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Age of A2 Horizon Charcoal and Forest Structure near Porto Trombetas, Pará, Brazil[1]

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ABSTRACT

To study the structure and composition of old-growth forest in the Saracá-Taquera National Forest near Porto Trombetas, Brazil, we established 36 0.25 ha plots and described the vegetation. We collected charcoal from the A2 soil horizon of each plot for radiocarbon dating. Although fires have been very rare in this forest during historic times, the presence of charcoal in these soils indicates fire at some earlier period. The ages (conventional radiocarbon age adjusted to 1997) of the charcoal ranged from 177 to 1547 years. These ages, however, did not correlate significantly with any of several measures of biodiversity or stand characteristics. The relative uniformity of the current old-growth forest indicates that either the prehistoric fires were of such low intensity that they had little long-term effect on the vegetation or that the present stands have progressed to near steady state.

Key words: *Amazon; fire; old-growth forest; radiocarbon; slash-and-burn agriculture; succession.*

Scientists have studied the vast high forests of the lower Amazon *terra firme* for many years (Prance *et al.* 1976, Murça Pires 1977, Uhl & Murphy 1981, Prance 1989), and much is yet to be learned. The Amazon high forest often has been referred to as primary. Local history and prehistory is sketchy and because it is difficult to prove that humans have not altered forests at some point in the past, Clark (1996) prefers to call these forests old growth rather than primary. There is ample evidence for a relatively large pre-European human population that subsisted through agriculture supplemented by fishing, hunting, and gathering (Ross 1978, Meggers 1985, Roosevelt *et al.* 1991). Portions of the lower Amazonian forest were certainly cleared for agriculture and reforested naturally afterward.

Although early secondary forests of the Amazon region vary a great deal depending on the nature of past disturbance, the forest type from which they originated, and site conditions, they are widespread and generally familiar to foresters and land managers. Early secondary forests of the Amazon region have been described by Uhl (1980), Heuveldop and Neumann (1983), and Silva (1989), and the authors have measured and studied such stands. Old late-secondary forests have the same general appearance as primary forests (Richards 1955, Budowski 1961, Brown & Lugo 1990) and can only be distinguished from them by a careful comparison of the component species or by referring to historical evidence. Old late-secondary forests have been described in Barro Colorado (Foster & Brokaw 1990), but do not appear to have been studied as such in the Amazon region.

Sedentary or semisedentary, agrarian hunter-gatherers of the Arawak cultural group populated the lower Amazon region until they disappeared 140–260 years ago. The causes of their disappearance are not fully documented, but certainly include new diseases contracted through contact with European colonists, slave raids, genocide, and emigration to more remote areas (Ross 1978, Meggers 1985, Roosevelt *et al.* 1991). The common presence of charcoal in the soil of forests that have not been known to burn in recent history has been noted elsewhere in the region (Sanford *et al.* 1985, Brown & Lugo 1990, Desjardines *et al.* 1996, Turcq *et al.* 1998; Fred Scatena, International Institute of Tropical Forestry, pers. comm.). The origin of the fires that created the charcoal is uncertain, but may have been slash-and-burn agriculture or natural and human-caused fires associated with catastrophic drought and historically drier climate.

We intended to compare stands in the Saracá-

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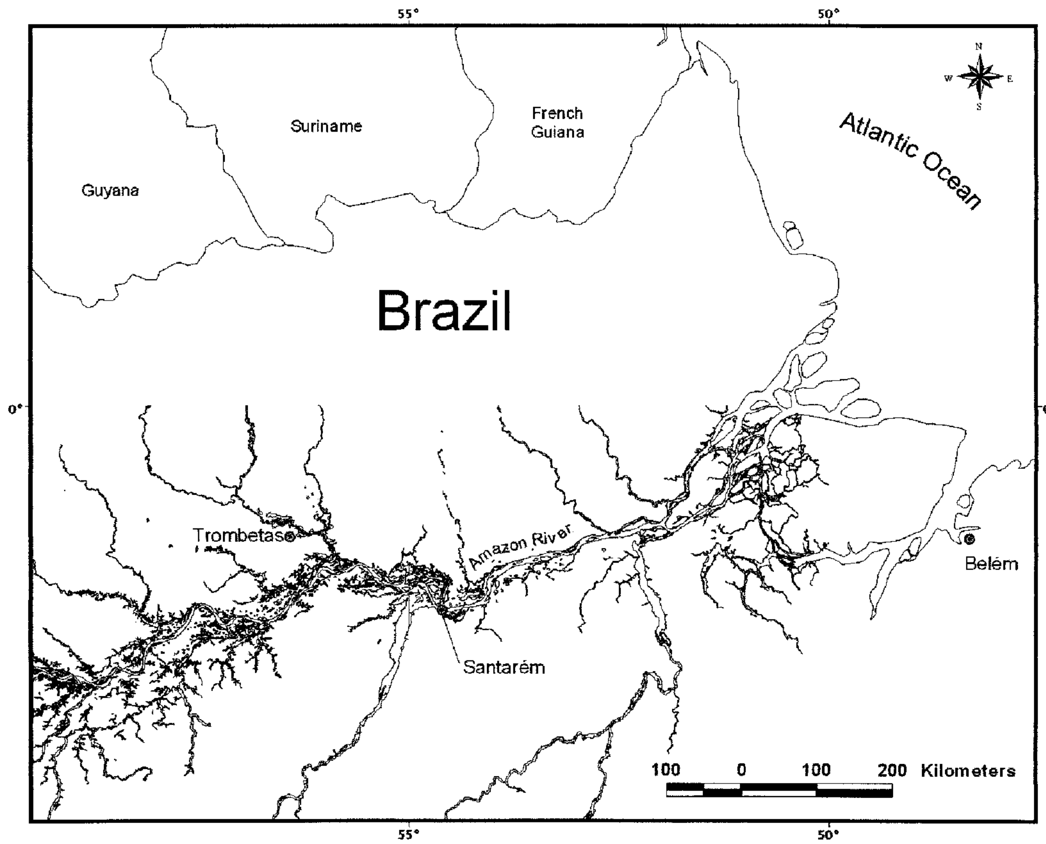

FIGURE 1. Map of the lower Amazon basin showing the location of Trombetas.

Taquera National Forest thought to have been disturbed by prehistoric slash-and-burn agriculture to stands lacking signs of disturbance, to better estimate the period necessary for Amazon forests to return to steady state. Amerindian village sites are common in the Trombetas area (Ferraz 1993, Francis & Knowles, pers. obs.) and peoples of that culture were known to have farmed to provide part or most of their caloric needs (Carneiro 1983). Slash-and-burn agriculture as practiced today, leaves a diffuse band of charcoal in the upper soil horizon, which is gradually buried by insect and animal activity (Piperno 1990). In the beginning, we assumed that soils with charcoal in the upper soil horizons had been farmed and those without charcoal were primary forest. The charcoal was to be collected and aged by C-14 methods to further refine the conclusions drawn; however, we quickly discovered that the entire area contained charcoal. In fact, all 37 sites examined across a 60 × 10 km transect had charcoal. We then began sampling with the intent of correlating vegetation characteristics with C-14 ages obtained from charcoal samples.

METHODS

We established 36 0.25 ha plots along a transect beginning at the Trombetas River near the town of Porto Trombetas, continuing south for *ca* 60 km (see Fig. 1 map for location in Brazil). This is an area of rolling sandy uplands, locally called "flanco," which was left after ancient erosion of the bauxite-bearing plateaus. Alluvial soils in areas near creeks and rivers were not included. Plot centers were located by driving 2–3 km along the Trombetas-Terra Santa highway and side roads and stopping at a location without evidence of disturbance from logging or construction. One side of the highway was chosen at random; we walked into the forest until the outer perimeter of the plot was clear of road-related disturbance and staked a plot center. The plot locations were documented with GPS equipment. Two plots were intentionally established *ca* 150 m distant from known Amerindian village sites. Village sites were identified by the presence of abundant potsherds and a thick band of charcoal-darkened soil buried a few centimeters under the surface. Charcoal was sampled on one plateau site (plateau 1) where no plot was established and no measurements of the forest were taken.

Each plot consisted of two concentric circles with 8.92 and 28.22 m radius that corresponded to areas of 0.025 and 0.25 ha. Slope at plot center was determined with a clinometer. Within the smaller circle, all trees $\geq$8.0 cm in diameter at breast height (DBH) were measured for diameter and height. In the outer circle, only trees $\geq$40 cm were measured. The lower diameter limit was used to avoid a near exponential increase in numbers of small stems to be measured, and the 40 cm limit coincides with a local lower size limit for sawlog trees. All vascular plant species were identified within the inner and outer plots. Because the flora of the area is not well understood or cataloged, many species could not be completely identified. About half of the tree species were identified to genus and species. Most of the rest were recognized and represented by the local common name. About two percent of the tree species were new to the field crew and were assigned a unique number. The vine and herb species were recognized as individual species, but in most cases could only be identified to genus or family. Each species was assigned a number.

Near the plot center, a soil pit was dug. Percent sand in the A2 horizon of soil was estimated by the feel method (Soil Survey Staff 1951). Depth to the top of the band of charcoal was determined by inspection of spade cuts (which show a dark smear when a piece of charcoal is cut) during excavation. The sandy soil was sampled to a depth of 30 cm and sifted to obtain charcoal for C-14 analysis. The charcoal pieces were picked from debris in the sifted residue by hand. Digging and sifting continued until *ca* 25 g of charcoal were obtained. Later, the charcoal was washed with tap water to loosen adhering clay and organic matter, and air-dried. The charcoal samples were sent to Beta Analytic, Inc. of Miami, Florida, where the C-14 ages were determined by the radiometric technique (assumed $^{13}C/^{12}C$ ratio = -25). Conventional radiocarbon ages (based on years before 1950) were adjusted to years before 1997 for statistical analysis.

Three ecological indices were used during evaluation of the data. The Shannon-Wiener index of diversity was calculated for all trees in the inner plots of the 36 plots and for trees $\geq$40 cm DBH over the entire 0.25 ha. Kulezinski indexes (number of species shared by two plots divided by the total number of species found on the two plots) were calculated for tree species in all possible combinations of the 36 measured plots. The Clark index was a quantification of the criteria given by Clark (1996) for distinguishing tropical old-growth stands from secondary stands. Each of seven criteria: (1) stand basal area, (2) distribution of diameters, (3) canopy organization, (4) large lianas and/or epiphytes, (5) large logs and woody debris, (6) very large trees, and (7) number of tree species with large animal-dispersed seeds, was given a rating of 1 to 3. Two of the original criteria (large logs and coarse woody debris) had been combined to form a single criterion. This gave a possible perfect score of 21 for old-growth tropical forests, whereas a young secondary stand would normally receive a score of 7. Pearson's correlation was used to accept or reject the existence of relationships between C-14 age and a number of variables such as numbers of plant species in several life-forms, relative number of plant species, depth to charcoal, percent sand in the A2, basal areas, and the above indices. Because a large number (40) of variables were tested, a probability for error of 1 percent was used for testing. For each tree species with presence in at least 6 and less than 31 of the plots, the C-14 ages of the plots where the species was present were compared with the C-14 ages of the plots where the species was absent by the unpaired *t*-test. The hypothesis tested was that if plots in which a species was present differed significantly in C-14 age from those in which it was absent, colonization or disappearance was in progress. Because nearly 200 species were to be tested, a probability for error of 0.005 was used. The chi-square procedure was used to test whether the number of species (biodiversity) observed within the four life-forms (variables), trees, palms, vines, and herbs, was independent of site (plots). If the probability value for the chi-square value for the 4×36 matrix exceeded 0.01, then the hypothesis of independence was to be accepted.

RESULTS

Carbon 14 ages for 37 sites and summary statistics for the 36 measured stands are given in Table 1. The C-14 ages measured ranged from 177 to 1547 years before 1997. The 37 sites averaged 7.2 km

TABLE 1. *Summary of site and stand attributes on 0.25 ha study plots.*

Plot	Age[a]	Dist.[b]	No. of species			Ba[c]	Height[d]	Clark
			Trees	Vines	Total			
	years	km				m^2/ha	m	
Village 1	1547	0.2	142	50	201	30	37	17
Village 2	497	0.2	154	57	227	13	32	14
Flanco 1	1297	1.1	133	51	200	15	29	19
Flanco 2	1077	2.3	125	63	206	24	36	16
Flanco 3	387	7.1	143	43	197	27	33	18
Flanco 4	607	7.1	148	60	218	25	32	16
Flanco 5	177	2.3	153	78	244	12	32	19
Flanco 6	877	1.9	146	53	210	12	35	16
Flanco 7	487	7.9	148	54	220	16	33	17
Flanco 8	737	1.5	129	33	173	17	33	18
Flanco 9	887	15.8	147	50	207	16	34	19
Flanco 10	917	6.0	150	48	209	18	33	18
Flanco 11	637	4.1	109	28	149	18	31	19
Flanco 12	537	8.3	155	65	231	23	36	18
Flanco 13	627	13.2	148	51	212	9	31	17
Flanco 14	637	15.8	140	47	204	20	31	19
Flanco 15	437	1.1	128	54	193	15	33	17
Flanco 16	927	6.0	153	48	219	14	30	19
Flanco 17	1137	9.4	154	44	209	15	30	17
Flanco 18	1027	9.0	124	41	177	26	34	18
Flanco 19	937	10.9	139	38	187	57	38	17
Flanco 20	427	13.5	125	32	165	20	32	17
Flanco 21	667	12.0	138	41	187	14	34	17
Flanco 22	927	11.6	150	51	210	14	31	16
Flanco 23	467	7.9	120	46	183	9	30	13
Flanco 24	1057	14.3	145	48	201	10	30	17
Flanco 25	877	6.0	168	59	236	30	33	18
Flanco 26	547	7.1	161	58	233	8	32	15
Flanco 27	637	7.1	132	40	185	11	32	16
Flanco 28	1217	8.3	150	43	209	26	31	15
Flanco 29	687	9.4	140	37	187	13	28	16
Flanco 30	697	8.3	150	40	199	8	31	14
Flanco 31	627	6.4	129	43	183	16	32	14
Flanco 32	697	3.8	125	34	169	7	30	11
Flanco 33	887	9.0	126	46	187	15	31	16
Flanco 34	887	8.3	133	43	192	37	35	17
Plateau 1	927	2.6	—	—	—	—	—	—

[a] Basal area per hectare of trees ≥40 cm DBH.
[b] Distance to the nearest known Amerindian village site.
[c] Ages given are before 1997; the 1-sigma confidence interval for uncalibrated conventional radiocarbon ages was usually 50 or 60 years.
[d] Dominant and codominant heights.

distant from the nearest known Amerindian village site, with a maximum distance of 15.8 km. The slopes of the plots were gentle (median = 4°) and the soils were sands and loamy sands. A total of 532 species were noted: 347 trees (and shrubs), 19 palms, 121 vines, and 45 herbs (including ferns and grasses). A species–area curve of tree species nearly ceased to add species to the cumulative list in the last few plots, indicating that the plot numbers were probably adequate. The low frequency of individual species is typical of continental tropical forests; *ca* 18 percent of the tree species were present on a single plot. Particularly notable was the large relative numbers of tree (65%) and vine species (23%) and low relative number of herbs (8%) present in this area. The size of the dominant trees was also striking. In the 9 ha encompassed by the 36 plots, 64 trees of 33 species exceeded 80 cm DBH. The largest of the dominant trees was *Dinizia excelsa* Ducke (maximum DBH = 328 cm). Other large trees with more than one representative were (in their order of frequency): "abiurana ver-

TABLE 2. *Pearson correlation coefficients (r) of C-14 ages and various site and stand characteristics. None of the values were significant at the* P = *0.01.*

Variable	*r*	Variable	*r*
Percent sand A2	−0.1699	No. stems/ha ≥40 cm	0.1562
Percent silt + clay	0.1699	No. stems/ha ≥60 cm	0.1403
Slope	0.0521	No. stems/ha ≥80 cm	0.2319
Depth to charcoal	−0.0205	BA ≥8 cm (S)	0.3089
Tree species LFAD[a]	0.0232	BA ≥40 cm (L)	0.2687
Tree species (L)	−0.0082	Mean D + C height	0.1551
Vine species (L)	−0.1289	Mean BA/tree	0.3481
Palm species (L)	0.3558	Relative tree (plot/area)	−0.0082
Herb species (L)	−0.1388	Relative vine (plot/area)	−0.1289
Total species (L)	−0.0400	Relative palm (plot/area)	0.3558
Relative tree species	0.0194	Relative herb (plot/area)	0.0388
Relative vine species	0.0194	Relative total species	−0.0400
Relative palm species	0.3364	Trees/total species	0.1208
Relative herb species	−0.0290	Shannon tree index (L)	0.2370
Total species (S)	0.1271	Shannon tree index (S)	−0.0199
Species (S)/(L)	0.1575	Clark index	0.1101
Stems (S)	0.0406	CV DBH ≥8 cm	0.0038
Stems ≥40 cm (L)	0.3603	CV DBH ≥40 cm	0.3681
Dist. to village site	0.0650	CV BA ≥8 cm	−0.1611
No. stems/ha ≥8 cm	0.0860	CV BA ≥40 cm	0.3681
No. stems/ha ≥20 cm	0.3336		

(L) = 0.25 ha plot; (S) = 0.025 ha plot.
[a] Large Fruit Animal Dispersed.

melho and abiurana arrepiado," *Pouteria* spp.; "itauba amarela," *Mezilaurus* sp.; *Swartzia polyphylla* A. DC.; "cuiarana," *Buchenavia* sp.; *Aspidosperma oblongum* A. DC.; *Ocotea myriantha* Mez; *Bertholletia excelsa* Humb. & Bonpl.; "fava timborana," Leguminosae-Papilionoideae; *Clarisia racemosa* Ruiz & Pav.; "tachí pitomba," Leguminosae-Caesalpinioideae; *Lueheopsis divicata* Mart.; *Parahancornia amapa* (Hub.) Ducke; "angelim aroeira," *Hymenolobium* sp.; *Minquartia guianensis* Aubl.; and *Trattinnickia rhoifolia* Willd.

The Clark indices are of particular interest because they indicate how near each stand is to the complete manifestation of old-growth characteristics. The stands measured in the 36 plots averaged 16.7 ± 0.3 and ranged in scores between 11 and 19. It should be noted that some of the loss of score from a perfect set of old-growth attributes is due to chance occurrence in this relatively small plot size (lack of very large trees, for example) and some may be attributed to random natural disturbance. No stand in our study supported high numbers of trees with large-fruited, animal-dispersed fruits compared to other Amazon forests known to the authors. This may be a unique feature of the local flora or an indication of slow recovery from widespread disturbance.

Charcoal in these soils ranged in size from dust to pieces 4 cm or more in diameter. The bulk of our samples consisted of pieces from *ca* 3 to 8 mm in diameter. The pieces of charcoal on some of the plots were large enough and in good enough condition to show the cell structure when broken. It should be possible to identify species (or at least families) contributing the charcoal and thus open a valuable window into the composition of predisturbance stands; however, lacking reference samples of the over 400 tree species growing in the area, the task seemed impractical during this study. Charcoal generally occurred in a band *ca* 10–20 cm thick beginning an average of 11.2 ± 0.8 cm deep with a range of 5 to 24 cm deep. The charcoal was presumably deposited on the surface by the fire or fires that formed it and has been buried over time. Burial through cultivation during slash-and-burn agriculture cannot be ruled out. Age of the charcoal did not correlate significantly with depth of burial (Table 2). While some degree of burial is slowly and constantly taking place by atmospheric particulate deposition and disbursed activity of invertebrates, apparently, random small areas of square decimeters to many square meters receive deposits of several centimeters at one time by leaf-cutter ants or mammals. The result is mostly random depth of burial within a relatively narrow band of soil.

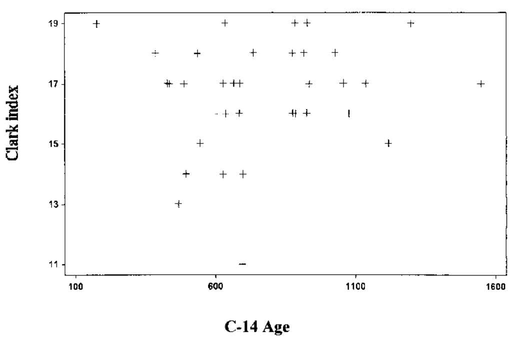

FIGURE 2. Clark indices of forest stands plotted against C-14 ages of charcoal on 36 plots in the Saracá-Taquera National Forest.

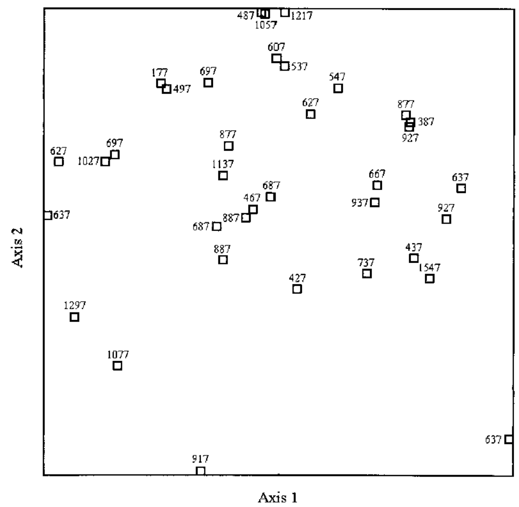

FIGURE 3. Polar ordination of percent similarity (Kulenzinski indices) of tree species in 36 plots; C-14 ages of charcoal in each plot are given for reference.

Pearson's correlation coefficients for the relationship between C-14 age and a number of stand and site characteristics are shown in Table 2. None of the stand or site characteristics were significantly correlated at the 1 percent level with C-14 age. A scatter diagram of Clark indices for the 36 plots and the C-14 ages of the same plots showed no discernible pattern (Fig. 2). The frequency of tree DBHs within the 0.025 ha plots demonstrates an elongated inverted j-shaped curve that is characteristic of old-growth stands. Frequency distributions of diameters in plots with older C-14 ages showed no discernible differences from distributions in plots with younger C-14 ages.

Kulezinski indices for all possible combinations of plot pairs ($N = 630$) ranged in value from 33 to 56 percent, had a relatively low coefficient of variation (CV = 9.4), and conformed to a normal distribution. Differences in C-14 age between plot pairs was not significantly correlated with Kulezinski indices of tree species in plot pairs. A two-axis polar ordination of the plot values revealed some minor clustering of unknown origin, but was apparently unrelated to differences in C-14 age (Fig. 3).

The unpaired t-test was employed to indicate whether C-14 ages of sites where individual tree species were present were different from C-14 ages of sites where they were absent (*i.e.,* whether a species is appearing or disappearing over time.) Of the 197 species tested, just one (*Vatairea sericea* Duke) was significantly associated with C-14 age at the $P = 0.005$ error level. If we specified a one chance in a thousand possibility of random type II error, no species would be significant. A chi-square test indicated that species numbers (biodiversity) within the four life-forms, trees, palms, vines, and herbs, were independent ($P = 0.94$) of site as manifest in the 36 plots measured, or differences in site characteristics (if present) did not affect numbers of species (biodiversity) within the four life-forms. Distance of plots from the nearest of six known village sites was tested for correlation with C-14 age and a number of the previously mentioned measures of biodiversity, with no significant correlations resulting. Real distances to the closest village used, however, may be inaccurate due to the presence of undiscovered village sites in the area.

DISCUSSION

The C-14 ages must be viewed only as approximate. Confidence intervals (based on conventional radiocarbon age), depending on the degree of statistical rigor demanded, range from 50 to as much as 300 years. More than one fire may have occurred in some of the sites, so that the sample is, if true, an average weighted by the amount of charcoal deposited at the point of sampling by each fire. The "old wood" effect conceivably could have skewed the ages by a few decades older than they really are; however, because slash-and-burn and wild fires in the humid tropics seldom burn more than 2 or 3 cm into large logs before the fire goes out naturally, we think that most of the charcoal originated from sapwood and limbs and is compensated for by the standard factor built into the conventional radiocarbon calculation.

Notwithstanding the possible qualifications, the wide range of times (>1000 years) indicated

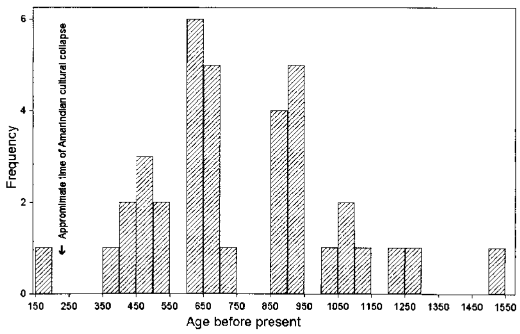

FIGURE 4. Histogram of fire frequencies over time as indicated by C-14 ages in the Saracá-Taquera National Forest, Brazil.

by C-14 dating since fire-caused disturbances appears to be real. Clearly, the C-14 ages do not describe a single catastrophic event, but several periods of disturbance (Fig. 4). Except for one recent event on one site, charcoal-producing fires occurred before the collapse of the aboriginal population. It is curious that no charcoal was dated older than 1550 B.P. We offer three possible explanations: (1) Amerindians were not present in the study area in numbers sufficient to start the fires or create the conditions for fire spread before that time; (2) charcoal nuggets may have disintegrated over time to particles too fine for sampling by the methods used; and (3) C-14 from recent fires may be overwhelming the signature of older charcoal.

Although the disturbance seems to have been local in nature, the coverage over time has been universal, or nearly so. Sanford *et al.* (1985) collected charcoal in several soils on Amazon terra firme forest near San Carlos, Venezuela (*ca* 1000 km to the northwest), and found depths of burial and C-14 ages similar to those we observed. Although the closed Amazon forest will not normally support fire, under rare extremely dry conditions, it can burn, which the many serious fires of 1997 to 1998 in the region clearly demonstrated. Almost all of those fires were human-caused, usually associated with intentional burning. This recent experience indicates that fire potential is particularly high during severe droughts when a mosaic of slashed fields, logged forest, and pasture (with high forest between) are burned off. The process is described in Cochrane *et al.* (1999). These ground fires do cause considerable tree mortality, especially in the smaller size classes (Peres 1999). Although we feel that this is the most likely scenario for prehistoric fires in the Saracá-Taquera National Forest, we have no direct evidence to favor it over the two other polar scenarios: slash-and-burn agriculture that eventually covered nearly every hectare of the area, or periodic natural fires over several centuries that reached near universal coverage.

We could not find fire scars on any veteran tree or large fallen log. While many species in this forest grow relatively rapidly when in dominant and codominant positions (on the order of 1 cm of DBH per year) and may not live beyond 100 to 200 years, at least *D. excelsa,* the widely scattered superdominant of the area, lives much longer. It requires openings larger than ordinary treefall gaps to successfully reproduce. We observed eight *D. excelsa* on the study plots, all greater than 56 cm DBH and no small trees. These old trees in plots that had charcoal from 700 to 1000 years old, could have gotten their start after earlier fire-related disturbance and may be the high forest's last remnants of the early secondary stands.

The "flanco" of the Saracá-Taquera National Forest today is remarkably uniform in species composition and stand structure. We believe that the variation among stands can ultimately be explained by minor site differences and by random patterns of species occurrence. The lack of correlation between C-14 ages of charcoal (or time since disturbance) and the vegetation and stand characteristics indicates that either the ancient fires were of such light intensity that they caused no significant changes in the vegetation or that the events occurred long enough ago that the vegetation has reached a near steady state. The presence of Amerindian village sites every few kilometers suggests that slash-and-burn agriculture was practiced and resulted in direct disturbance to some of the area and probably was the source of many small to medium fires during drier cycles of climate. Such events would have resulted in a mosaic of disturbed areas interspersed with many short-term refugia. Such a pattern of disturbance would allow vegetation to return to relative uniformity more easily than severe fires covering thousands of hectares. The results of this study do not indicate whether stability, refugia, or continuous change currently being debated defined the Quaternary biogeography of the region (Meadows 1999) because vegetation previous to this relatively recent disturbance remains unknown; however, relatively uniform forest cover in the Trombetas area after widespread historical disturbance indicates the great resilience of Amazonian forest cover and makes it more difficult to reject any scenario requiring quick recovery after disturbance or community response to environmental change.

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