The production of charcoal during Agricultural Burning in Central Panama and its deposition in the Sediments of the Gulf of Panama*

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RESUMEN. *Las quemas agrícolas, durante la estación seca en la vertiente Pacífica de Panamá, constituyen un importante fenómeno ecológico. Durante este período, más del 10% de la superficie terrestre sufre los efectos de las quemas dando lugar a la producción de grandes cantidades de carbón. La mayoría permanece en la tierra, pero el 5% es transportada por los ríos y vientos hacia los sedimentos del Golfo de Panamá.*

El transporte de las partículas de carbón por los vientos alisios que soplan del NE fue medido por colectores de deposición seca y de aerosol. Las concentraciones de carbón en el medio rural de Panamá durante la época de las quemas, se aproximan a las de las zonas urbanas de Norte América y Europa. Más del 60% de la masa de carbón en el aerosol aparece en forma de partículas finas (< 2 µm de diámetro) lo cual sugiere que es posible que se transporten a grandes distancias.

Los flujos de deposición seca, correlacionados directamente con la extensión de superficie quemada, son más de una orden de magnitud menor que los flujos de carbón a los sedimentos costeros marinos del Golfo de Panamá. Esto implica que el transporte eólico no es el mecanismo principal de movilización del carbón de las quemas a los sedimentos costeros. Los altos valores de desagüe por unidad de área, en la vertiente del Golfo, sugieren que éste es el mecanismo principal de transporte.

Por otra parte, el carbón puede servir como indicador de las quemas históricas. En 1979 se obtuvieron núcleos de sedimentos del Golfo de Panamá. Para determinar las velocidades de sedimentación en la región, se sometieron los núcleos a análisis de radioplomo

*Manuscrito aprobado en marzo de 1985.

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(Pb-210). Las partículas de carbón fueron aisladas por métodos químicos y se analizaron sus flujos, distribuciones de tamaño y morfologías. La uniformidad de estos índices en los sedimentos marinos durante 200 años de deposición indica que los patrones de las quemas han sido estables por dos siglos.

INTRODUCCION

Agriculture in the tropics in dependen upon fire for slash-and-burn "shifting" cultivation, deforestation stimulated by cattle production, and savanna and grassland maintenance. Agricultural burning in Panama has been described by Guzman (1956), Fuson (1958), and Myers (1981), yet quantitative data have not been reported.

Phytomass burning is an important process in the global carbon cycle and is probably more significant at low latitudes than at middle or high latitudes (Hampicke, 1979; Bramryd, 1979; Seiler and Crutzen, 1980). For example, Seiler and Crutzen (1980) suggest that over 80% of the annual phytomass burn occurs in the "developing countries." This combustion releases important quantities of CO_2 (Adams *et al.*, 1977; Woodwell *et al.*, 1978, 1983), CH_4 (Greenberg *et al.*, 1984), and particulates (Root, 1976) to the atmosphere.

Relatively inert and indestructible charcoal (also referred to as elemental carbon or particulate carbon) is a major component of the particulates released during burning. Lewis and Macias (1980) as well as Weiss and Waggoner (1982) determined that charcoal content for urban and rural aerosols ranges between 10 and 20%. Seiler and Crutzen (1980) suggest that 40% of the mass of atmospheric particulates formed during burning in charcoal.

The importance of tropical burning in the global carbon cycle, combined with this dearth of quantitative information about it, motivated my research on charcoal produced by agricultural burning in central Panama. I report data on present-day charcoal production and discuss transport mechanisms to Gulf of Panama sediments. Data on charcoal isolated from sediment cores in the Gulf of Panama shed additional light on the regional charcoal budget and trace this burning activity back several centuries.

EXTENT OF BURNING

Fires were monitored during the 1981 dry season (january to may) in a study area (50×30 km^2; Fig. 1), located in Coclé Province, central Panama. The quadrant borders the northwestern corner of the Gulf of Panama and extends inland to the continental divide. The terrain and vegetation in the study area are representative of that surrounding the western half of the Gulf of Panama. Most of the region can be classified as Köppen's "Awi" type climate (tropical savanna climate). Higher elevations are in the "Ami" or tropical humid climate zone (Atlas Nacional de Panamá, 1975).

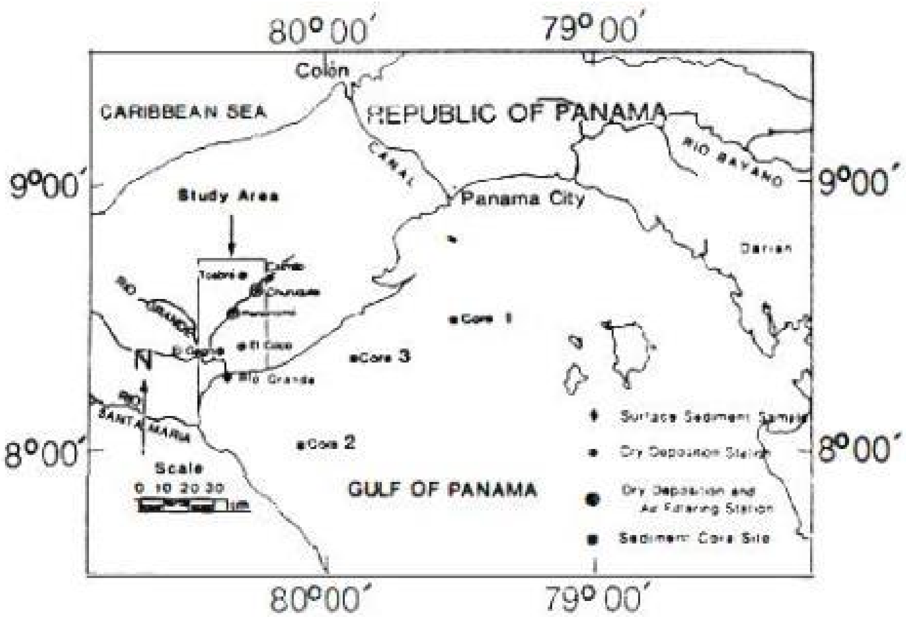

Fig. 1. Map of Panama sediment core locations and atmospheric sampling locations.

Mangrove swamps extend in a band several kilometers wide along the coast. A coastal savanna, usually less than 50 m in elevation, begins where the mangroves end and continues 20 or 30 km farther inland. This coastal plain supports rice and sugar cultivation and extensive cattle raising based on introduced grasses. Occasional wooded areas which may be used for slash-and-burn plots are also found.

Further inland (about 20 to 50 km from the coast) a mountainous zone of rugged hill rises to over 500 m height at the continental divide. Although zones of secondary forest are present and wooded areas are abundant especially on higher elevations, large areas of these hills have been denuded and are covered only with grasses. This is a zone of both slash-and-burn plots and grassland burning (Fig. 2).

The study area covered 689 km² of coastal plain and 456 km² of low hills. The land surfaces burned were mapped through surface reconnaissance (Fig. 3), and a polar planimeter was used to determine the area affected by fire. The 1981 observations indicated that approximately 83 km² (12%) of the lowlands and 48 km² (10,5%) of the mountainous terrain were burned. Thus, 11,5% of this corridor from the central cordillera south to the Gulf of Panama was affected by fire. Grass-covered areas accounted for 84% (110 km²) of the 131 km² of burned vegetation in the quadrant.

A large percentage of the charcoal produced by vegetational burning in the circum-Gulf region must be mobilized to the sediments of the Gulf of Panama by the watershed's extremely high river runoff per unit area (Forsbergh, 1969) and by the

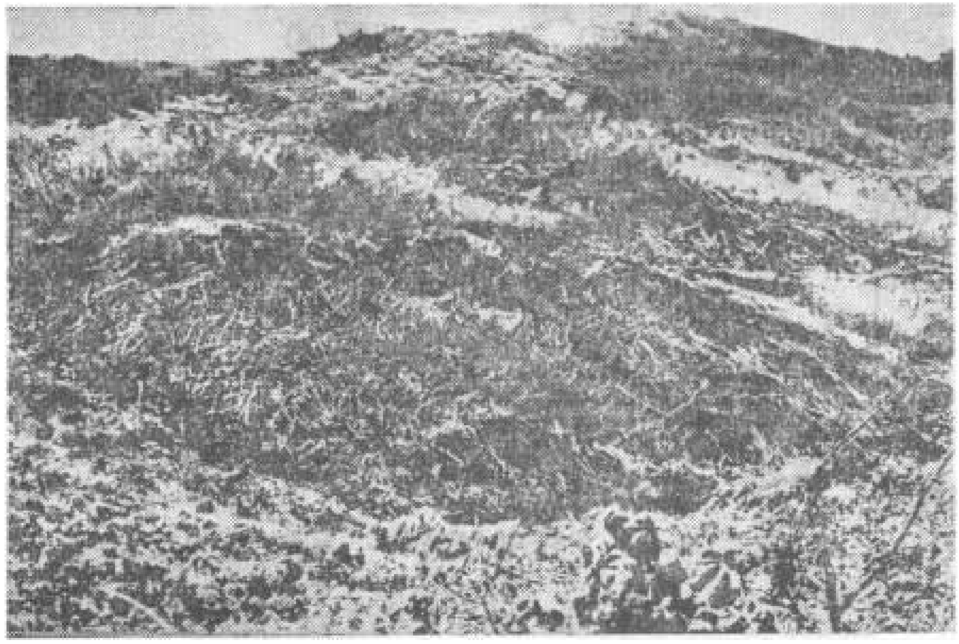

Fig. 2. Two typical slash-and burn plots on a hillside north of Penonomé. The plots have been burned and are ready for planting.

northeasterly Trade Winds which are dominant during Panama's dry season (Northern Hemisphere Winter) Schwerdtfeger, 1976).

DRY DEPOSITION CHARCOAL

To obtain information concerning aeolian transport of charcoal, the charcoal fallout was continuously collected during the 1981 burning season at six stations within the sudy area (Fig. 1). Wet deposition has been ignored since agricultural burning is a dry season phenomenon. Dry deposition collectors, stationed clear of vegetation on 5 m towers, consisted of 61 cm × 61 cm plywood squares which served as bases for smooth glass plates. Square covers (91 cm × 91 cm) supported at 20 cm height by metal rods prevented particles produced in the inmediate vicinity from falling on the plates. The plates were coated with petroleum vaseline applied in a chloroform slurry to trap deposited particles. Vaseline was scraped from the plates weekly and stored in small vials. Samples were degreased with trichloroethylene and were treated with HCl and HF to remove carbonates and silicates, respectively, and KOH/H_2O_2 to solubilize organic carbon (Griffin and Goldberg, 1975). The percentage charcoal in the residue (generally ranging between 60 and 100%) was determined by weight loss after ignition at 600° C for 1 hour (Malissa, 1979) and by infrared spectrometry (Smith and Griffin, 1975).

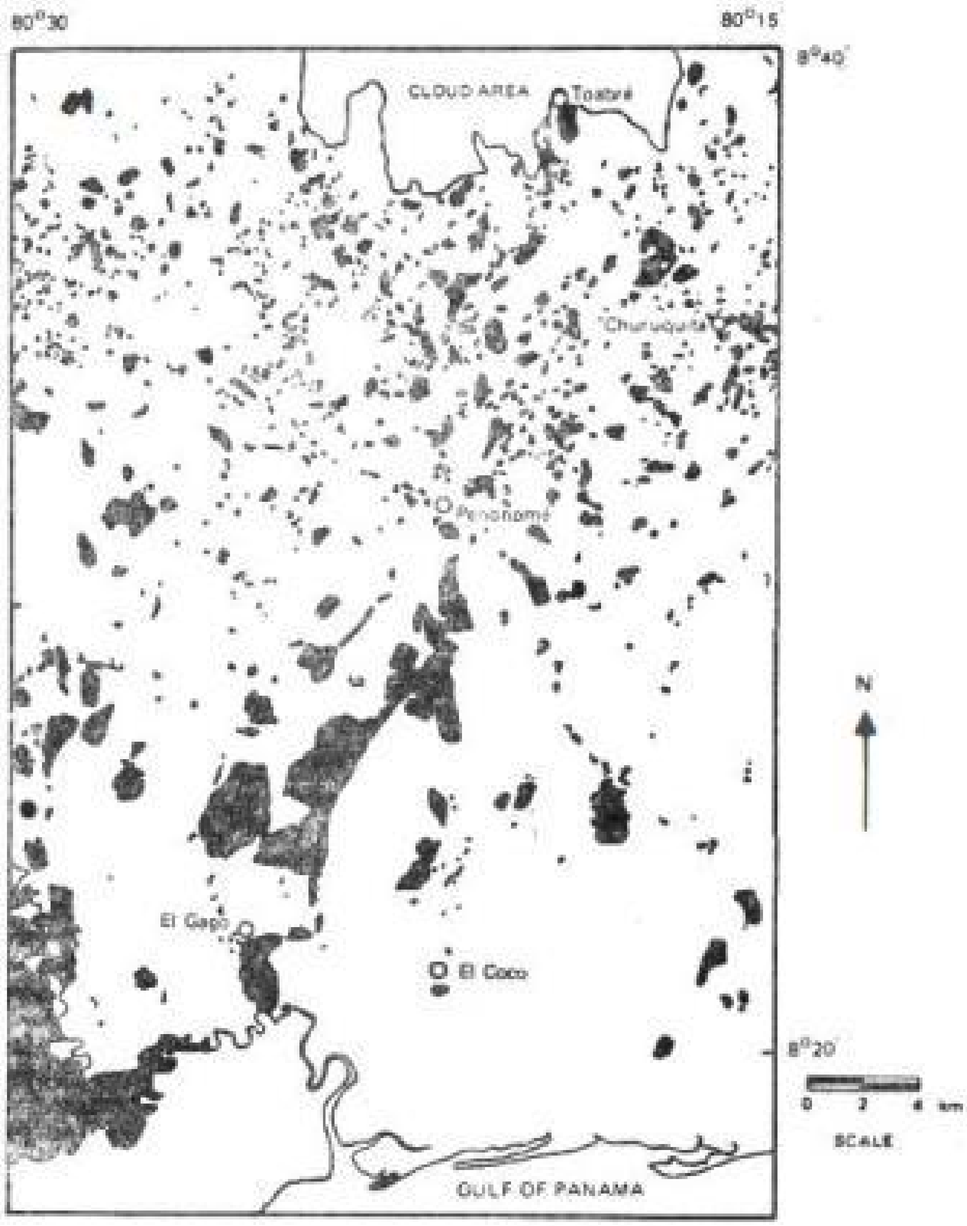

Fig. 3. Fires in the study area, 1981. The blackened areas indicate vegetational burning.

The charcoal fluxes at all the six stations were highest between the last week in March and the second week in April. This maximum charcoal deposition correlates well with the end of the dry season which is marked by the greatest areal extent of burning as indicated in the burning survey (Suman, 1983). The dry deposition charcoal fluxes range from 1,1 μgC/cm².yr for the northern station in Toabré to 5,6 μgC/cm².yr for the southernmost station at El Coco.

Size distribution analyses of the charcoal fallout particles collected on the deposition plates were performed using a point counting technique (Allen, 1974; Orr and Keng, 1976; Suman, 1983). These analyses classified charcoal particles into 16 size classes from 0,05 to 38 μm. The number and mass frequencies were determined as a function of each particle's Martin diameter (length of a line parallel to the fixed direction of scan that divides the particle into two equal areas).

Analysis of particles with diameters between 2 and 38 μp was performed with the optical microscope, while the scanning electron microscope (H-500 Hitachi Electron Microscope) was utilized for particles less than 2 μm diameter.

The data obtained by analyzing particle fields of varying magnifications were correlated by accounting for differences in the area of the fields that were counted. The analysis of each sample involved sizing more than 1 500 particles with diameters less than 2 μm and over 600 particles between 2 and 38 μm diameter.

Mass frequencies of particles were extrapolated from the number frequencies in each size category assuming the particles were spherical with density 1,8 g/cm³. In this extrapolation the number frequencies were multiplied by the mass of an average particle in each size class.

An additional method of particle size determination involved settling tubes and was based on Stokes' law of settling velocities and its underlying assumptions (Krumbein and Pettijohn, 1938). The adaptation of this technique to charcoal particles was reported by Griffin and Goldberg (1983). Size fractions of charcoal separated in this process were < 2 μm, 2-8 μm, 8-16 μm, and 16-38 μm. Greater than 38 μm particles were previously separated by sieving.

Most of the charcoal particle mass in the dry deposition samples is concentrated in the coarse (> 2 μm) fraction (Fig. 4). Similar results were obtained after analysis of 10 dry deposition samples using both techniques. The large settling velocities of these coarse particles preferentially remove them from the atmosphere.

A morphological classification scheme for > 38 μm charcoal particles has been developed using standard combustion materials (Suman, 1983). It has been possible to identify particles on the basis of their wood, grass, or petroleum origins. A useful concept to study the grass and wood contributions to the charcoal particles is the "Gramineae Index." This is the percentage of particles of grass origin in the total number of particles classified with confidence as grass and wood. In over 20 ana-

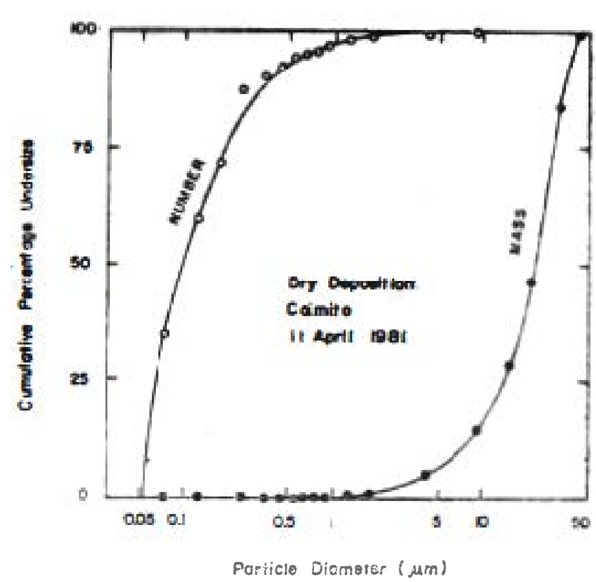

Fig. 4. Size distribution determined by point counting of dry fallout charcoal particles. The curves were fitted by eye. These results are similar to those of 10 other sites.

lyzed samples isolated from sediments, aerosols, and fallout, I have been able to assign over 65% of the > 38 μm charcol particles to grass or wood morphological categories.

The morphologies of the > 38 μm charcoal particles collected as dry deposition were observed with optical and electron microscopy. Grass epidermal fragments similar to those shown in Fig. 5 were abundant in these samples. Gramineae Indices of the three analyzed samples, Caimito (5-11 April), Penonomé (14-21 March), and El Gago (7-14 April) were, respectively, 90%, 86%, and 92%.

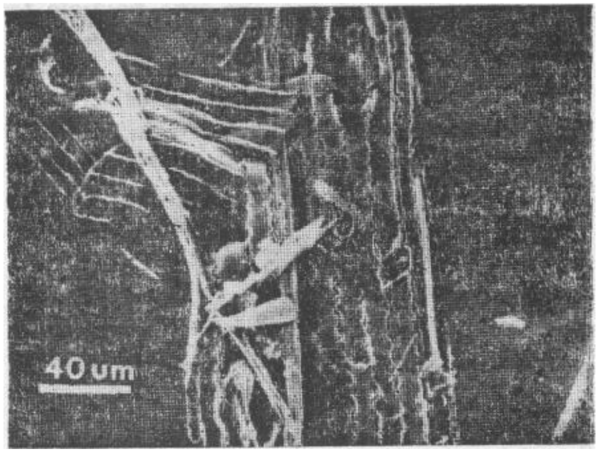

Fig. 5. Electron micrograph of dry deposition charcoal particles from Caimito (11 April 1981). The above particles are all gramineous epidermal fragments.

AEROSOL CHARCOAL

During the 1981 agricultural burning season, samples of atmospheric particulates were collected at Penonomé and Churuquita (Fig. 1) from March 25 to April 16. These locations are upwind from the Gulf of Panama and about 25 km from the coast. High-volume air pumps (Model 500, Unico Environmental Instruments) were positioned at 8 m heights on towers and were fitted with glass fiber filters (Gelman Spectro Grade Type A with 99,9% DOP efficiency for 0,3 μm particles). Samples were collected during periods ranging from 49 to 77 hours with an average air flow of 305 liters per minute. Standard sampling specifications suggested by Jutze and Foster (1967) were followed.

The digestion technique for the aerosol particulate samples involved an initial treatment with concentrated HF to dissolve the glass fiber filters and dust of aerosol origin, followed by the digestion technique which was previously mentioned. The percentage charcoal in the final residues was determined by weight loss after ignition at 600°C. for 1 hour.

The range of aerosol charcoal concentrations extends from 0,4 to 3,1 $\mu gC/m^3$. The highest charcoal concentrations were measured at Penonomé on March 25 and

April 2 and correspond to the high charcoal dry fallout in the collection periods ending on March 28 and April 6 as well as to the most intense burning period marking the close of the dry season.

Size analyses of the aerosol charcoal particles performed by particle point counting indicate that essentially all of the particles were less than 2 microns in diameter and that this fine fraction accounted for over 60% of the aerosol charcoal mass. Fig. 6 summarizes the size analysis from the Penonomé (2 April 81) aerosol sample which is typical of all of the aerosol samples. The settling technique for the six samples suggested that between 70 and 100% of the charcoal mass is concentrated in the fine particle fraction.

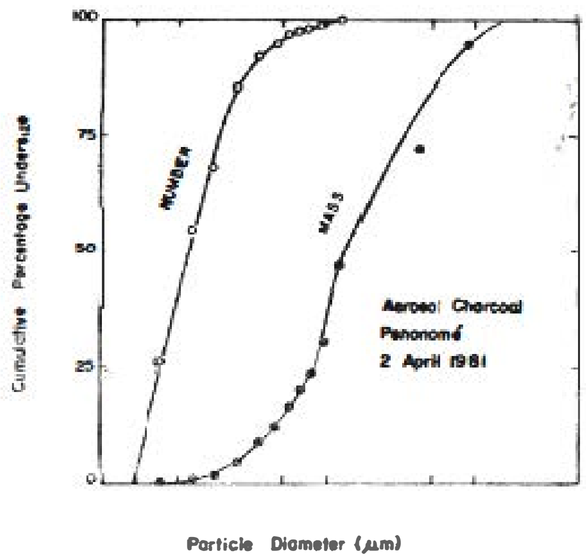

Fig. 6. Size distribution determined by point counting of aerosol charcoal particles.

SEDIMENTARY CHARCOAL

In July 1979 three box cores of sediments from the western half of the Gulf of Panama were recovered (Fig. 1). Time frames were introduced into the marine sediment cores through Pb-210 geochronologies. The analytical techniques of Pb-210 isolation from sediments and measurement of its activities were those of Koide *et al.* (1973) and Koide and Bruland (1975). Maximum sedimentation rates calculated for these sites range from 0,17 to 0,51 cm/yr. Fig. 7 illustrates the Pb-210 activities for Core 1.

The sediment samples were chemically digested to isolate the charcoal residue (Griffin and Goldberg, 1975) and charcoal concentrations in the residue were determined by an infrared spectrometric technique (Smith and Griffin, 1975). The charcoal concentrations in the sediment samples

TABLE 1. *Charcoal Fluxes to Gulf of Panama Sediments.*

Core Number and Depth	Sedimentation Rate	Deposition Period	Charcoal Flux
CORE 1	0,22		
1-3		1965-1974	127
5-7		1947-1956	129
9-11		1929-1938	139
13-15		1911-1920	100
17-19		1893-1902	87
19-21		1884-1893	106
21-25		1865-1884	108
25-29		1847-1865	99
33-37		1811-1829	106
37-41		1793-1811	94
CORE 2	0,17		
0-1		1973-1979	165
1-3		1961-1973	126
5-7		1938-1950	114
7-9		1926-1938	133
9-11		1914-1926	84
11-13		1903-1914	94
13-15		1891-1903	132
15-17		1879-1891	108
17-19		1867-1879	110
19-21		1867	116
21-25		1867	126
25-29		1867	160
29-33		1843-1867	92
33-37		1820-1843	139
37-41		1796-1820	122
41-45		1773-1796	125
45-47		1761-1773	147
CORE 3	0,51		
1-3		1976-1978	353
3-5		1973-1976	291
7-9		1969-1971	318
11-13		1965-1967	256
15-17		1960-1962	302
17-19		1958-1960	469
21-25		1951-1956	443
25-29		1947-1951	390
29-33		1942-1947	407
33-37		1938-1942	259
37-39		1936-1938	410
(cm)	(cm/yr)		(μgC/cm².yr)

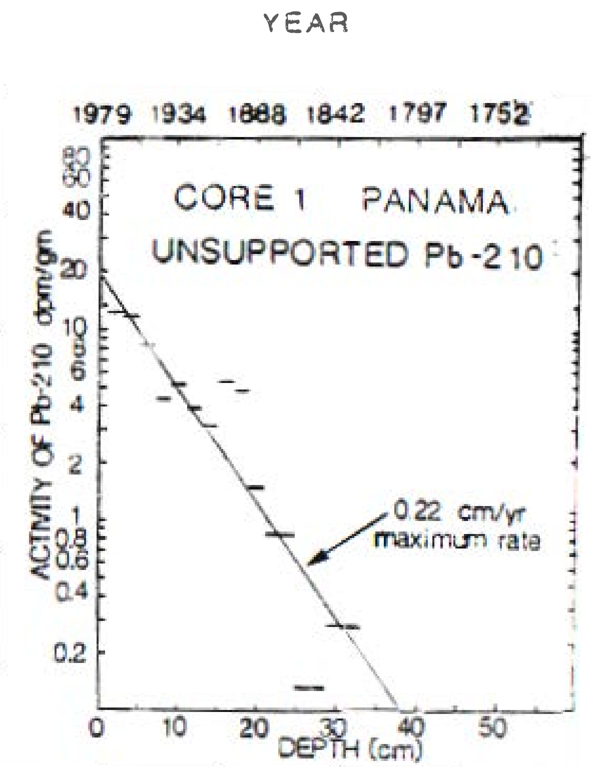

Fig. 7. Pb-210 activity as a function of depth in Core 1.

ranged between 200 and 1000 ppm dry sediment.

The charcoal fluxes to the sediments have been calculated as the product of Pb-210 sedimentation rates, measured sediment densities, and charcoal concentrations. The three Gulf of Panama sediment cores do not show clear trends in charcoal fluxes during the past centuries (Table 1). The fluxes range from 84-469 μgC/cm^2.yr.

Size distributions were obtained for sedimentary charcoal particles by settling analyses. In all of the 59 samples analyzed the < μm diameter charcoal fractions carry 50% of the charcoal mass while the < 8 μm diameter fractions account for 85% of the charcoal mass. Five sediment sections were processed for size distribution by the point counting method. An average of 65% of the charcoal mass is associated with the fine particle fraction (Fig. 8).

The morphologies of the > 38 μm charcoal fractions from the sediments were extensively studied with optical and scanning electron microscopy. In spite of the combustion, transport, and sedimentation pro-

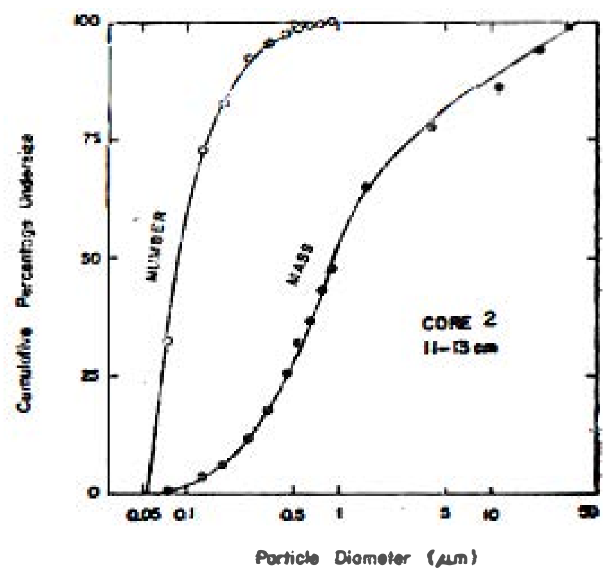

Fig. 8. Size distribution determined by point counting of sedimentary charcoal particles. Results are similar to those of 4 other analized samples.

cesses, the large charcoal particles produced by phytomass burning retain characteristics of their original plant structure (Fig. 9).

The morphological classification scheme was applied to the charcoal particle isolated from Core 1. "Gramineae Indices" for this core are consistently high (between 74% and 90%) indicating that grass charcoal particles are much more abundant than wood charcoal particles in the sediments of this area of the Gulf of Panama. Additionally, plant charcoal morphologies vary little during the 200-year depositional period.

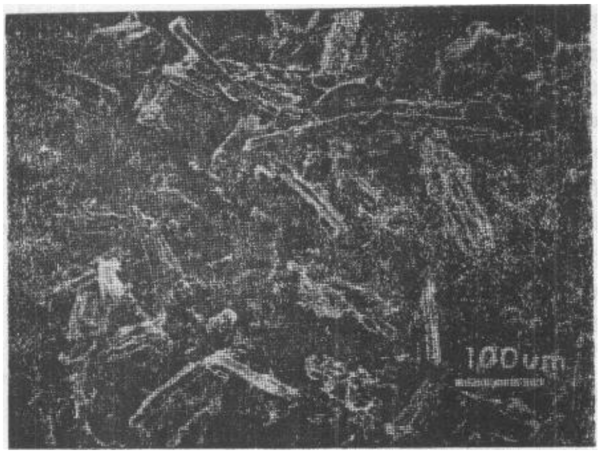

Fig. 9. Electron micrograph of a field of charcoal particles from Core 1 (17-19 cm). Note the abundant plant fragments.

DISCUSION

Charcoal fluxes to the sediments of the Gulf of Panama are an order of magnitude higher than those reported for nearshore sediments from the Saanich Inlet and the Santa Barbara Basin (Griffin and Goldberg, 1975). This may be due to the exceptionally high runoff in the Gulf of Panama watershed (Forsbergh, 1969) and to the widespread occurrence of agricultural burning which produces the charcoal. The burning survey in the Coclé study area indicates that over 10% of the land surface was affected by fire in a single burning season. As a comparison, Minnich (1983) suggests that only 7,6% of the land in the southern California coastal zone (adjacent to the Santa Barbara Basin) was burned in the eight year period from 1972 to 1980.

The charcoal concentrations measured in the central Panama aerosol also reflect the widespread use of fire. The highest Penonomé values, during the burning maxima, are similar to aerosol charcoal concentrations in urban areas of the United States (Rosen *et al.*, 1982). Charcoal concentrations in the aerosol during off-peak burning in rural Panama are similar to "remote" values and several times greater than Arctic observations (Wolff *et al.*, 1982).

Evaluation of wind vs river transport mechanisms

Particulate charcoal is carried from its origin on the Isthmus to the coastal marine sediments by river and air transport and coastal runoff. Charcoal particle size distribution, fluxes, and morphologies can be used to estimate the relative importance of each transport mechanism.

Dry deposition charcoal fluxes were measured in the study area about 10 km upwind (north) of the Gulf of Panama core sites. The largest dry deposition charcoal flux to the southernmost Isthmian station was 5,6 $\mu gC/cm^2.yr$. The charcoal fallout to the surface waters of the Gulf of Panama as the air mass moves seaward is, in fact, probably less than this value due to the transport distance from the burning sources. However, *even this upper limit dry fallout flux is more than an order of magnitude less than the average charcoal fluxes to the top sections of the three sediment cores, 215 µgC/cm².yr.*

An additional dry fallout flux was calculated from the size analysis of aerosol charcoal in Penonomé. The aerosol charcoal concentration at that station (2 April 1981) was determined to be 2,4 µgC/m³, and the mass percentages per size class were deduced by particle point counting. The product of the Stokes' settling velocity (v_d) and the atmospheric charcoal concentration per size clas (C_d) equals the dry deposition flux (F_d). Summation of the 16 size class fluxes gives a value of 16 µgC/cm².yr. Both dry charcoal fluxes suggest that the majority of c arcoal must be carried from its origin to the Gulf sediments through continental runoff rather than by atmospheric transport.

Similar evidence is provided by size analyses of sedimentary charcoal particles whose size distributions were determined for 16 size classes from 0,05 to 38 µm. Point counting methods for five samples of sedimentary charcoal indicate that approximately 65% of the charcoal mass is associated with fine (< 2 µm) particles. The log of the c arcoal flux was plotted as a function of the median particle diameter of each size class (Fig. 10). All analyzed samples of sedimentary charcoal showed fluxes which varied only by an order of magnitude a a function of particle diameter. On the other hand, the charcoal fluxes to the Penonomé dry deposition station manifest a four rder of magnitude decrease with decreasing particle size. The large fluxes of fine charcoal particles to the sediments cannot be accounted for solely by dry deposition; continental runoff must be the important transport mechanism.

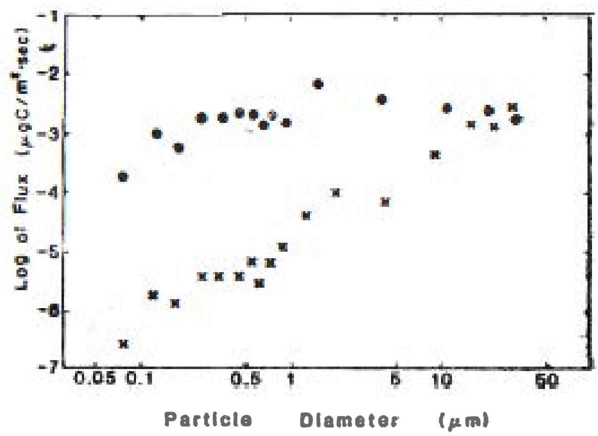

Fig. 10. The log of the charcoal particle flux to the sediments of Core 2, 11-13 cm, (●), and of the charcoal particle flux to the Penonomé dry deposition station, 6-13 April 1981, (X), plotted as a function of medium particle diameter of each size class.

The particle morphologies provide additional evidence for transport mechanisms. The charcoal particles in the upper sections of Core 1 give Gramineae Indices of 75%. Well-preserved gramineous epidermal particles like those in Fig. 5 accounted for only about 9% and 14% of the total particles. The charcoal from the sediments at the mouth of the Río Grande, the major river flowing through the study area, exhibited morphological similarities to particles found in the marine sediments. The Gramineae Index of the Río Grande charcoal was 72% and gramineous epidermal particles accounted for 11% of all particles.

The three dry deposition charcoal samples studied (Penonomé, 21 March; Caimito, 11 April; El Gago, 14 April) contained a large grass contribution. Well-preserved, gramineous, epidermal particles contributed 39%, 42%, and 41%, respectively, of all particles. Likewise, the respective Gramineae Indices of 86%, 90%, and 92% were relatively high.

The morphological similarity between the charcoal particles at the mouth of a major river in the study area (Río Grande) and those in the surface marine sediments and their distinctly different character from atmospheric fallout is additional evidence favoring rivers over winds as the principal charcoal transport path to the Gulf sediments.

The case for the secondary importance of atmospheric charcoal deposition to nearshore sediments in regions of high continental discharge is further substantiated by other investigators. In a study of Orinoco Delta and shelf sediments, Muller (1959) concluded that airborne transport of pollen was of minor importance compared to waterborne pollen transport. Prospero (1981) calculated that aeolian mineral fluxes to the world ocean were small in comparison to the suspended load carried by rivers. This should especially be the case in areas of high river discharge (such as the Gulf of Panama) where a large portion of the suspended load is deposited in shelf sediments.

Elemental carbon budget

The different charcoal concentrations and fluxes which have been measured can be used to model the circum-Gulf of Panama geographic region. Since relatively little burning occurs around the eastern half of the Gulf (Darién) and since no charcoal data are available from that región, only the land surrounding the western half of the Gulf will be considered. Additionally, since most burning occurs during the dry season, wet deposition has been ignored. Even with limited data, such a model is useful in understanting the fate of charcoal in this region.

In order to estimate charcoal mass produced by agricultural burning, data from the areal survey in Coclé Province, which is assumed to be representative of the western circum-Gulf land, are extrapolated. Twelve percent of that land was burned of which 84% was grassland savanna and 16% tropical woodland. The Gulf of Panama watershed from Punta Mala in the southwest to the head of the Gulf around the Río Bayamo contains 12 000 km^2 of land (Atlas Nacional de Panamá, 1975). Extrapolations indicate that 1 400 km^2 (1 180 km^2 of savanna and 220 km^2 of woodlands) are burned annually. The following equation (Seiler and Crutzen, 1980) determines the biomass (M) burned

$$M = A B \alpha \beta$$

where A is the land area burned annually, B is the biomass per unit area, α is the fraction of above-ground biomass, and β is the above-ground biomass burning efficiency. Values of biomass per unit area used in these calculations were 4 kg/m^2 for savannas and 15 kg/m^2 for woodlands which are within the ranges suggested by Seiler and Crutzen (1980), Whittaker (1975), and Ajtay, Ketner, and Duvigneaud (1979). In this region 2,5 $\times$ 10^{12} g savanna biomass and 6,7 $\times$ 10^{11} g woodland biomass are estimated as the annual burn. It can be reasonably assumed that 20% of this burned mass is charcoal (Seiler and Crutzen, 1980; Hopkins, 1965). Therefore, 6,3 $\times$ 10^{11} g/yr of charcoal may be produced on lands surrounding the western half of the Gulf.

The charcoal flux to the sediments of the western side of the Gulf of Panama can be extrapolated from the approximate area (15 000 km^2) and the average charcoal flux to the top 10 cm of the three cores (196 $\times$ 10^{-6} gC/cm^2.yr). Clearly, this value of 3 $\times$

10^{10} gC/yr is an upper limit since the core sites have a nearshore bias. The result indicates that a maximum of 5% of the charcoal produced on land has a sink in these sediments. Alternatively, 1% of the above-ground burned biomass, estimated using Seiler and Crutzen (1980) guidelines, may be deposited as charcoal in the Gulf sediments.

The biomass burned on the western circum-Gulf lands (3,2 $\times$ 10^{12} g) can be used to calculate the atmospheric loading of charcoal. Turco *et al.* (1982) describe the charcoal (elemental carbon) emission factor as the fraction weight of material burned which is emitted as atmospheric charcoal particles and suggest a value of 5 $\times$ 10^{-4} for agricultural and forest fires. Seiler and Crutzen (1980) suggest a charcoal emission factor of 4 $\times$ 10^{-3} for savanna burning. Using these factors, 1,6 — 13 $\times$ 10^9 g charcoal annually pass into the Isthmian atmosphere. An atmospheric box model which assumes a 1 km mixed layer, a 150 km wide zone over the western half of the Gulf of Panama and adjacent land, and 14 km/hr wind velocities toward the Pacific Ocean over the Gulf, indicates that a volume of 4,5 $\times$ 10^6 km^3 air passes over this zone in the three month burning period. The theoretical charcoal atmospheric loading of 0,4-2,9 μgC/m^3 agrees well with the measured Penonomé and Churuquita concentrations which range from 0,4-3,1 μgC/m^3.

A simplified sketch (Fig. 11) of the charcoal budget in the western half of the Gulf of Panama and its drainage area indicates the known charcoal concentrations and estimated fluxes. The average dry deposition flux (3 $\times$ 10^{-3} mgC/cm^2.yr) was multiplied by the land area (12 000 km^2) to obtain a regional dry deposition flux of 3,6 $\times$ 10^8 gC/yr. From the size analyses, I compute that 97% of the charcoal flux to sediments

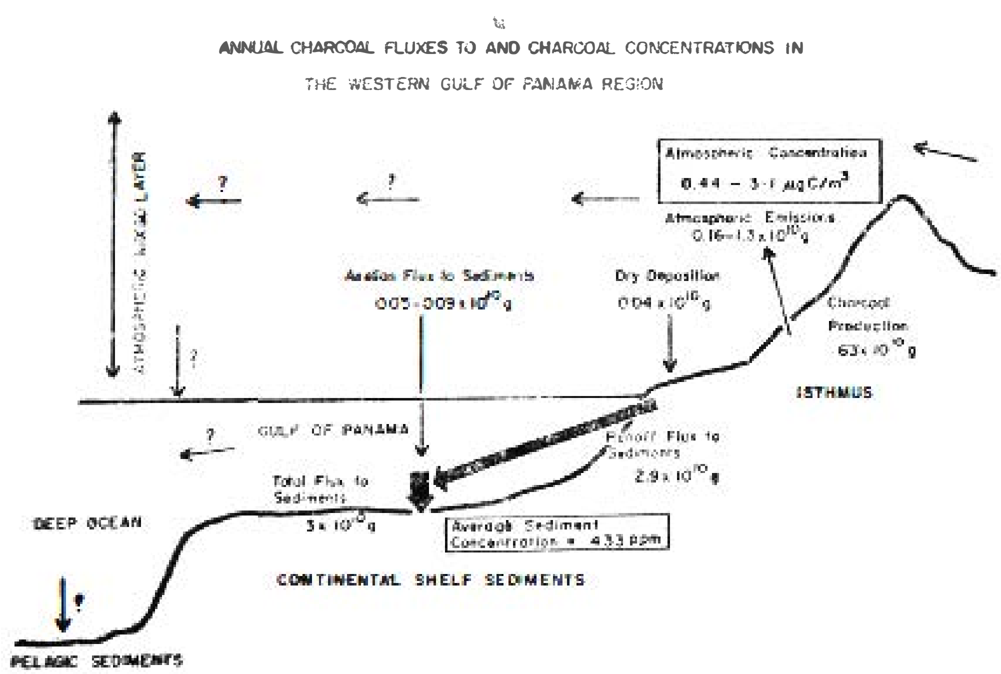

Fig. 11. Charcoal budget in the western Gulf of Panama region.

is transported to the Gulf by runoff, while 3% is wind-transported. Dry deposition flux estimates to the Gulf surface range from 4,5 to 8,8 $\times$ 10^8 gC/yr. The former value extrapolates the estimated fallout fluxes to the Gulf surface while the latter is simply 3% of the charcoal flux to the sediments. Data are lacking on the atmospheric charcoal concentrations over the Gulf and further offshore, wet deposition fluxes, charcoal concentrations in the water, and charcoal fluxes to nearby pelagic areas such as the Panama Basin. Nevertheless, these initial results are internally consistent and suggest that nearshore sediments may be sinks of secondary importance for charcoal in areas of heavy biomass burning. Most of the charcoal appears to accumulate on land. Soil contents of charcoal, when determined, could assess this argument.

Historical record

Bennett (1968) and Sauer (1969) cite accounts by early Spanish explorers (Espinosa and Andagoya) describing central Panama as savanna without forest. This region appears to have remained largely grass-covered during the centuries following the Conquest, in spite of major decreases in the rural populations of central Panama, followed by a gradual increase toward the 19th Century. Wafer's map of the Isthmus (1704) shows savanna from the Río Chepo (Bayano) located 45 km east of Panama City westward past Natá at the western end of the Gulf of Panama.

Jaén Suárez (1979) documents the introduction of cattle to the area by the Spanish and the spread of cattle raising on the Isthmus savanna. Fire was a tactic used to maintain the grass cover of the savannas in central Panama.

Data on sedimentary charcoal fluxes, size distributions, and morphologies elucidate burning and, therefore, the agricultural history of adjacent land during the last two centuries. Sedimentary charcoal fluxes to the Gulf of Panama vary less than a factor of two during the past 200 years. Although bioturbation, runoff remobilization of soil charcoal, and variations in river discharge all tend to smear the sedimentary record, fair consistency of the charcoal fluxes implies that there has been no important change in burning practices on the adjacent land during this time frame in spite of the population increases. These results contrast with those reported by Griffin and Goldberg (1981) for an industrial region adjacent to Lake Michigan (USA) in which they note a significant increase in charcoal fluxes to the lacustrine sediments beginning with the onset of industrialization around 1910 with its increased burning of fossil fuels.

Griffin and Goldberg (1983) have reported a case of a charcoal particle size distribution which changed notably in the sediment core. Before 1910 the > 38 µm charcoal fraction accounted for less than 5% of the total charcoal mass. These large charcoal particles probably resulted from the long-distance transport of charcoal particles produced by wood burning. After this date, more than 25% of the charcoal mass is associated with the coarse > 38 µm particle fraction. Particle fallout from nearby sources of fossil fuel burning account for the increased coarse particle flux.

No such change in charcoal particle size distribution was noted in the Panama cores. Throughout the time frames of these cores, over 85% of the charcoal mass is associated with particles < 8 µm in diameter. The consistent good sorting indicates that charcoal inputs and transport mechanisms have been stable during the last two centuries in Panama. Size distributions skewed toward small particles indicate long-range transport from the particle source.

The morphologies of the coarse charcoal particles provide additional evidence regarding the stability of burning regimes in central Panama. During the period investigated, a discernible shift in plant particle morphology was not observed. Carbonized grass particles are more abundant than wood charcoal particles throughout the cores. Thus, the coastal savanna regime surrounding the western half of the Gulf has probably been stable for at least the past two centuries and been regularly burned during that period.

CONCLUSIONS

Based on extrapolations of agricultural burning and charcoal transport from a study area in central Panama and on charcoal abundances in the Gulf of Panama sediments, a charcoal budget for the watershed of the western half of the Gulf of Panama was derived. The majority of the charcoal produced remains on land, while 5% has a sink in Gulf of Panama sediments. Charcoal particle size distributions and flux data indicate that atmospheric transport of charcoal from continental production sites to deposition in nearshore sediments is of secondary importance. The large river discharge in the area during the 8-month annual rainy season seems to be the major transport mechanism of charcoal particles.

Agricultural burning practices of the past can be inferred through studies of charcoal particles deposited in sediment cores recovered from the Gulf of Panama. During the past 200 years of sedimentary deposition, charcoal fluxes have remained fairly constant as have particle morphologies and size distributions. This implies that, during this period, the watershed has supported grass and savannas which have been consistently burned. No record of massive deforestation and increased charcoal production appears in sediment strata from recent decades. This watershed has been colonized by man and ecologically disturbed for many centuries.

Similar studies need to be undertaken in other tropical areas where burning occurs in order to better understand the impact of agricultural burning in the global carbon cycle. Geochronologies spanning periods of thousands of years are needed in various tropical areas to assess for natural and anthropogenic alteration of the environment.

ACKNOWLEDGEMENTS

This research was funded by the National Science Foundation (NSF grant EAR80-17491 to Edward Goldberg), the Organization of American States, Scripps Institution of Oceanography, and the Smithsonian Tropical Research Institute in Panama. I would like to thank Marcelo Esteban, John Bullister, Jim Weinberg, and Edward Goldberg for reviewing this manuscript.

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Ciencias de la Tierra y del Espacio, 14, 1987

THE PRODUCTION OF CHARCOAL DURING AGRICULTURAL BURNING IN CENTRAL PANAMA AND ITS DEPOSITION IN THE SEDIMENTS OF THE GULF OF PANAMA

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ABSTRACT. *Widespread agricultural burning during the dry season in the Pacific watershed of Panama is an important ecological phenomenon. During that time over 10% of the land surface (woodlands and savannas) is annually burned with the resulting production of large amounts of charcoal. The majority of the charcoal remains on land, but 5% is mobilized by river runoff and winds to the sediments of the Gulf of Panama.*

The aeolian transport of particulate charcoal by the northeasterly Trade Winds has been monitored by dry deposition and aerosol particulate collectors. During the burning season atmospheric charcoal concentrations in rural Panama can be similar to urban concentrations in North America or Europe. Over *60% of the charcoal aerosol mass was carried by fine particles (<2 μm diameter), suggesting that longrange transport is possible.*

Dry deposition fluxes, which are positively correlated to the areal extent of land burned, are more than an order of magnitude less than the charcoal fluxes to the surface, nearshore sediments in the Gulf of Panama. This implies that aeolian transport is not the principal mechanism of charcoal mobilization to these sediments. The extremely high runoff per unit area in the Gulf of Panama watershed is probably responsible for the predominance of continental runoff as the charcoal transport mechanism in the region.

The relatively indestructible charcoal can also be used as a tracer for past burning activities. Sediment box cores have been recovered from the Gulf of Panama, and Pb-210 geochronologies were utilized to determine sedimentation rates. The charcoal particles were isolated by chemical methods and their fluxes, size distributions, and morphologies, analyzed. The uniformity of these measurements in the marine sediment geochronologies indicates stability of burning patterns in central Panama during the last two centuries.