUFF150373		411±29	500	325
			Fabaceae	14P09A78	LACUFF150374	15	365±29	472	311
			unidentifiable	14P09A79	LACUFF150375	15	2431±33	2696	2337

Uncertainty in the interpretation of charcoal radiocarbon ages can be introduced, as previously discussed, due to the non-sysmetic offsets caused by inbuilt age. Long-lived species can be categorized into two successional groups. Late secondary succession species may have lifespans between 40 and 100 years (Maciel et al. 2003); long-lived species show slow or very slow growth with long lifespans of more than 100 years (Maciel et al. 2003). Amongst the families identified in this paper, Fabaceae, Sapotaceae and Combretaceae include several long lifespan species, although they also include some short-lived pioneer and early secondary species, while Goupiaceae is frequently a pioneer.

Out of the 16 sets of charcoal fragments identified, five–contained more than one taxonomic type. For the radiocarbon dating of sample sets with more than one family, some of the dates are statistically similar, such as sample sets 66 and 77. In both cases, one fragment could not be identified but could be distinguished from the others, suggesting the fragments belonged to two different families that were contemporaneous. Other sample sets had differences in age of hundreds of years. In sample set 52 the age difference is very large and again the oldest fragment remains indeterminate.

Differences in dates at a given site might be attributed to inbuilt age. In sample set 87, only the youngest fragment could be identified, making it difficult to evaluate such a possibility. Another reason for differences in ages could be if the different fragments represent different fire episodes. In this case, the different fragments could be disturbed by the action of bioturbation.

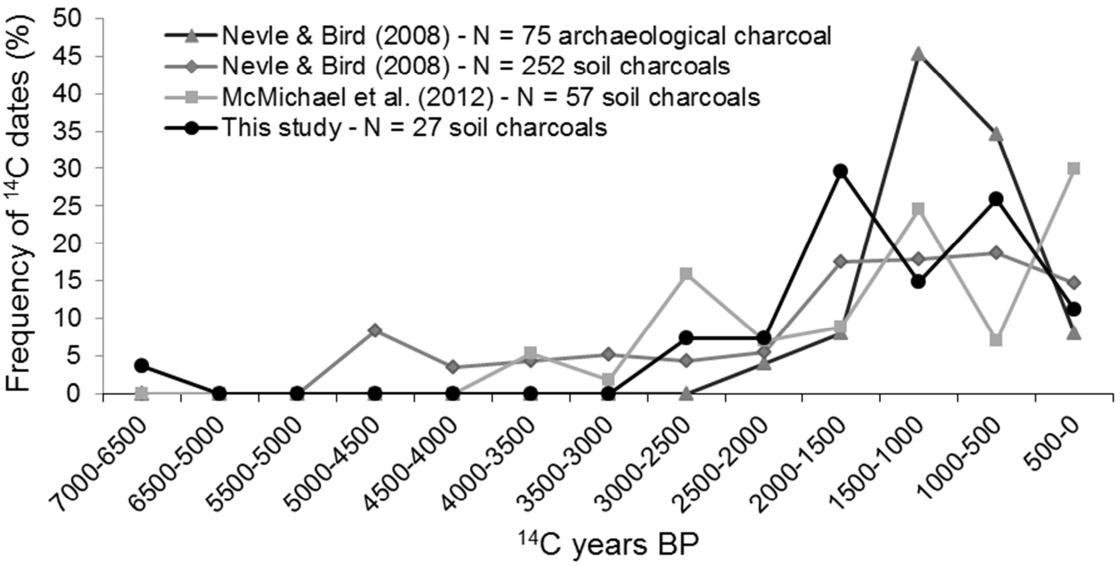
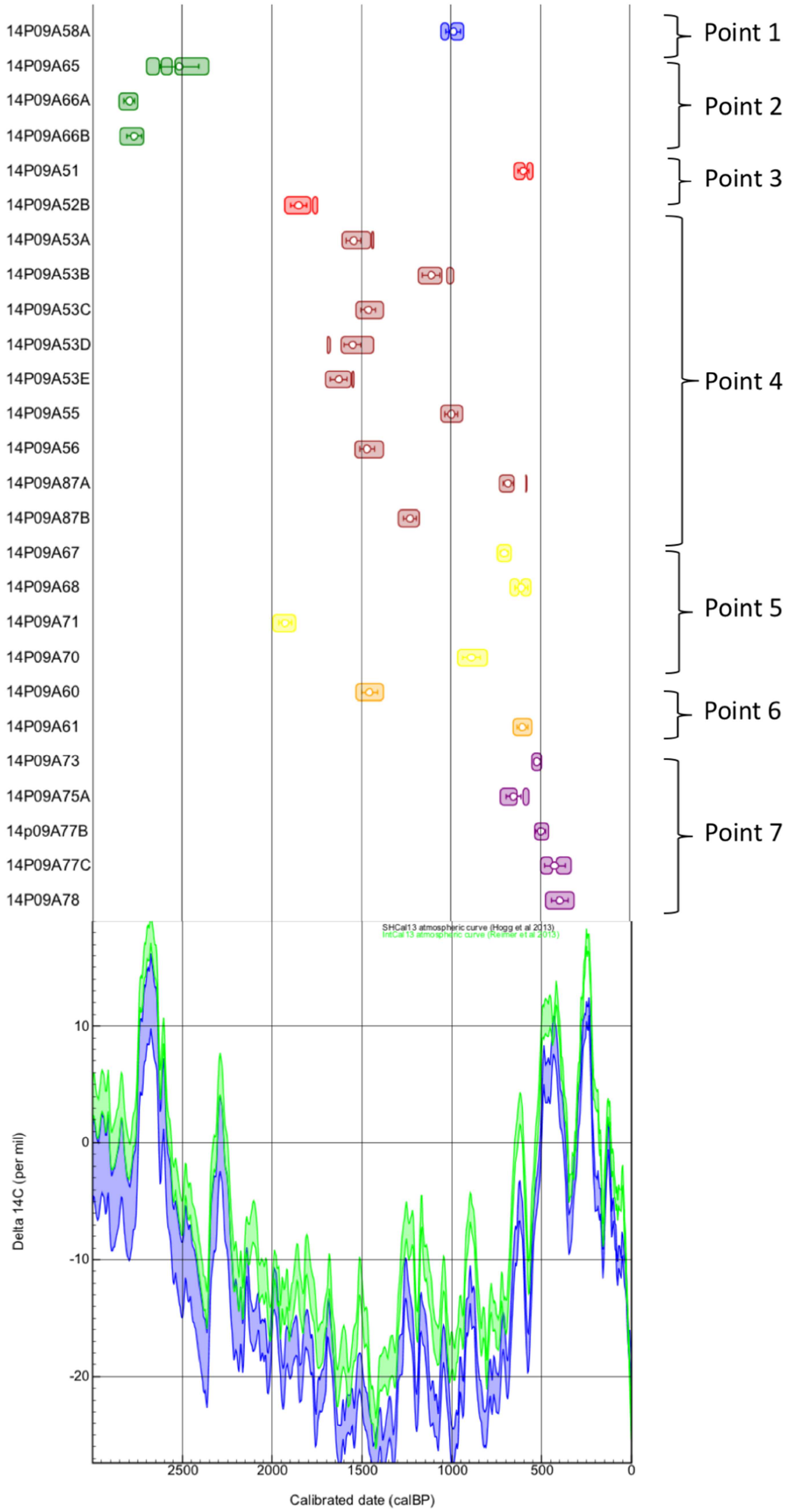


Figure 2. Frequency of charcoal samples in percentage per period of time before present (BP). Figure adapted from Nevle and Bird (2008). We added dates of soil charcoal presented in McMichael et al. (2012) and dates from this study. Charcoal dates are shown in age classes of 500 ^{14}C years. All dates presented in the figure are from charcoal collected in soils.

Another interesting result is the case of sample set 53, with five different families identified. Four of the individual samples (53A, C, D and E) yielded statistically similar results, while sample 53B was dated 400 years younger. Moreover, this sample was also the only in the group to present convergent rays, which are a sign of young ramification (Marguerie and Hunot 2007). Therefore, either the fire occurred about 1000 yr BP and most of the trees were already centenary, or the set of samples represents different fire events.


14P09A58A
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14P09A52B
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14P09A53B
14P09A53C
14P09A53D
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14P09A67
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14p09A77B
14P09A77C
14P09A78
Point 1
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Point 3
Point 4
Point 5
Point 6
Point 7
SHCal13 atmospheric curve (Hogg et al 2013)
IntCal 13 atmospheric curve (Reimer et al 2013)
Delta 14C (per mil)
10
0
-10
-20
2500
2000
1500
1000
500
0
Calibrated date (calBP)

Figure 3. Calibrated ages of samples in the range from 3 to 0 kyr cal BP. and atmospheric $\Delta^{14}C$ values from curves SHCal13 (Hogg et al. 2013) and IntCal13 (Reimer et al. 2013).

Conclusions

Our analysis of the calibrated ages of the charcoal dates shows that the chronology coincides with both climatic events that occurred in the Holocene and with the inferred timing of human occupation in the Amazon region. Most of the dates are consistent with other datasets and with reported climatic events around the world. The higher density of results in our study corresponds to periods of more intense human occupation, with little evidence of recent fire in mature forests.

A total of 13 different families were identified, suggesting that a wide diversity of species was burned in the past. The presence of potentially long-lived species amongst charcoal samples indicates that chronology should be analysed with care. The variety of species within a single set of charcoal fragments suggests a need for multiple radiocarbon dates to be undertaken. Comparison of dating results from charcoal fragments belonging to the same sample set revealed large variation in dates which may reflect different fire episodes, inbuilt age, or the action of bioturbation.

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