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Holocene Charcoal Stratigraphy from Laguna Tortuguero, Puerto Rico, and the Timing of Human Arrival on the Island

David A. Burney and Lida Pigott Burney

Department of Biological Sciences, Fordham University, Bronx, NY 10458, U.S.A.

R. D. E. MacPhee

Department of Mammalogy, American Museum of Natural History, Central Park West at 79th Street, New York, NY 10024, U.S.A.

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An 8 m sediment core from Laguna Tortuguero, Puerto Rico, provides a 7000 calendar year history of fire occurrence and sedimentation on the island's north coast. After *c.* 5300 cal-BP, microscopic charcoal particle concentration and influx increase abruptly, and values remain high for the next two millennia. Subsequent to *c.* 3200 cal-BP, fire occurrence gradually declines to more moderate levels. It seems likely that the mid-Holocene acceleration in fire frequency documented here may signal the onset of human disturbance of the landscape. Indirect detection of human arrival on oceanic islands from a sudden increase in stratigraphic charcoal may be a useful technique in other island contexts, although it is important to consider that wildfires can occur without a human ignition source.

Keywords: CHARCOAL STRATIGRAPHY, FIRE HISTORY, PUERTO RICO, OCEANIC ISLANDS, HUMAN ARRIVAL, LANDSCAPE MODIFICATION.

Introduction

Establishing a reasonably firm date for earliest human arrival on an oceanic island is an essential goal in the course of investigations that seek to reconstruct the prehistory of the island's biota and human colonizers (e.g. James *et al.*, 1987; Burney, 1987*a*, 1993; Steadman, 1989). This goal has generally been elusive, however. The prehistoric colonizers of remote islands may initially be few in number, and their earliest impacts may be difficult to detect. The earliest clearly-defined archaeological sites providing unequivocal evidence of settlement often trail by several centuries or more such indirect evidence of earliest human activities as landscape modification, introduction of alien species, and impacts on indigenous biota.

Madagascar is a good case in point: the earliest dated archaeological site indicating human settlement (Dewar & Wright, 1993) is about a half millennium later than evidence from a sudden increase in microscopic charcoal particles in sediment cores (e.g. Burney, 1987*b*, 1993), pollen of introduced plants in sediment cores (Burney, 1987*a*), and human-modified bones of extinct megafauna (MacPhee & Burney, 1991). Similar disparities between the earliest direct archaeological evidence and indirect evidence of humans have been noted on Pacific islands, such as Mangaia (Kirch, Flenley & Steadman, 1991), and Hawaii (Hunt & Holsen, 1991). These examples point to the value of looking to palynology and palaeontology when pursuing this somewhat elusive archaeological goal.

It is not surprising that a seeming disparity would exist between earliest cultural evidence for human habitation versus detectable human impacts on the environment. Investigators have generally concluded that the founding human populations on remote islands were likely to have had effects on island environments and biota out of proportion to their small numbers, owing to the sensitive nature of island habitats and organisms (reviewed in Diamond, 1984, Olson, 1989). Likewise, a distinction should necessarily be recognized in these cases between human "arrival" and effective colonization by humans. The former may or may not signal the onset of permanent colonization, and small founding human populations in any case require, even with very low infant mortality rates, several centuries to fully "explode" through exponential population growth (Mosimann & Martin, 1975). It is also conceivable, as postulated in the case of Cyprus, for instance (Held, 1991), that humans may visit and temporarily settle on an island one or more times before permanent settlement is successfully attained.

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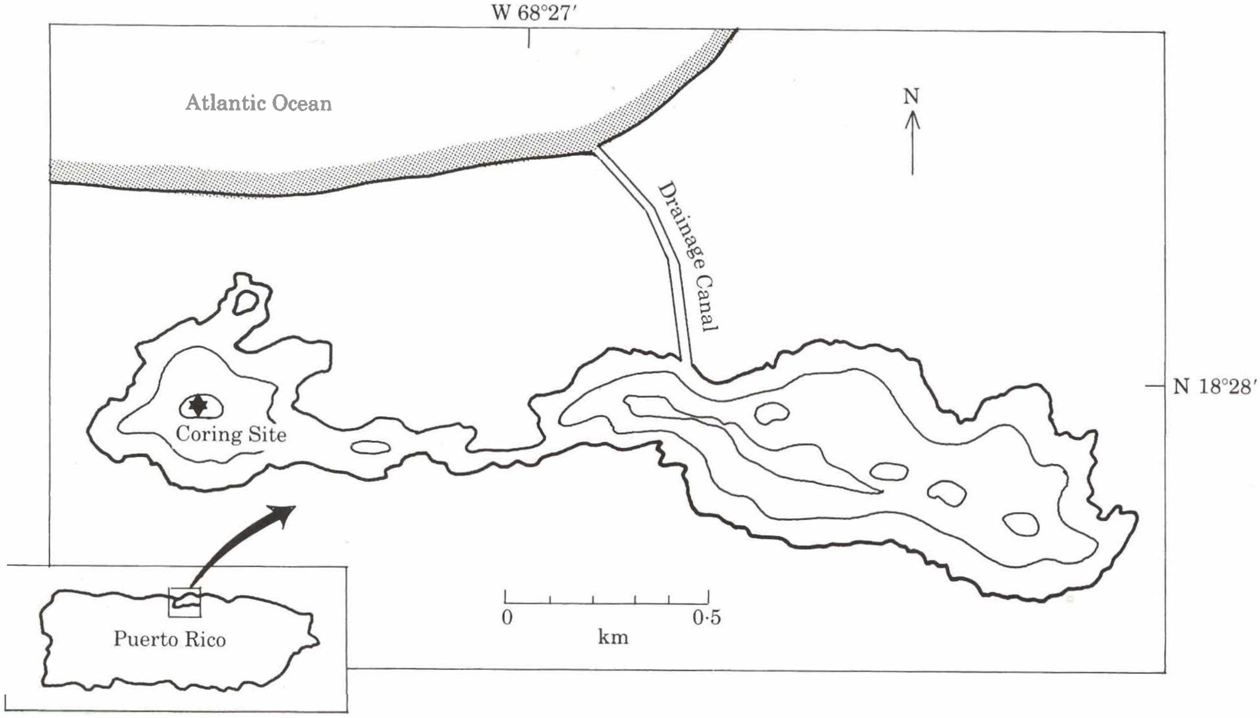

Figure 1. Location of Laguna Tortuguero, Puerto Rico. Bathymetric contour intervals are 1 m. Map redrawn from Fusté & Márquez (1978).

From the palaeoecological perspective, reconstructing what has happened in recent millennia on oceanic islands requires one to recognize (and, if possible, place in chronological sequence) four types of events, each of which may leave traces in the stratigraphic record. These are: (1) modification of the landscape with fire, forest clearance, cultivation, etc.; (2) the introduction of exotic organisms; (3) the decline and extinction of at least part if not the majority of the larger and more disturbance-sensitive endemic forms; and (4) establishment of human settlements. The order in which these events occur, the rapidity of any transformations effected, and the final outcome of the interactions between these factors, provide the kind of historical background and conceptual framework needed for understanding human and natural dynamics on oceanic islands. Despite the clear value of studies of this type for archaeologists, palaeoecologists, palaeontologists, and other specialists, work of this sort is in its infancy everywhere. The conventional method for fixing earliest human occupation or visitation of an area is archaeological, that is, through the discovery of datable elements of material culture. Finding direct evidence of this sort usually requires the commitment of significant resources and time over decades. It is therefore useful to ask whether some stratigraphic method might provide a reliable short-cut, allowing the detection of earliest human activity in the vicinity in lieu of finding the very earliest archaeological sites.

We explore in this paper, using Puerto Rico as a test case, the hypothesis that human modification of the fire ecology of a landscape, detected stratigraphically as a sudden and sustained increase in charcoal particles, may be one of the earliest general indicators of human presence on an oceanic island.

Methods

The selected site for this study is a cut-off lagoon on the north coast of Puerto Rico, Laguna Tortuguero (Figure 1). This oligohaline lake is separated from the sea by a line of high vegetated dunes. Although the lake drains into the Atlantic Ocean by a ditch constructed about 1940, the presence of an aquatic macrophyte community in the lake that is intolerant of high salinity suggests that storm-driven tidal inputs are infrequent. Mean annual precipitation in the area is about 1500 mm, and the vegetation surrounding the lake is a mixture of trees, shrubs, and grasses typical of areas on the north coast of Puerto Rico with relatively high levels of human disturbance. The surface elevation of the lake is *c.* 1·0 m ASL, but was probably nearly 1·0 m higher before construction of the ditch (Bennett & Giusti, 1972).

The maximum water depth is *c.* 2·8 m. We chose for sediment coring a site near the geographic centre and in the deepest part of the western basin of the lake. A core of *c.* 8 m was collected in May, 1987, using a piston-corer of the Livingstone sampler type.

The core sections were opened and described in the Paleoecology Laboratory at Fordham University.

Table 1. ^{14}C age estimates for Laguna Tortuguero core samples

Core depth (cm)	Laboratory no.	Uncalibrated ^{14}C age (^{14}C years bp)*	Calibrated age range $\pm 1\ \sigma$ (cal-BP)†
120–139	β-54719	1490 ± 80	1504–1307
218–227	β-24613	3940 ± 120	4539–4239
439–458	β-22349	3640 ± 80	4087–3855
628–647	β-54720	4560 ± 70	5321–5055
757–781	β-22350	5960 ± 90	6893–6727

*Results corrected for isotopic fractionation to a base of $\delta^{13}C = -25$ per mil.
†Calibrated from 20 year atmospheric curves used in Stuiver & Reimer (1986).
Errors are 68·3% confidence limits.

Samples for pollen and charcoal analysis were processed according to the standard methods described in Faegri & Iversen (1975). Although samples were filtered through a 275 µm sieve, inspection of the screens under a dissecting microscope showed that this mesh size was large enough to allow all the sedimentary charcoal to pass through. Charcoal was quantified in pollen slides by a method described in Patterson, Edwards & MacGuire (1987), in which projected area of charcoal pieces is measured with an ocular grid on transects across microscope slides, and these pieces are tallied in size classes. Addition of a spike of exotic *Eucalyptus* pollen of known quantity to the samples allowed results to be converted to concentrations. Visual determinations of graminoid charcoal were made as described in Burney (1987*b*). Five radiocarbon dates were obtained from sediment samples that had been picked for rootlets, pre-treated with HCl to remove carbonates, and rinsed to neutrality. All dates were corrected for isotopic fractionation, and calibrated to calendar years using the CALIB 2.1 FORTRAN microcomputer program (Stuiver & Reimer, 1986), based on the 20 year atmospheric curves. The charcoal diagram was plotted on TILIA version 1.09 software provided by Eric Grimm.

Results

Core description

From the bottom of the core at 782 cm up to 302 cm, the sediment is a uniform black detrital gyttja (Munsell wet colour N 2/0). Some macroscopic wood fragments are visible in the lower part of this unit, being especially numerous between 740–700 cm. Roots are uncommon except for a dense mass of fine roots between 540–530 cm.

At 302 cm the sediment changes abruptly to a unit composed of complex laminae of fine-grained algal gyttja. The bottom of this unit contains a mixture of algal mud and fine molluscan shell fragments. The small shell fragments become very scarce above 280 cm, where the laminae become more distinct. The horizontal structures are clearly delineated, with no apparent lateral variability. They consist of bands each ranging from <1 cm to 7 cm thick, alternating between dark reddish brown (5YR 2/2), slightly fibrous subunits, and pale red (10R 6/4) subunits with a gel-like consistency. The latter subunits contain an abundance of dinoflagellate cysts. Above 200 cm the laminae are replaced by a sandy gyttja, mottled with reddish-gray (5YR 5/2) to very dark gray (5Y 3/1) background colours. Fine particles of mollusc shells are present throughout this sandy unit. At *c.* 165 cm the sediment changes gradually to very dark brown detrital gyttja, with a few small, thin shell fragments. The sediment lightens in colour toward the present surface, to dark brown (10YR 3/3), with the concentration of mollusc shell fragments increasing again from *c.* 10 cm to the surface.

Radiocarbon chronology and sedimentation rates

Of the five radiocarbon dates obtained from the Laguna Tortuguero core (Table 1), four showed an internally-consistent depth–age relationship (Figure 2),

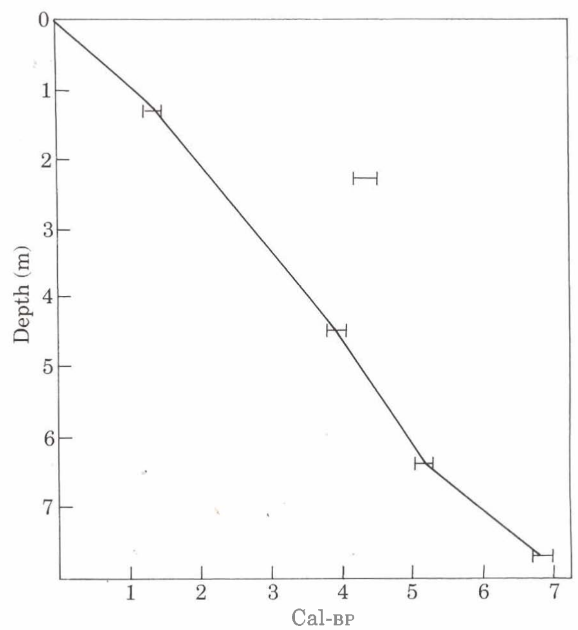

Figure 2. Plot of cal-BP age versus depth in the Laguna Tortuguero sediment core. Vertical bars=sediment intervals dated; horizontal bars=cal-BP range at 1 σ.

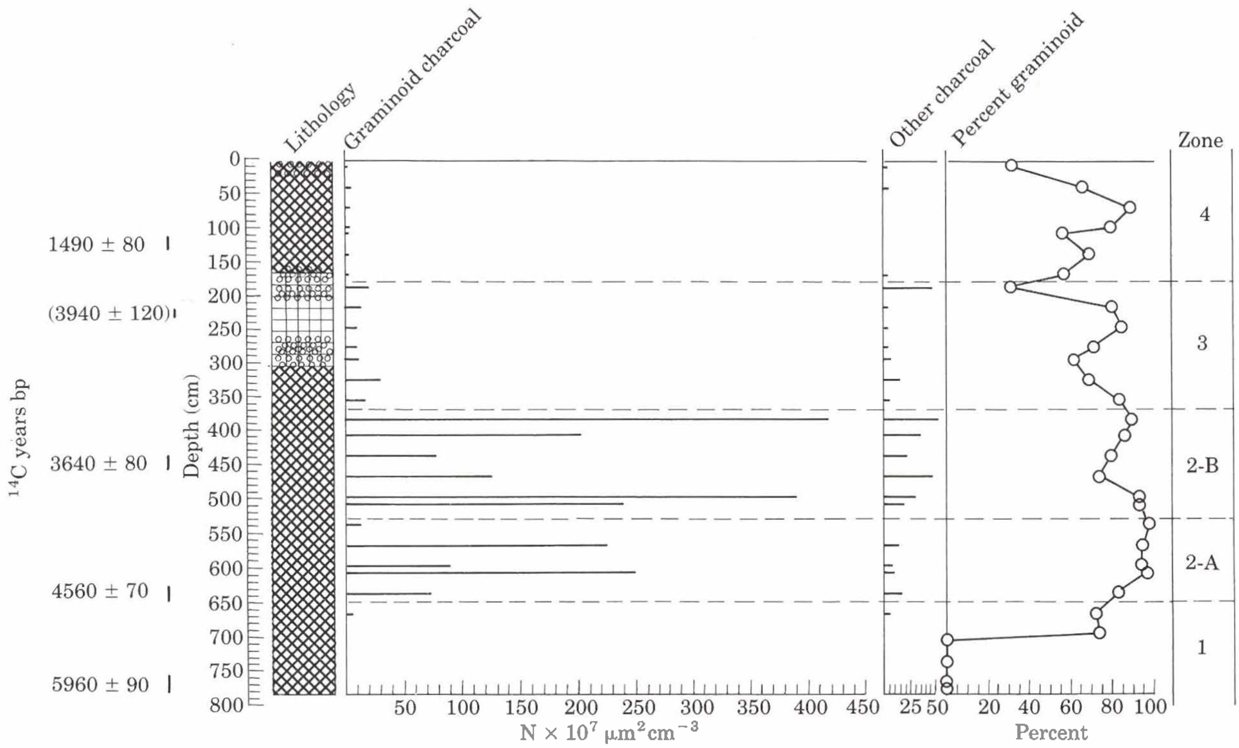

Figure 3. Charcoal diagram and lithology for the Laguna Tortuguero sediment core. See Table 1 for calibrations of ^{14}C ages, Table 2 for charcoal particle size distributions, and Figure 2 for cal age–depth relationships. Key to lithology: ▩, detrital gyttja; ▦, laminated algal gyttja; ○, molluscan shell fragments. Charcoal concentrations of Zone 1 can be converted to influx by dividing by 11·7 calendar years cm^{-1}. For Zones 2–4 charcoal influx, divide by 8·3 calendar years cm^{-1}.

but the fifth (β-24613) appears to be too old by *c.* 2000 years. Although the other four samples are from detrital gyttja units of uniform appearance, the anomalous date is from the laminated algal gyttja unit with much fine shell debris (see lithology, Figure 3). A change in lake chemistry to more concentrated waters and a lowering of lake level at the time of deposition of this unit is inferred from the sedimentology. Likely consequences of this limnological change that might affect the apparent radiocarbon age are hard-water effects from increased concentration of waters derived from the karstic Aymamón Aquifer that feeds the lake (Bennett & Giusti, 1972), incorporation of old carbon by the molluscs that were apparently abundant at this stage, and redeposition of old carbon from erosion of the exposed lake bed. The result in any of these cases would be an increase in the apparent age of the associated sediments, and the proposed explanations are not mutually exclusive.

The depth–age relationship for the other four dates suggests that the sedimentation rate has been essentially constant for the last *c.* 5000 calendar years (8·3 calendar years cm^{-1}), as the upper three dates plot a virtually straight line that intersects the *y*-axis near the sediment-water interface. Interpolation between the lower two dates in the sequence, however, suggests a lower sedimentation rate (11·7 calendar years cm^{-1}) between *c.* 7000–5000 cal-BP.

Charcoal analysis

It is clear from Figure 3 that the charcoal stratigraphy in this core falls into four distinct phases. Samples in the earliest phase (Zone 1, *c.* 7000–5300 cal-BP) are characterized by the virtual absence of charcoal in the sediments, and by small fragments only (Table 2). In an interval dated 4560 ± 70 ^{14}C years bp (1 σ cal range = 5321–5055 cal-BP, intercept = 5293 cal-BP), graminoid charcoal values abruptly increase to $7{\cdot}5 \times 10^8$ μm^2 cm^{-3}, and "other" (i.e. non-graminoid, probably derived primarily from trees and shrubs) also shows an increase. Particles in larger size classes (Table 2) are relatively numerous. Generally high charcoal values (Zone 2-A) are recorded up to 540 cm in the core, at which point a single level with low values occurs (this was the level characterized by a mass of roots), followed by very high values for both graminoid and other charcoal (Zone 2-B). At a level extrapolated to *c.* 3500 cal-BP, the highest values in the entire core are recorded ($4{\cdot}2 \times 10^9$ and $5{\cdot}0 \times 10^8$ μm^2 cm^{-3} for graminoid and other charcoal, respectively). These are high values by any standards. Modern charcoal concentrations in comparable types of sediments from present-day slash-and-burn areas of Madagascar ranged from *c.* 0·1–2·0 × 10^8 μm^2 cm^{-3} for total (graminoid + other) charcoal (Burney, 1987*b*).

Table 2. Number (× 10³) of graminoid and non-graminoid charcoal fragments per cm³ by size class in the Laguna Tortuguero core

Depth in core	Size class (μm²)							
	50–99	100–199	200–399	400–799	800–1599	1600–3199	3200–6399	6400–12,799
Graminoid charcoal fragments								
10	9·4	14·1	13·3	4·7	1·6	0·0	0·0	0·0
40	8·7	4·8	4·8	0·0	0·0	1·0	2·9	1·0
70	4·7	11·7	7·0	2·3	2·3	4·7	0·0	0·0
99	5·8	9·7	13·5	7·7	0·0	1·0	0·0	1·0
109	16·0	16·8	13·3	3·1	0·9	0·0	0·0	0·0
139	17·1	17·9	4·5	0·7	0·0	0·0	1·5	0·0
169	31·2	18·0	5·5	3·3	5·5	2·2	0·0	0·0
187	42·6	118·0	98·4	45·9	45·9	23·0	0·0	0·0
217	107·0	84·7	41·0	54·7	27·3	2·7	2·7	0·0
247	33·8	32·8	28·7	23·6	16·4	3·1	6·2	0·0
277	40·5	62·3	38·3	30·6	13·1	5·5	1·1	1·1
295	71·1	65·6	76·5	38·3	5·5	10·9	0·0	0·0
325	80·2	175·0	96·6	56·5	40·1	29·2	10·9	3·6
355	26·7	40·3	62·9	50·6	32·1	12·3	1·4	2·1
385	552·0	1350·0	1450·0	672·0	372·0	202·0	109·0	169·0
408	90·2	635·0	869·0	648·0	209·0	135·0	111·0	16·4
438	246·0	574·0	521·0	171·0	75·4	59·0	16·4	9·8
468	251·0	358·0	691·0	372·0	219·0	87·5	41·0	8·2
498	601·0	951·0	640·0	705·0	497·0	569·0	169·0	32·8
508	508·0	1310·0	820·0	607·0	246·0	90·2	148·0	32·8
538	44·3	60·7	41·3	25·5	9·7	4·9	2·4	3·0
568	715·0	728·0	928·0	748·0	325·0	72·2	59·0	52·5
597	109·0	242·0	453·0	282·0	109·0	50·7	28·3	16·4
607	306·0	656·0	842.0	732·0	443·0	186·0	65·6	38·3
637	414·0	492·0	385·0	135·0	77·9	36·9	16·4	16·4
667	29·5	19·7	23·0	9·8	0·0	0·0	6·6	0·0
696	19·7	1·6	3·3	0·0	0·0	0·0	0·0	0·0
706	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0
736	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0
776	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0
Non-graminoid charcoal fragments								
10	47·6	24·2	11·7	3·1	3·1	0·8	0·0	0·8
40	18·3	22·2	4·8	2·9	1·9	1·9	0·0	0·0
70	21·1	2·3	2·3	0·0	0·0	0·0	0·0	0·0
99	13·5	8·7	4·8	1·9	1·0	0·0	0·0	0·0
109	29·7	12·0	7·1	1·3	1·3	0·0	0·0	0·0
139	29·8	8·9	2·2	0·0	1·5	0·0	0·0	0·0
169	35·0	11·5	2·2	1·1	0·5	0·0	0·5	0·5
187	525·0	820·0	417·0	118·0	26·2	6·6	0·0	3·3
217	145·0	38·3	10·9	8·2	5·5	0·0	0·0	0·0
247	86·1	23·6	10·2	3·1	1·0	0·0	0·0	0·0
277	107·0	60·1	28·4	5·5	1·1	2·2	0·0	0·0
295	290·0	87·5	38·3	10·9	5·5	0·0	0·0	0·0
325	279·0	248·0	54·7	16·4	7·3	7·3	5·5	0·0
355	134·0	51·9	17·1	4·8	1·4	1·4	0·0	0·0
385	1120·0	656·0	164·0	54·7	21·9	10·9	16·4	10·9
408	2870·0	570·0	402·0	82·0	8·2	4·1	0·0	4·1
438	505·0	318·0	187·0	23·0	19·7	9·8	0·0	0·0
468	626·0	757·0	454·0	126·0	19·1	2·7	2·7	2·7
498	661·0	487·0	219·0	11·0	27·3	16·4	5·5	0·0
508	385·0	312·0	107·0	49·2	8·2	8·2	0·0	0·0
538	103·0	5·5	2·4	0·0	0·0	0·0	0·0	0·0
568	256·0	361·0	141·0	19·7	3·3	0·0	0·0	0·0
597	65·6	61·1	79·0	14·9	3·0	1·5	0·0	0·0
607	60·1	92·9	98·4	27·3	5·5	0·0	0·0	0·0
637	65·6	135·0	82·0	102·0	20·5	4·1	0·0	0·0
667	13·1	9·8	3·3	0·0	0·0	0·0	3·3	0·0
696	9·8	1·6	0·0	0·0	0·0	0·0	0·0	0·0
706	0·0	1·5	0·7	0·0	0·0	0·0	0·0	0·0
736	0·0	1·6	0·0	0·0	0·0	0·0	0·0	0·0
766	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0
776	0·0	0·0	0·4	0·0	0·0	0·0	0·0	0·0

Immediately following this level, charcoal values decrease to moderately low levels for the entire Zone 3, extrapolated to the period *c.* 3200–2000 cal-BP. One level near the end of this zone shows an increase in charcoal probably derived from woody sources. This is the only time in the entire core, other than the top sample, representing modern conditions, in which the percentage of graminoid charcoal falls below 50%.

After this anomalous sample, charcoal values fall to low levels and remain so throughout Zone 4, beginning prior to the level dated 1490 ± 80 ^{14}C years bp (1 σ cal range=1504–1307 cal-BP) and continuing up to the present.

Discussion

Fire history at Laguna Tortuguero

The stratigraphic charcoal record for Laguna Tortuguero suggests that fire has not always been a key component in the ecology of the region. Between *c.* 7000–5300 cal-BP, charcoal hardly occurs in these sediments at all. The slower sedimentation rate inferred suggests that productivity or erosion rates were lower than afterwards, and that charcoal influx, relative to the rest of the core, was effectively lower even than the low values indicated by the concentrations shown in Figure 3. It is reasonable to suggest that, during this time period, wildfires were not occurring frequently in the area. The small size of the particles detected in Zone 1, as compared to the rest of the core (Table 2), suggests that long-distance transport, even from another island or the continental mainland, may account for the low background levels detected. Fragments of wood in this portion of the core confirm that woody vegetation was present at the site, but it is clear from preliminary pollen data (unpublished) that grasses and sedges were also present. Perhaps the coastal dunes adjacent to the site were dominated by herbaceous vegetation as some of them are today.

A major event in the Holocene fire history of the island occurred *c.* 5300 cal-BP, as the charcoal signal suddenly becomes quite strong. Values begin to rise *c.* 20 cm below the first high values, but some mixing cannot be ruled out in this part of the core, as no fine-scale horizontal structures are visible in the sediments of this unit. Sediments from the onset of the charcoal increase yield an intercept of 5293 cal-BP (3344 cal-BC). At 95% confidence (2 σ—see Table 1 for 1 σ ranges), this date calibrates to a range of 5459–4989 cal-BP (3510–3040 cal-BC). However, it should be noted that true confidence for this date could be somewhat lower, as the sediment dated is from a depth range of 647–628 cm. Thus sediments of slightly different age were combined in order to obtain enough material for conventional dating. If the sediments have a mixing rate of perhaps *c.* 20 cm as suspected, this would add further to the uncertainty. The σ values for these radiocarbon dates merely reflect counting error in the dating lab, not these other uncertainties. However, unless the sedimentation rate was changing rapidly during the dated interval, or mixing effects upward or downward in the sediments were unequal, the intercept value for the calibration is likely to be unaffected.

This sudden spike in charcoal is a sustained phenomenon; the next four levels yield high values for graminoid charcoal, and also significant amounts of charcoal from other sources, including some pieces recognizable as being derived from wood. The highest values of the entire sequence occur in the interval between *c.* 4000–3500 cal-BP, with a strong signal from both graminoid and non-graminoid sources. It would appear that the site went from essentially no burning to high rates of burning in short order, first primarily in open vegetation, but later increasingly in woody vegetation as well.

The cause of the decline in charcoal concentration after *c.* 3200 cal-BP is not clear. Since it predates by several centuries any detectable change in sediment type, it is not likely to be an artefact of a change in sedimentation rate or character. Indeed, the depth–age relationship in Figure 2 suggests that sedimentation rates have been essentially constant for the last 5000 years. Therefore, charcoal concentrations and charcoal influx in sediments during this time should show precise correspondence. A change in climate at the onset of this charcoal decrease is a possible explanation, as the type of sediment does change a few centuries later as noted above. However, the nature of this sediment change, as well as the regional climate trends inferred in core data from Hispaniola (Binford *et al.*, 1987; Hoddell *et al.*, 1991) suggest the onset of drier conditions in the late Holocene, perhaps beginning *c.* 3200 ^{14}C years bp and intensifying *c.* 2400–1500 ^{14}C years bp. Any such climatic trend seems more likely, other things remaining equal, to result in a pattern of increased burning, rather than the opposite condition observed. The likely outcome of the climate changes would be a longer dry season and the expansion of open grassy areas that would be likely to burn if an ignition source is provided during the right season.

Finally, the even lower charcoal values in the period beginning just prior to the level calibrated at 1 σ to 1504–1307 cal-BP (446–643 cal-AD), and continuing up to the present, suggest that fire occurrence in the latest part of the Holocene up through historic times has been extremely low, although not quite as low as in the pre-5300 cal-BP era. It thus appears that the Laguna Tortuguero vicinity has been characterized by only one period of extremely high fire frequency during the last 7000 years—the period between *c.* 5000–3000 cal-BP. Since no ready explanation for such a clearly-delineated trend, in terms of such relevant climate variables as total rainfall, seasonality, or lightning frequency, arises from regional palaeoclimatic trends, our results prompt the question: what was the role of the indigenous peoples of Puerto Rico in the island's fire history?

Prehistoric fires and human activity in Puerto Rico

Despite renewed interest in dating the earliest peopling of the West Indies (e.g. Kozlowski, 1974; Veloz Maggiolo & Ortega, 1976; Veloz Maggiolo & Vega, 1982; Meggers & Evans, 1983; Rouse, 1989, 1992; Moore, 1991), this important event is not yet well

Table 3. Current earliest ^{14}C age estimates for confirmed archaeological sites in the Greater Antilles

Island	Locality	Uncalibrated ^{14}C age (^{14}C years bp)	Calibrated age range $\pm 1\ \sigma$ (cal-BP)*	Reference
Hispaniola (Haiti)	Vignier III	5580 ± 80	6455–6301	Moore (1991)
Cuba	Levisa	5140 ± 170	6172–5675	Kozlowski (1974)
Puerto Rico	Caño Hondo	3010 ± 70	3344–3086	Rouse (1992)
Jamaica	Bottom Bay	1300 ± 120	1310–1070	Rouse & Allaire (1978)

*Calibrated from 20 year atmospheric curves used in Stuiver & Reimer (1986).
Calibration ranges are 68·3% confidence limits.

constrained. As noted in the Introduction, artefacts provide unequivocal evidence for human *presence*. However, unless the archaeological record for a given area is unusually dense, even good assemblages may be poor indicators of the actual antiquity of human occupation. This problem can be illustrated for Puerto Rico and the rest of the Greater Antilles by reference to current evidence for "earliest" human residency on these islands. Rouse (1989) argues that people—the antecedents of his Casimiroids—probably first began to enter the Greater Antilles around 7000 BP (5000 BC), probably from a Middle American source. Other routings into these islands may also have been used, such as the South America/Lesser Antilles pathway taken at some early date by Ortoiroid peoples (I. Rouse, pers. comm.). This possibility does not affect the argument being made here, however, since we are concerned only with the timing of human arrival, not its direction. Current "earliest" radiometric dates for confirmed archaeological sites certainly support Rouse's basic inference, especially after calibration to the tree-ring record. However, as Table 3 illustrates, "earliest" archaeological dates are not coeval across the Greater Antilles: those for Cuba and Hispaniola are considerably older than those for Puerto Rico and Jamaica. This disparity could be real if, as Rouse (1992: 69) also suggests, the former two islands were occupied much earlier. But at our present level of ignorance we cannot exclude the possibility that the time difference is simply an artefact, due to sampling error, and that available dates do not accurately reflect the time of first occupation. Choosing between these possibilities on the basis of archaeological criteria will probably remain difficult, if only because direct evidence, in the form of material culture, is almost always thinly distributed. The alternative is to search for a source of proxy data that is easily recovered, densely distributed, and apparently free of major ambiguities in the signal it delivers. The results described in the preceding section suggest that charcoal stratigraphy may be such a source, if carefully interpreted.

Our fundamental contention (Burney, 1987*b*) is that, whereas fires certainly occur in highly seasonal environments in the absence of a human ignition source, an increase in charcoal values above background levels often co-occurs with human arrival. For example, both these situations (high pre-human charcoal values and a detectable increase about the time humans are believed to have arrived in the area) are illustrated in a core from Lake Tritrivakely, Madagascar (Burney, 1987*b*: 277). Approximately coeval with the charcoal surge documented from Madagascar, however, are changes in pollen spectra, implying vegetational alteration (Burney, 1987*a,c*, 1993), and evidence of human predation on now-extinct megafauna (MacPhee & Burney, 1991).

In the West Indies, a faunal collapse also occurred (Morgan & Woods, 1986), but at present it is quite unclear whether it was of short duration or protracted over many thousands of years (MacPhee, Ford & MacFarlane, 1989). Palynological investigations are few (e.g. Binford *et al*., 1987; Hodell *et al*., 1991), and it is equally unclear from this evidence when human-induced environmental alteration began. On the other hand, we present here a charcoal stratigraphic history for Puerto Rico that shows a sudden change in state around 5300 cal-BP (3350 cal-BC), at a time when people were already present in the western Greater Antilles. We think that it is plausible to infer that this change in state was due to a new factor in the Puerto Rican environment—anthropogenic burning. This inference implies that people were indeed present on this island in the sixth millennium BP, and this has two interesting implications. One is that the "earliest" archaeological date for this island (Table 2: Caño Hondo, 3344–3086 cal-BP) seems to underestimate the time of the probable first occupation of Puerto Rico by approximately two millennia. The other is that the peopling of Puerto Rico may not have lagged so far behind Cuba and Hispaniola as the strictly archaeological evidence suggests.

Over ensuing centuries, perhaps as a result of increasing human density on the landscape, the frequency or intensity of fire-setting increased, and forest burning became more prevalent. As noted, we cannot explain why fire frequency or intensity apparently decreased after *c*. 3000 cal-BP. A drier climate may have yielded less biomass for burning, or perhaps the human population density or resource exploitation changed, affecting the anthropogenic burning regime. In any case, the phenomenon does not seem to be isolated. In the case of Madagascar, all available charcoal diagrams spanning the period of human arrival and subsequent colonization (Burney, 1987*a,b,c*, 1993) show the same trend: a rapid increase in charcoal at the presumed time of human arrival, with peak values obtained within a few centuries, followed by a more gradual decline over the rest of the record, to more moderate values at present. More detailed interdisciplinary study, and particularly more charcoal data from otherwise parallel situations on other oceanic islands, could help reveal whether this trend, if it has a degree of universality, is primarily a reflection of the landscape changes associated with increasing human density and the consequent changes in human land use, or a more fundamental ecological response, such as biomass reduction or microhabitat changes that might produce a less flammable substrate over time.

Although many questions remain to be answered regarding the general relationship between fire history and island colonization, these preliminary results from Puerto Rico add to the growing body of evidence suggesting that charcoal stratigraphy in lake and bog sediments may provide one of the more useful tools for early detection of human modification of island environments.

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References

Bennett, G. D. & Giusti, E. V. (1972). *Groundwater in the Tortuguero Area*. U.S. Geological Survey, Water Resources Bulletin **10**.

Binford, M. W., Brenner, M., Whitmore, T. J., Higuera-Gundy, A., Deevey, E. S. & Leyden, B. (1987). Ecosystems, paleoecology and human disturbance in subtropical and tropical America. *Quaternary Science Reviews* **6**, 115–198.

Burney, D. A. (1987*a*). Pre-settlement vegetation changes at Lake Tritrivakely, Madagascar. *Palaeoecology of Africa and the Surrounding Islands* **18**, 357–381.

Burney, D. A. (1987*b*). Late Quaternary stratigraphic charcoal records from Madagascar. *Quaternary Research* **28**(2), 274–280.

Burney, D. A. (1987*c*). Late Holocene vegetational change in central Madagascar. *Quaternary Research* **28**(1), 130–143.

Burney, D. A. (1993). Late Holocene environmental changes in arid southwestern Madagascar. *Quaternary Research* **40**, 98–106.

Dewar, R. E. (1984). Recent extinctions in Madagascar: the loss of the subfossil fauna. In (P. S. Martin & R. G. Klein, Eds) *Quaternary Extinctions: A Prehistoric Revolution*. Tucson, AZ: University of Arizona Press, pp. 574–593.

Dewar, R. E. & Wright, H. T. (1993). The culture history of Madagascar. *Journal of World Prehistory* 7(4), 417–466.

Diamond, J. (1984). Historic extinction: a Rosetta Stone for understanding prehistoric exctinctions. In (P. S. Martin & R. G. Klein, Eds) *Quaternary Extinctions: A Prehistoric Revolution*. Tucson, AZ: University of Arizona Press, pp. 824–862.

Faegri, K. & Iversen, J. (1975). *Textbook of Pollen Analysis*. New York: Hafner.

Fusté, L. A. & Márquez, F. (1978). *Limnology of Laguna Tortuguero, Puerto Rico*. U.S. Geological Survey, W.R.D., WRI 77-122.

Held, S. O. (1991). Colonization and extinction on early prehistoric Cyprus. *Studies in Mediterranean Archaeology and Literature*, Pocket-book **117**, 104–164.

Hodell, D. A., Curtis, J. H., Jones, G. A., Higuera-Gundy, A., Brenner, M., Binford, M. W. & Dorsey, K. T. (1991). Reconstruction of Caribbean climate change over the past 10,500 years. *Nature* **352**, 790–793.

Hunt, T. L. & Holsen, R. M. (1991). An early radiocarbon chronology for the Hawaiian Islands: a preliminary analysis. *Asian Perspectives* **30**(1), 147–161.

James, H. F., Stafford, T. W., Jr., Steadman, D. W., Olson, S. L., Martin, P. S., Jull, A. J. T. & McCoy, P. C. (1987). Radiocarbon dates on bones of extinct birds from Hawaii. *Proceedings of the National Academy of Sciences, USA* **84**, 2350–2354.

Kirch, P. V., Flenley, J. R. & Steadman, D. W. (1991). A radiocarbon chronology for human-induced environmental change on Mangaia, southern Cook Islands, Polynesia. *Radiocarbon* **33**(3), 317–328.

Kozlowski, J. K. (1974). *Preceramic Cultures in the Caribbean*. Zeszyty Naukowe, Uniwerstytetu Jagiellonskiego, vol. 386, Prace Archeologiczne, Zezyt 20. Kraków, Poland.

MacPhee, R. D. E. & Burney, D. A. (1991). Dating of modified femora of extinct dwarf *Hippopotamus* from southern Madagascar: implications for constraining human colonization and vertebrate extinction events. *Journal of Archaeological Science* **18**, 695–706.

MacPhee, R. D. E., Ford, D. C. & MacFarlane, D. A. (1989). Pre-Wisconsinan mammals from Jamaica and models of late Quaternary extinction in the Greater Antilles. *Quaternary Research* **31**, 94–106.

Meggers, B. J. & Evans, C. (1983). Lowland South America and the Antilles. In (J. D. Jennings, Ed.) *Ancient South Americans*. San Francisco, CA: Freeman, pp. 287–335.

Moore, C. (1991). Cabaret: lithic workshop sites in Haiti. In (E. N. Ayubi & J. B. Haviser, Eds) Proceedings of the 13th International Congress of Caribbean Archaeology. *Reports of the Archaeological-Anthropological Institute of the Netherlands Antilles* **9**, 92–104.

Morgan, G. S. & Woods, C. A. (1986). Extinction and the zoogeography of West Indian land mammals. *Biological Journal of the Linnean Society of London* **28**, 167–203.

Mosimann, J. E. & Martin, P. S. (1975). Simulating overkill by Paleoindians. *American Scientist* **63**, 304–313.

Olson, S. L. (1989). Extinction on islands: Man as a catastrophe. In (D. Western & M. Pearl, Eds) *Conservation for the Twenty-first Century*. New York: Oxford University Press, pp. 50–53.

Patterson, W. A., Edwards, K. J. & MacGuire, D. J. (1987). Microscopic charcoal as a fossil indicator of fire. *Quaternary Science Reviews* **6**, 3–23.

Rouse, I. (1989). Peopling and repeopling of the West Indies. In (C. A. Woods, Ed.) *Biogeography of the West Indies*. Gainesville, FL: Sandhill Crane Press, pp. 119–136.

Rouse, I. (1992). *The Tainos: Rise and Decline of the People Who Greeted Columbus*. New Haven, CT: Yale University Press.

Rouse, I. & Allaire, L. (1978). The Caribbean. In (C. W. Meighan, Ed.) *Chronologies in New World Archeology*. New York: Academic Press.

Steadman, D. W. (1989). Extinction of birds in eastern Polynesia: a review of the record, and comparisons with other Pacific Island groups. *Journal of Archaeological Science* **16,** 177–205.

Stuiver, M. & Reimer, P. J. (1986). A computer program for radiocarbon age calibration. *Radiocarbon* **28,** 1022–1030.

Veloz Maggiolo, M. & Ortega, E. (1976). The Preceramic of the Dominican Republic: some new finds and their possible relationships. In (L. S. Robinson, Ed.) Proceedings of the 1st Puerto Rican Symposium on Archaeology. *Fund. Arqueol. Antropol. Hist. Puerto Rico, Rep.* **1,** 147–201.

Veloz Maggiolo, M. & Vega, B. (1982). The Antillean Preceramic: a new approximation. *Journal of New World Archaeology* **5**(2), 33–34.