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Upland Soil Charcoal in the Wet Tropical Forests of Central Guyana

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ABSTRACT

A soil charcoal survey was undertaken across 60,000 ha of closed-canopy tropical forest in central Guyana to determine the occurrence, ubiquity, and age of past forest fires across a range of *terra firme* soil types. Samples were clustered around six centers consisting of spatially nested sample stations. Most charcoal was found between 40 and 60 cm depth with fewest samples yielding material at 0–20 cm depth. The first core yielded charcoal at most stations. Charcoal ages of a random subsample ranged from less than 200 YBP to 9500 YBP with a noticeable peak between 1000 and 1250 YBP. Results reinforce a view that most closed-canopy tropical forests in eastern Amazonia have been subject to palaeo-fire events of unknown severity with a peak in charcoal age consistently appearing between 1000 and 2000 YBP. The two samples dated to the early Holocene represent some of the oldest indicators of paleo-fire known from upland Neotropical forest soils. Ubiquitous soil charcoal in central Guyana further indicate both forest resilience to fire and the widespread propensity for regional forests to burn, particularly during anomalous periods of drought.

Key words: disturbance history; El Niño-Southern Oscillation; Guiana Shield; fire; Precambrian; radiocarbon.

RADIOCARBON DATING IS INCREASINGLY EMPLOYED IN THE NEOTROPICS as a proxy for detecting palaeoclimatic change (Soubiés 1979, Santos *et al.* 2000) and to anchor both palynological profiles and artifactual evidence of prehistoric human occupation (Dillehay 2000, Lavallée 2000). Our current knowledge of paleo-fire events in the Neotropics, whether attached to artifactual evidence of human activity or not, is largely restricted to charcoal radiocarbon dates obtained from *terra firme* situated in regions dominated by thick Tertiary and Quaternary sediments, such as the Amazon Downwarp (Piperno & Becker 1996, Francis & Knowles 2001), the Llanos (Venezuela and Colombia), and Central America (Horn & Sanford 1992, Piperno 1994). In particular, charcoal derived from lake and swamp sediments have been employed, often in tandem with palynological or phytolith data (*e.g.*, Haberle & Ledru 2001).

Records of radiocarbon-dated charcoal from shallower sediment facies interspersed atop Precambrian Shield regions are few by comparison. Several studies from the Brazilian Shield region have been carried out at or near its northern (*e.g.*, Soubiés 1979) and southern (Vernet *et al.* 1994, Boulet *et al.* 1995) margins, but dates from the interior of the Guiana Shield, an expanse of largely Precambrian crust wedged between the Orinoco and Amazon rivers, are relatively sparse (see Hammond 2005c). The only published radiocarbon dates of deposits beneath *terra firme* forests in this region come from the upper Rio Negro district ($N = 37$) (Sanford *et al.* 1985, Saldarriaga & West 1986), at Nouragues in northern French Guiana (Tardy *et al.* 2000), the Gran Sabana in southeast Venezuela (Fölster 1992), and a pair of preliminary dates obtained in north central Guyana (Hammond & ter Steege 1998). Highland peat formations commonly forming in the Pantepui region of the Venezuelan Guayana have also been dated, but do not complement existing lowland site information given the contrasting environmental conditions and nature of carbon-dated material (Schubert & Fritz 1985).

Charcoal fragments ranging in size from several milligrams to over 250 g are a common constituent of most deep forest soils in central Guyana (van Kekem *et al.* 1996). In particular, soils that typify many of the gently sloping landscapes of the regions consistently yield charcoal. These include soils with relatively high sand content, typically classified as Ferrasols, Acrisols, Arenosols and Podzols (*sensu* FAO 1998). This paper presents charcoal radiocarbon data collected for the first time from these soil types across a 60 km^2 swathe of closed-canopy tropical forest in central Guyana.

METHODS

STUDY AREA.—The Mabura Hill region of central Guyana (5° N, 58° W; elevation 50–200 m asl) lies between the Essequibo and Demerara rivers. The region receives 2400–3000 mm of rainfall annually and records indicate a mean annual temperature of 25°C. Most rainfall occurs from May to August and November to December, though monthly rainfall rarely drops to less than 60 mm per month during the intervening periods. The exception to this wet tropical climate occurs during severe warm phases of the Southern

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Oscillation. Precipitation failure consistently affects the study area over the January–March period during the final phase of these El Niño events. Historic documentation of forest fire events over the last 150 years in the area shows that they are strongly correlated with these periods of precipitation failure (Hammond & ter Steege 1998, Hammond 2005b).

The region is approximately 250 km south of the Atlantic seaboard and forms part of the southernmost extension of Pleistocene sediments deposited during a localized phase of subsidence and consequent sea level transgression into the Berbice Depression (Gibbs & Barron 1993). The study area is dominated by unconsolidated sediments deposited during this period, interspersed with hills and ridges formed by Neogene laterization of exposed intrusives and silts deposited through modern river activity (see Hammond 2005a). Precambrian crystalline basement rock and clastics underpin and surround this patchwork of localized facies.

Due to the geological age and moderate topography of the study area, soil properties principally reflect *in situ* chemical weathering of underlying parent material and their position within the catena, rather than more dynamic physical weathering processes. Consequently, soil types with contrasting properties are distributed in patches, often with abrupt transition boundaries. Distinct changes in soil hydrological properties are largely related to clay-loam content and permeability. Sand-dominated soils, typically classified (*sensu* FAO) as Ferralsols, Acrisols, albic Arenosols and carbic Podzols (van Kekem *et al.* 1996), are characterized by very high water infiltration rates and little or no lateral surface flow except during periods of extremely high water table stands (Jetten 1994, Brouwer 1996).

Drainages dominated by vertical infiltration create an ideal environment for studying *in situ* charcoal production. Marine, lake or swamp sources of charcoal almost invariably reflect paleodepositional processes that act to consolidate materials originating across much larger watersheds (*e.g.*, Amazon, Piperno 1997). In contrast, charcoal fragments found in the upland sandy soils dominating the study area are buried principally through long-term action of vertical infiltration catalyzed by biological action (*e.g.*, tree uprooting, burrowing, nesting, decomposition). Consequently, the likelihood of sampling allochthonous charcoal fragments at individual sampling sites in the study area is very small.

The sample area is situated within a 6000 km^2 logging concession that afforded unprecedented access throughout the forested study area via a dendritic network of narrow access roads. A series of timber companies have undertaken commercial logging in the study area since 1978. Small-scale rubber tapping and gold prospecting have been sporadically carried out since the late 19th century, but the upland forests of the region were largely free from intensive historic use prior to commercial-scale logging, principally due to poor navigability of the major rivers and extensive forest cover (Hammond 2005c). Proxy indicators of expansive prehistoric clearance and cultivation, such as midden piles, *terra preta* soils, pottery and stone tools, are largely unknown from upland *terra firme* forests of the area, but the region is also poorly surveyed. These indicators are, however, more commonly encountered at levee sites along the larger rivers and coastline (Hammond 2005c).

SAMPLE COLLECTION.—To sample the various upland soil types at a broad spatial scale given the staff and time available, we clustered our effort around different sampling "centers." Six centers, 20 km apart, were identified that accommodated both scientific and logistical concerns, and these were used to delimit a 600 km^2 diamond-shaped area covered by the sampling scheme (Fig. 1, inset). Two centers were located equidistant from four outer sampling centers forming the sample area perimeter (Fig. 1, inset).

Each of the six centers was composed of a nested series of radial transects at 2 km, 200 m, and 20 m distances (Fig. 2) summing to a total of 40 sampling stations per sampling center and 240 stations in total. Sample stations were located within both logged and unlogged forest, but no samples were taken in or near skidtrails, access roads, former timber camps or other areas where the substrate had obviously been disturbed by logging, mining, or other extractive industries that have operated commercially in Guyana's forestlands over the last century (Hammond 2005c).

Using an Eijkelkamp Edelman auger (Eijkelkamp Agrisearch Equipment, The Netherlands), several augerings were carried out along the transect at each point, or "station." Five auger samples were taken in a cross pattern, each to a depth of 80 cm (see Fig. 2). If charcoal was not present in any of these five cores, then an additional four cores were taken at the points located as in Figure 2. Finally, if no deposits were found at these additional points, then a sample pit (50 × 30 × 60 cm) was excavated. The pit encompassed the central augerings and allowed close inspection of three adjacent profiles as detailed in Figure 2. Macroscopic charcoal particles found at the stations were bottled and the depth was measured.

Each augering was made to a depth of 80 cm. After removing the surface humus layer, a series of four sequential augerings, each covering a 20 cm profile of soil, was made. The 70-mm-diameter auger head was designed to accommodate this exact depth and retrieve approximately 770 cm^3 of soil when filled. Once the auger head was replete, the core was extracted carefully and placed immediately into a series of fine mesh sieves (1 mm and 0.25 mm, ISO 3310). Sieves were closed and shaken vigorously until no further soil particles passed through the mesh. Any macroscopic particles remaining in the sieve were placed on a plastic tray and examined for physical signs of past burning, such as uniform black color and glossy sheen that indicate cell wall fusion using a flashlight and hand lens where necessary. The presence of extremely small microscopic, and potentially exogenous, charcoal was not examined in this study. Sampled macroscopic charcoal was placed in unused Nalgene bottles and labeled by location and depth. The presence of charcoal at each interval was recorded.

Notes were also taken to classify soil types and the relative abundance and frequency of charcoal at each sampling station as well as presence of noncharcoal content in the sample cores, such as roots, gravel, and artifactual evidence of past human occupation (ceramic shards and stone implements). No sites exhibited vegetation structure or composition that would be consistent with recent (<20 yr) forest succession following slash-and-burn agriculture.

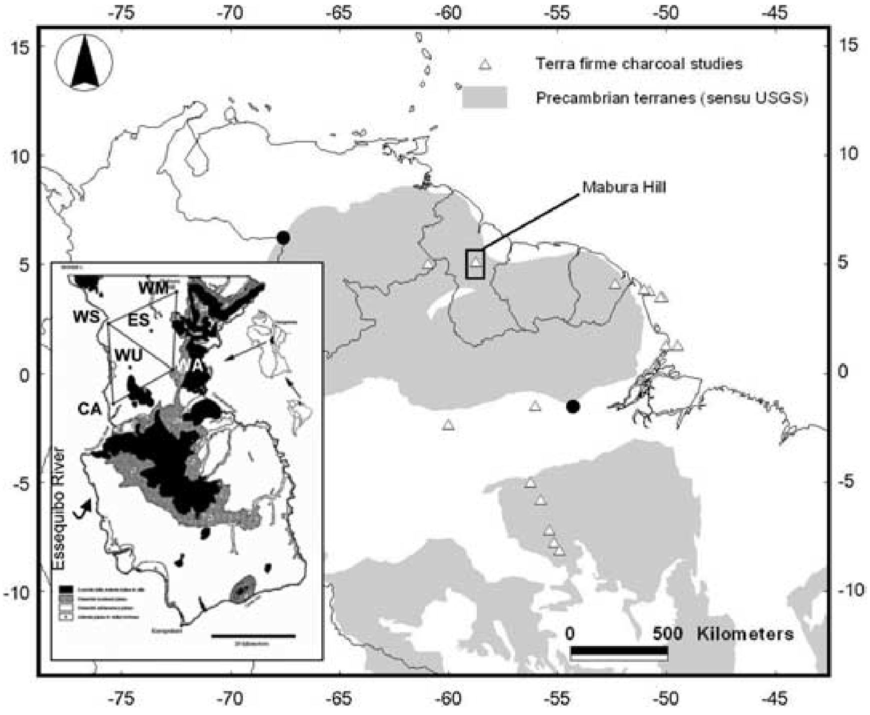

FIGURE 1. Location map showing Mabura Hill region of central Guyana and its proximity to Precambrian shield and published *terra firme* charcoal study sites. Inset: location of sampling area indicating six equidistant stations used to anchor sample clusters. Filled area on inset map—lateritic hills, doleritic dykes and sills; hatched—dissected erosional plains; empty—dissected sedimentary plains. A = alluvial plains, WS = West Seballi, ES = East Seballi, WA = Wappu, Ca = Camoudi, WU = Waraputa, WM = West Maiko. Earliest proposed dates for human occupation (filled circles) are located near Puerto Ayacucho in Venezuela and Monte Alegre near the north bank of the lower Amazon main stem.

LABORATORY WORK.—A subset of 30 charcoal samples (13% of total sample sites) was randomly selected without regard to depth size or location and ^{14}C-analyzed by Accelerator Mass Spectrometry (AMS; van der Borg *et al.* 1997) at Utrecht University, The Netherlands. Applications with radionuclides, in particular radiocarbon dating, benefit from the high sensitivity AMS and its ability to analyze very small samples (down to 0.05 mg of material).

The analyzed samples were generally small, ranging from 0.24 to 2.28 mg of treated material (Table 1). Materials were carefully examined in the laboratory to reconfirm field identification as soil charcoal, and pretreated to eliminate contaminants using acid–alkali–acid treatment. The measured ^{14}C/^{12}C ratios were compared to those of reference material (blanks and HOX-II). The ^{13}C/^{12}C ratios, expressed as δ^{13}C-values relative to the VPDB standard, were obtained by gas mass spectrometry and used to obtain conventional radiocarbon ages (Stuiver & Polach 1977). Results are presented here using both radiocarbon (^{14}C yr BP) and calibrated (cal yr BP) ages for broader comparability with other studies. The radiocarbon ages were converted to calendar age ranges using the calibration code Oxcal 3.1 (Bronk-Ramsey 2001).

RESULTS

Charcoal fragments varying in size and depositional depth were found at all 240 sample sites. More than 85 percent of the sample sites presented charcoal in the first auger hole (see Fig. 3A) and more than half across multiple 20-cm depth increments down to the maximum auger depth of 80 cm (Fig. 3B). Macroscopic charcoal fragments were most commonly present at the 40- to 60-cm depth interval and least frequently in the uppermost layer from 0 to 20 cm depth (Fig. 3C). A *G*-test of independence (Sokal & Rohlf 1995) indicates that the frequency of macroscopic charcoal present in the sampled soil cores was not independent of depth ($G_{\text{corrected}} = 105.3$, $P << 0.001$, df = 3). Cochran's test of linear trend (Systat 1998) further indicates that charcoal frequency increases with depth (Cochran's $LT = 58.7$, $P << 0.001$, df = 1), due to the proportion of charcoal increasing between the 0–20 and 40–60 cm depth intervals. This pattern was consistent across all six sampling clusters (40 sites per cluster) (Fig. 3C), although sites furthest from the main stem of the Essequibo river (WU, ES) showed considerably lower fractions than sampling centers located further down the local stream catchments (CA, WA, WS) (see Fig. 1, inset).

The radiocarbon ages show a pair of isolated dates starting at 9250 and 8010 ^{14}C YBP (11,000 and 9000 cal BP), followed by a rather continuous sequence from 1750 to 750 ^{14}C YBP (1800–900 cal BP), and thereafter isolated dates between 750 and 250 ^{14}C YBP (600–350 cal BP) (Fig. 4). Four samples, each taken from different sampling centers, were dated Modern (<200 ^{14}C YBP or AD 1810 to AD 1976 in calibrated years) (Table 1), but sample ages date across most of the main transitional climate phases

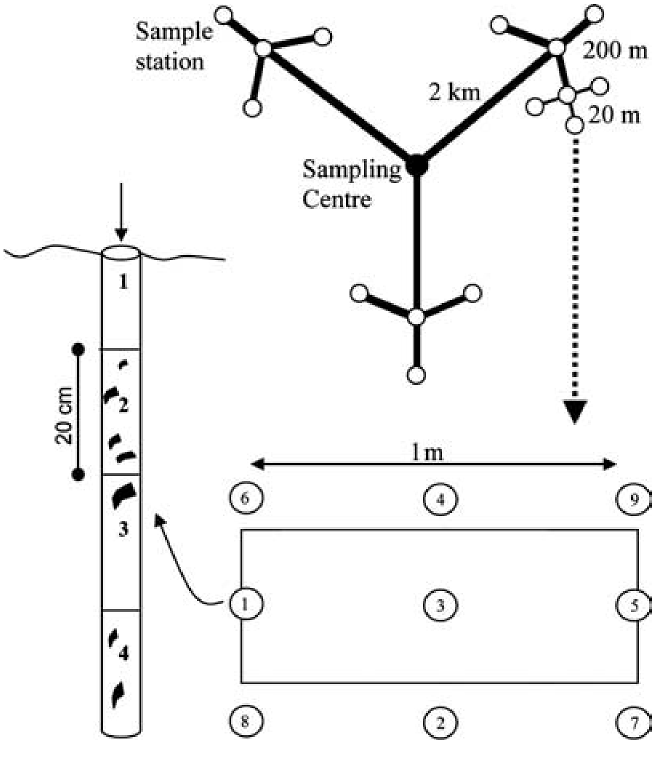

FIGURE 2. Distribution of sample stations, soil sampling at each station and within each auger hole. Auger holes were sampled in chronological order until macroscopic charcoal was recovered.

currently believed to have affected regional precipitation throughout the Holocene (Vernet *et al.* 1994, Flenley 1998, Haberle & Ledru 2001). The samples at 11,000 and 9000 cal BP of the early Holocene "thermal maximum" (10,500 to 5400 ^{14}C YBP) (Haug *et al.* 2001) represent the oldest evidence of past fire events from the study area.

The δ^{13}C values for these and other samples ranged from −29.4 to −25.4 permille. This indicates that all of the charcoal was formed from C3 plants that typify modern tropical forest habitat (Table 1).

TABLE 1. *AMS results from carbon isotopic analysis of the charcoal sample subset collected across 60-km*^{2} *forest area south of Mabura Hill, central Guyana.*

Utc No.	Sample Location	Depth	Mass (mg)	δ^{13}C (permille)	^{14}C Age (BP)
7842	ESC	3	1.40	−25.4	1165 ± 42
7843	ES7	3	0.43	−28.5	8810 ± 70
7844	ES1	2	2.10	−27.4	1348 ± 39
7921	ES19	2	2.08	−29.1	988 ± 46
7922	ES17	2	2.16	−28.3	990 ± 39
7923	ES12	3	2.13	−27.0	1310 ± 45
7924	CAC	2	1.47	−26.2	1010 ± 50
7925	CA62	2	0.57	−28.1	1019 ± 46
7926	CA43	3	0.31	−28.0 e)	1350 ± 60
7927	CA66	3	0.42	−28.6	Modern
7928	CA60	1	1.74	−26.1	618 ± 43
7929	CA71	2	1.51	−26.8	880 ± 50
7930	WA10	4	1.88	−29.2	1792 ± 45
7931	WA18	3	2.16	−26.9	1588 ± 38
7932	WA15	1	1.83	−28.8	1625 ± 38
8214	WA19	3	0.18	−28.0 e)	360 ± 70
7933	WA25	1	2.07	−27.1	901 ± 41
7934	WA26	1	2.28	−29.4	Modern
7935	WU22	3	1.27	−26.7	Modern
7936	WU30	3	0.45	−27.1	1200 ± 70
8161	WU31	3	1.96	−26.6	1732 ± 44
8162	WU46	3	1.70	−26.1	1137 ± 32
8163	WU25	3	2.03	−27.6	1147 ± 30
8164	WU21	3	2.28	−24.6	1312 ± 34
8165	WS25	2	2.21	−29.0	1048 ± 36
8166	WS36	3	2.24	−27.9	1016 ± 37
8167	WS37	3	2.18	−27.0	1482 ± 49
8168	WS18	1	2.14	−28.1	358 ± 35
8215	WS58	1	0.24	−27.7	Modern
8169	WS14	4	2.13	−26.7	9250 ± 50

Depth: 1 = 0–20 cm, 2 = 20–40, 3 = 40–60, 4 = 60–80.

^{e}Estimated.

*Modern (<200 yr BP) = calendar age AD 1810 to AD 1976.

DISCUSSION

The macroscopic charcoal record from the central Guyana study area indicates that fire has affected forests in this region over the last two millennia. The widespread presence of large charcoal fragments in *terra firme* uplands at the site suggest that the charcoal record reflects *in situ* fire events rather than depositional dynamics attached to atmospheric or surface flow patterns (Ohlson & Tryterud 2000). The δ^{13}C values of analyzed samples further indicate that charcoal was formed exclusively from C3 source plant material that is largely indicative of woody dicotyledonous forest plants.

The dates of 9.2 and 8 ^{14}C ka BP extend this record to the earliest Holocene. They represent two of the earliest radiocarbon dates for upland soil charcoal known from the Guiana Shield. Only radiocarbon ages of charcoal collected by Tardy and colleagues (Charles-Dominique *et al.* 1998, Tardy *et al.* 2000) from the *terra firme* forest soils at Nouragues, French Guiana, are of similar antiquity. The charcoal ages presented here are broadly comparable to the earliest proposed dates for human occupation in the entire lowland Neotropics at Pedra Pintura (10,300–11,200 ^{14}C YBP) (Monte Alegre) (Roosevelt *et al.* 1996), and at the Provincial site near Puerto Ayacucho (9000 ^{14}C YBP) (Barse 1990). Samples collected in Venezuelan Guayana (Saldarriaga & West 1986, Fölster 1992), along the north perimeter of the Amazon mainstem (Piperno & Becker 1996, Santos *et al.* 2000, Francis & Knowles 2001), and

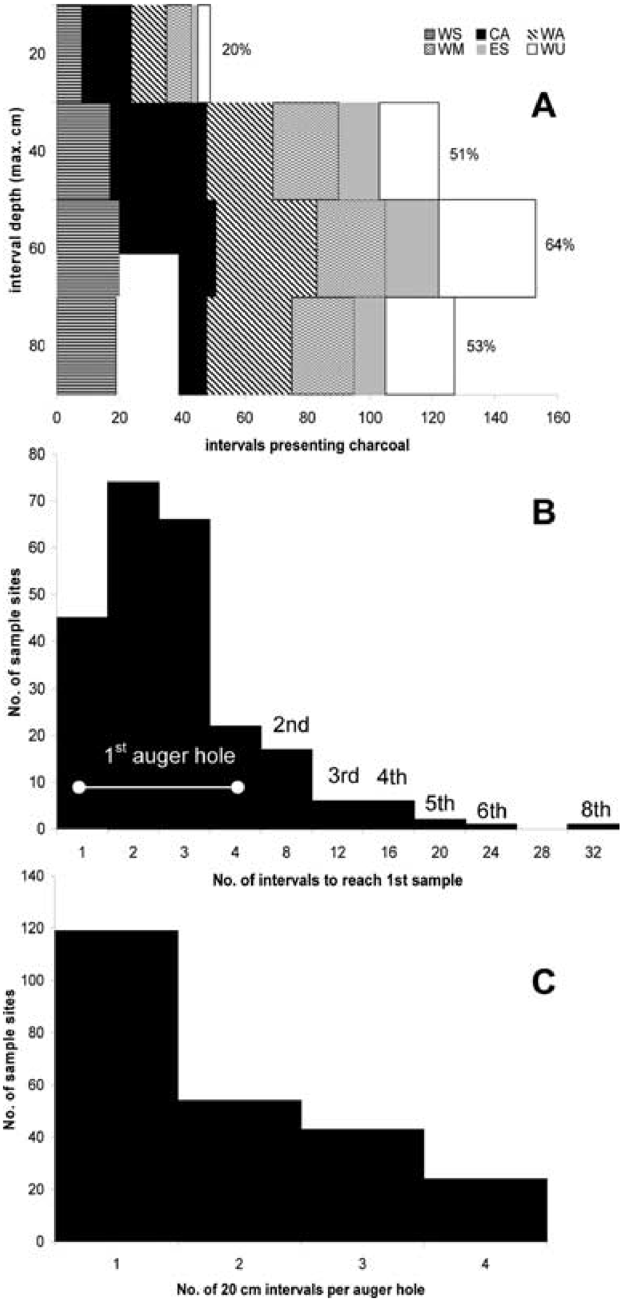

FIGURE 3. (A) Distribution of charcoal by depth interval and sampling center. Percentages given of total samples taken. (B) Number of 20-cm samples needed to reach first macroscopic charcoal deposits. Four samples per auger hole. Sequence of 80-cm deep auger holes noted by 1st,2nd,3rd, etc. (C) Uniformity in charcoal depth distribution. The number of depth intervals (1–4) containing charcoal in each auger hole sampled.

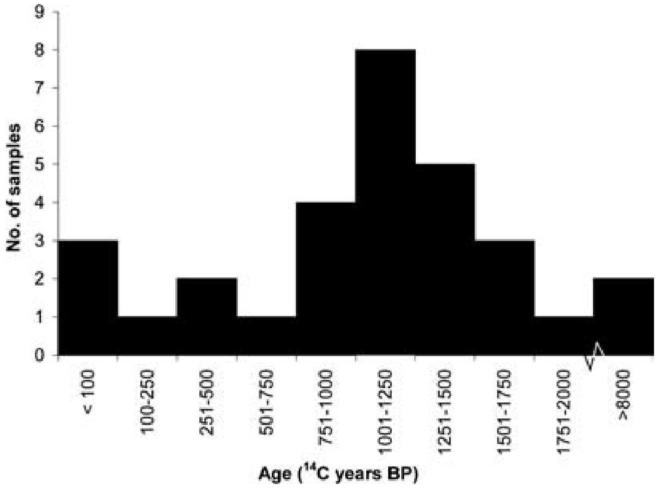

FIGURE 4. Frequency distribution of AMS-derived radiocarbon ages for analyzed charcoal samples.

in Central America (Horn & Sanford 1992), have strikingly similar mean and modal ages clustered between 1000 and 2000 ^{14}C YBP with only one date, at San Carlos, extending beyond 4000 ^{14}C YBP (see Hammond 2005a). Dating of upland collections from the Precambrian Brazilian shield at Carajás (Soubiés 1979) and Salitre (Vernet *et al.* 1994) yielded much older sample ages, but the oldest dates at these sites are younger than those obtained at the Mabura Hill study area.

SOURCE ERRORS IN CHARCOAL AGING.—Two sources of error may have produced the disparate maximum charcoal ages found at different Neotropical sites: (1) varying maximum depth of sampling; and (2) the "in-built" age of charcoal. The oldest charcoal fragments analyzed at Mabura Hill were located at the deepest sampled soil depths (40–60 and 60–80 cm), although the relationship between charcoal age and depth is weak (Table 1) and discordant with the significant soil depth and macroscopic charcoal frequency relationships found here. Maximum sampling depths range between 30 and 100 cm across different sample locations in the Neotropics and this discrepancy could affect maximum charcoal ages reported by different studies. However, despite these differences in sampling methods, charcoal ages are not strongly associated with depth at some locations (Francis & Knowles 2001). Even though many samples at other site have been recovered from equal or deeper depths, all consistently fall below the maximal ages of the deeper fragments recovered at Mabura Hill. Unlike lake or swamp sediments, however, a clear and consistent depth–age relationship is less likely in forest soils as these are affected repeatedly by soil mixing resulting from treefall uprooting, animal burrowing, and various human impacts.

The age of the live wood from which charcoal was formed could also potentially distort relative differences between mean and maximal calendar ages if charcoal at some sites was formed, on average, from significantly older wood material. Large Neotropical trees living 500 to 1000 years are not uncommon (Chambers *et al.* 1998, Laurance *et al.* 2004), and at this timescale significant differences between the age of a fire event and age of the resulting burnt material, as determined by radiocarbon dating, could form an important source of error for Holocene deposits. This would hinge on the larger contribution of older heartwood to charcoal formation relative to sapwood, a dynamic that appears unlikely based on modern burn patterns (*e.g.*, Cochrane *et al.* 1999), but possible if paleo-fire events were of greater intensity. If stand turnover and average tree longevity vary considerably between geographic locations, as suggested by Whitmore and da Silva 1990, Verburg *et al.* 2003, and Hammond 2005b, then this may represent a significant source of error. In this case, charcoal ages presented in this study and others over-estimate actual age of fire events by several hundred years.

DRIVERS OF PREHISTORIC CHARCOAL PRODUCTION.—Pre-Colombian land-use, climate-induced drought, or a combination of these factors must be responsible for the ubiquity of soil charcoal at upland *terra firme* forest sites in central Guyana. Determining whether charcoal is derived primarily from anthropogenic or climatic events is wrought with pitfalls. Human activity would lead to more intense or frequent events (*e.g.*, slash-and-burn) and thus more charcoal production. This build-up would dilute charcoal formed solely through drought-induced fire (see also Francis & Knowles 2001). Concomitantly, severe drought, such as that driven by very warm El Niño phases of the Southern Oscillation (ENSO), could have been a necessary precondition for the spread of human-ignited fires into surrounding forests, as was the case at various locations during the 1997–1998 event (Hammond & ter Steege 1998, Nelson & Irmão 1998, Murty *et al.* 2000).

No artefactual evidence was found at the 240 sample sites to suggest that widespread human activity strongly shaped the charcoal record, although the peak sample age frequency certainly rests well within bounds defined by artifactual evidence for the region. Archaeological studies and historical accounts, however, show that pre-Colombian settlement in the region was largely restricted to riverbank levees near exposed doleritic dykes and sills. These sites afford numerous advantages for travel, fishing, and agriculture in an otherwise relatively oligotrophic environment (Williams 1996, Hammond 2005c). The absence of artifactual evidence at upland Mabura Hill sites is largely consistent with results from Nouragues (Charles-Dominique *et al.* 1998) and Manaus (Piperno & Becker 1996), although Amerindian settlement in these areas and at sites in the San Carlos and Porto Trombetas regions are well documented (Hurault 1972, Gassón 2002). Again, absence of phytolithic analysis makes it difficult to fully discount prehistoric slash-and-burn activity as a source of soil charcoal in the study area.

Charcoal produced solely through drought-induced fire events is also difficult to deduce, since ignition through lightning that accompanies rain storms is a minor event during these rainless periods. Most modern fires in the region are ultimately linked to human activity (Kauffman & Uhl 1990, Hammond & ter Steege 1998) indicating that pre-Colombian dwellers may also have started fires that then spread over larger areas of forest when fuel loads increased during significant dry down periods (Cochrane & Schulze 1999). The study area is subject to some of the most extreme precipitation changes during anomalous phases of ENSO (Ropelewski & Halpert 1987, Ropelewski & Halpert 1996, Dai & Wigley 2000) and frequently suffers substantial precipitation decline during warm ENSO periods (Hammond & ter Steege 1998, Hammond 2005a) and consequent buildup of fuel loads. Acceleration of ENSO over the latter half of the Holocene, as hypothesized by Haug *et al.* 2001, based on Ti/Fe fluxes in the nearby Cariaco Basin, combined with increasing human presence, provides a compelling explanation for a peak in charcoal production between 1000 and 2000 ^{14}C YBP at the study site and other regional sites similarly affected. The pair of early dates corresponding to Holocene "thermal maximum" (*sensu* Haug *et al.* 2001) and predating any artifactual evidence of interior shield occupation by prehistoric residents (Hammond 2005c) are more difficult to explain as a consequence of an "ENSO-human synergy" hypothesis (Meggers 1994). Ultra-severe or extended ENSO phases would, together with the high sand content and considerable infiltration rates of soils at the study site, make forests in central Guyana particularly susceptible to anomalous decline in precipitation during dry season months, but it remains unclear whether the region was affected by such events during the early Holocene.

Ubiquitous charcoal from numerous sites indicates that closed-canopy forests throughout the Guiana Shield region have been subject to fire events of unknown intensity over the last several millennia. Results presented here augment the view that most eastern sectors of Amazonia have been affected by fire. This presents both the prospect of forest resilience after modest human intervention and the potential for dramatic forest fires in the tropical wet forests of Guyana and across eastern Amazonia. Similar sampling is much needed from western and central Amazonia to determine the full extent to which paleo-fires have affected the life history of modern Neotropical forests and how these may be linked to past interactions of climate and human land-use change.

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