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Carbon, nitrogen, and phosphorus content and ^{210}Pb-derived burial rates in sediments of an Amazon floodplain lake*

by

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Abstract

The C, N and P content of surficial sediments, ^{210}Pb-derived accumulation rates, and burial rates of C, N and P were determined in Lake Calado, a dendritic lake located on the floodplain of the central Amazon basin. A significant positive, linear relationship was found between distance from the river and C, N and P content of the sediments (r^2 = 0.93, r^2 = 0.92, p <0.001 for C and N, respectively, and r^2 = 0.64, p <0.05 for P), indicative of high organic matter content on the floodplain and a greater proportion of clay near the river. Average sediment accumulation rates derived from two cores collected from each of three stations ranged from 41 to 117 mg cm^{-2} yr^{-1}. Lake-wide, annual burial rates are estimated to be 3.5 mol C m^{-2}, 0.28 mol N m^{-2} and 0.016 mol P m^{-2}.

Keywords: **Burial, carbon, nitrogen, phosphorus, Amazon, floodplain.**

Resumo

Foram determinados no Lago Calado, um lago dendrítico localizado na planície inundada da Amazonia Central, os conteúdos de C, N e P na camada superficial dos sedimentos, taxas de acumulção de ^{210}Pb-derivado, e taxas de enterramento de C, N e P. Foi encontrada uma relação linear e significantemente positiva entre distância do rio e os conteúdos de C, N, e P nos sedimentos (r^2 = 0.93, r^2 = 0.92, p <0.001 para C e N, respectivamente, e r^2 = 0.64, p <0.05 para P), indicando um alto conteúdo de matéria orgânica na planície inundada e uma maior proporção de argila perto do rio. As taxas de acumulação de sedimentos derivadas de duas amostras coletadas em cada uma de três estações variaram de 41 a 117 mg cm^{-2} yr^{-1}. As taxas de enterramento foram estimadas em 3.5 mol C m^{-2}, 0.28 mol N m^{-2} e 0.016 mol P m^{-2}.

Introduction

Within the middle reaches of the Amazon River is a large floodplain (95,000 km^2; SIP-

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PEL et al. 1998) consisting of a mosaic of rivers and channels, flooded forest, and floating emergent macrophytes, with thousands of lakes of various shapes and sizes (SIPPEL et al. 1992). The morphology of the floodplain is complex and includes erosional and depositional regions, with lakes being a large proportion of the depositional areas. The annual flood of the Amazon River inundates the floodplain for several months with as much as 25 % of the discharge during the flood (RICHEY et al. 1989). These floodwaters deposit and rework organic and inorganic sediments on the floodplain (DUNNE et al. 1998), and fertilize it with dissolved and particulate nitrogen and phosphorus (FISHER & PARSLEY 1979; FORSBERG et al. 1988; LESACK 1988; ENGLE & SARNELLE 1990). However, with the exception of organic carbon burial in two small lakes (DEVOL et al. 1984), there are no measurements of carbon, nitrogen or phosphorus accumulation in the sediments of Amazon floodplain lakes.

Lakes on the Amazon floodplain vary in the relative importance of their local catchment, the mainstem river or floodplain plankton, periphyton, floating macrophytes and flooded forest as sources of the material deposited in their sediments. In dendritic lakes, such as our study site (L. Calado), which extend from the mainstem river into the fringing uplands, these sources will vary in importance through the lake. Our sampling included major habitats within the lake which are representative of the central Amazon floodplain. We present ^{210}Pb-derived sediment accumulation rates and burial rates of C, N and P in a moderate-sized Amazon floodplain lake and examine spatial variations in sediment chemistry and burial rates. Our findings are a necessary component of mass balance analyses of carbon and nutrients for the Amazon floodplain (e.g., MELACK & FORSBERG 2001), and to evaluations of how land use changes may influence sedimentation rates on floodplains.

Study site

Lake Calado, situated on the north bank of the Solimões River, is located 80 km west of the confluence of the Solimões and Negro rivers at 3°5'S, 60°34'W. L. Calado is a narrow, dendritic lake, and its shape is suggestive of a drowned-river valley (Fig. 1). Its main axis runs in a north to south orientation perpendicular to the Solimões River. The lake's maximum depth and surface area fluctuate between 1-12 m and 2-8 km^2 and are controlled by the annual rise and fall of the Solimões River. Once the lake reaches a depth of 3-5 m, its water-column thermally stratifies, but stratification does not persist until the lake reaches a depth of 6 m (MACINTYRE & MELACK 1984). At depths of 7 m or greater, the hypolimnion remains anoxic for extended periods of time (MACINTYRE & MELACK 1988).

Lake Calado's geomorphology and local catchment influence the depositional environments and particulate inputs. To the north, L. Calado is narrow and is fed by small streams. Inputs are dominated by the flooded forest growing along the shores and clearwater streams draining upland forest. To the south, the lake widens and forms a basin parallel to the levee separating the lake from the river. Inputs are dominated by the suspended load of the Solimões River, which annually spills into the lake through the connecting channel or occasionally over the levee (about once every 10 years; LESACK 1988). In this portion of the lake, approximately 25 to 50 % of the area is covered by floating emergent macrophytes during the rising and high water periods (FISHER & MOLINE 1992). The middle section of the lake is intermediate along the continuum from stream to floodplain geomorphology. A number of streams enter this portion of the lake, and the influence of the Solimões River is sometimes detected. Floating emergent macrophytes and flooded forests occur. During the high water period, the waters of a neighboring lake (L. Miriti) drain into this middle reach from the west through a macrophyte and shrub filled channel.

The catchment of Lake Calado was subjected to changes in land cover during the twentieth century with increasing rates of deforestation observed more recently. Based on examination of aerial photographs from 1955 and Landsat images from 1977 and 1984, the sequence of land cover conversions occurring during the period of sedimentation represented in our cores was evident (J.M. MELACK & M.R. WILLIAMS, unpubl. data). In 1955, 97 % of the catchment was covered by mature forest with about 2 % second growth forest and only about one percent crops. By 1984, 60 % remained mature forest with about 19 % covered by low-stature second growth forest and about 21 % crops. The majority of the deforestation and regrowth, planting of crops and construction of houses occurred on the lake shore.

Lake Calado's lakebed consists of two zones: lacustrine sediments (i.e., sediments that remain flooded throughout the year) and soils that are periodically inundated. The stippling in Figure 1 represents the areal extent of lacustrine sediments. MELACK & FISHER (1983, 1990), SETARO & MELACK (1984), FISHER et al. (1988), ENGLE & MELACK (1993), DOYLE & FISHER (1994), LESACK & MELACK (1995), and MELACK & FORSBERG (2001) provide further limnological, hydrological and ecological information about L. Calado. The sediments and paleoecology of L. Calado are described by IRION (1982), who ^{14}C-dated a core spanning most of the Holocene (sampling site located on Fig. 1).

Methods

An EKMAN dredge was used to collect sediments from eleven stations throughout L. Calado (Fig. 1): nine open water sites (sites 1-9), one stream site (site 10), and one site where emergent floating aquatic macrophytes occur during the high water period (site 11). Two separate casts were made per site, and a sub-sample of the top (approximately 2 cm) of material was collected in screw-top, glass bottles. These samples were returned to the University of California, Santa Barbara, and analyzed for carbon, nitrogen and phosphorus as described below.

One sediment core per site was collected in March, 1982, and in February, 1984, from three stations (1, 3, 4) located along the north to south axis of the lake (Fig. 1). The 1982 cores were collected with a piston corer (inside diameter of 3.8 cm) inserted into the sediments with rods from the surface. The 1984 cores were collected with a coring device consisting of polyvinylchloride plastic pipe (inside diameter of 10 cm) and a one-way valve. The overlying water within both corers was clear, indicating that the cores collected were undisturbed. After collection, the cores were processed immediately at a floating laboratory anchored in the middle of the southern portion of the lake. The 1982 cores were extruded and sectioned at 1 cm intervals, and the 1984 cores were extruded and sectioned at 1 cm intervals near the top and at 2 cm intervals elsewhere.

The water and solid masses were determined by weighing aliquots of wet sediment before and after drying at 80 °C. Only the central portion of each section was used for analyses. The sediment porosity (ø) values were obtained using the relationship:

$$ø = M_w[M_w + (M_s/s)]^{-1} \qquad (1)$$

where M_w and M_s are the masses of water and solids (g), respectively; and s is the specific gravity of dry solids (2.2).

The carbon and nitrogen content in the dried sediment samples was determined with a PERKIN-ELMER CHN analyzer. Phosphorus was measured by digestion in 1 N HCl after ignition for 1 hour at 550 °C (ANDERSEN 1976), followed by spectrophotometric determination of orthophosphate (STRICKLAND & PARSONS 1972). The method of FOLK (1969) was used to determine the sand, silt and clay fractions of the 0-2 cm and 10-12 cm intervals. The sediment samples were dispersed with a 5 g l^{-1} solution of Calgon and sieved through a 64 µm sieve. The proportion remaining in the sieve was considered the sand fraction. The silt (5-63 µm) and clay (<5 µm) fractions were determined by pipette analysis based on settling time.

The determination of ^{210}Pb was based on the measurement of ^{210}Po, the ^{210}Pb granddaughter that is assumed to be in secular equilibrium with its grandparent. This assumption should be satisfactory because both isotopes should have low solubility in these low salinity waters, and because several months elapsed between sample collection and analysis. The analysis followed procedures outlined in FULLER (1982). Dried sediment (0.2-1.0 g) and a spike of 5-20 dpm of ^{208}Po were placed in a Teflon beaker. Solid phases were totally dissolved by sequential leaching with concentrated hydrochloric, nitric plus perchloric, and hydrofluoric acids. After the sample was dissolved, it was dried, and the residue was dissolved in 1 N HCl. Ascorbic acid was added to complex iron, and polonium isotopes were spontaneously electroplated onto a silver disk. Activity on the disk was counted in an alpha spectrometer to measure the ratio of ^{210}Po to ^{208}Po. Solutions remaining after plating were stored, and selected samples were combined for analysis of ^{226}Ra, measured by in-growth of ^{222}Rn and alpha scintillation procedures (HAMMOND & FULLER 1979).

The elemental composition of seston located within the epilimnion was determined on a monthly basis during the period of thermal stratification (February-August 1984). One-liter water samples were collected with a VAN DORN sampler at the sub-surface and above the hypolimnion, filtered in duplicate onto tarred pre-combusted 45 mm GELMAN AE glass-fiber filters and dried at 80 °C. The filters were weighed and analyzed for carbon and nitrogen as described above.

Results

Sediment characteristics: The sediment characteristics of the cores collected in 1982 and 1984 are shown in Table 1. Surface sediment porosities are high (0.87-0.96), which indicates the predominance of silts and clays in L. Calado, as % water (1-ø) and sediment grain size are negatively related (HÅKANSON & JANSSON 1983). The sediments in the southern section of the lake (site 4) contain a smaller proportion of sand (<1 %) compared to sites 1 and 3. Site 4 receives sediment inputs mainly from the Solimões River, whose suspended load contains mostly silts and clays (MEADE 1985), while sites 1 and 3 receive sediment inputs primarily from the numerous streams entering the lake. The streambeds consist of sandy substrata, that is washed into the lake during periods of high flow (pers. observ.).

Sediment composition: Distributional trends are evident in carbon, nitrogen, and phosphorus in the surficial sediments (Tables 1, 2). The sediment composition obtained from the two sets of cores (sites 1, 3, 4; Table 1) have significant positive, linear relationships between surficial C, N, and P content versus distance from the Solimões River ($r^2 = 0.99$, $r^2 = 0.98$, $r^2 = 0.51$; $n = 6$; $p < 0.05$, respectively). The open water sites of the sediment survey (sites 1-9; Table 2) have the same trend as the cores (r^2 = 0.93, r^2 = 0.92, p = <0.001 for C and N, respectively, and r^2 = 0.64; n = 9; p <0.05 for P). No significant correlation between depth of water at time of sampling and surficial C, N, or P content of the surveyed sediments occurred (p >0.05).

Although C, N, and P concentrations increase with distance from the river, their concentrations, relative to each other, do not change consistently over the transect (Table 2). For example, relative to nitrogen the sediments at the southern end of the lake are poorer in P than at the northern end of the lake (N:P at site 1 = 27.0, N:P at site 4 = 10.3). The same trend is observed for carbon concentrations relative to nitrogen (C:N at site 1 = 18.0, C:N at site 4 = 9.8).

The composition of the lacustrine sediments reflects the sources of the inputs. The C:N and N:P ratios of site 1 and the stream (site 10) are nearly identical (Table 2), which suggests that stream inputs are important in the region of the lake near site 1. The carbon-poor sediments of the southern portion of the lake reflect the importance of inorganic inputs from the Solimões River. The sediments collected from below floating emergent macrophytes (site 11) are enriched in C and N in comparison to the sediments collected from the nearby open water sites (4, 5, 6) of the southern basin (C:N and N:P for macrophyte site 11 = 17.4 ± 0.2 and 24.0 ± 4.6, respectively; average C:N and N:P for sites 4-6 = 9.4 ± 0.3 and 7.9 ± 2.1). This suggests that macrophyte-derived particulate material collects locally and may not contribute much organic material to the sediments in the southern section of the lake.

Visible core stratigraphy was absent in all of the cores collected, and the patterns in the vertical profiles of porosity, C, N and P are similar for both the 1982 and 1984 sets of cores. Consequently, only the 1982 core profiles are illustrated in Figure 2. At site 1, porosity remained relatively constant with depth. At sites 3 and 4, porosity decreased by approximately 8 % over the 0-27 cm depth interval measured. This decrease in porosity indicates compaction.

The vertical profiles of C and N at sites 3 and 4 had similar patterns: C and N decrease by about 15 % through the depth range sampled. This decrease might reflect an increase in deposition of organic material in recent times, perhaps related to deforestation and agricultural activity on the lake shore, or diagenetic decomposition of organic matter during burial. The C:N ratios at these stations do not have a significant change with depth (Fig. 3), suggesting that any diagenesis down-core does not enrich solids in either element. In contrast, at site 1, C and N remained constant within the top 8 cm, increased with depth from 8 to 20 cm, and remained constant from 20 cm to the bottom of the core. This pattern indicates that the composition of sediment delivered to this site has become less rich in organic content in recent years. Also, the C:N ratio at site 1 increases from about 15 near the top of this core to about 17 at depth (Fig. 3). Because diagenesis at the other two sites does not introduce a significant change downcore, the observed change in the C:N ratio at site 1 probably indicates a temporal change, perhaps related to land use, in the nature of the organic carbon reaching this site, as the older sediments are enriched in organic material characterized by a high C:N ratio (Fig. 3).

Seston Composition: The composition of epilimnetic seston is shown in Table 3. The carbon content of the particulate matter ranged from 36.8-105 μM, and the nitrogen content ranged from 4.3-15.5 μM. The seston was most carbon- and nitrogen-rich in the central portion of the lake and averaged 75.8 and 10.4 μM, respectively. The N:P ratio of the seston was relatively constant throughout the lake and averaged 7.8.

^{210}Pb Geochronology: Measurements of ^{210}Pb are shown in Table 4. At least one composite sample consisting of 3 or more depth intervals was analyzed for ^{226}Ra in each core to estimate the supported ^{210}Pb activity (i.e., the quantity of ^{210}Pb activity derived from the disintegration of the ^{226}Ra within the sediments). The composite samples from replicate cores are somewhat more variable than anticipated, but are within about 15 % of each other. We assumed that ^{226}Ra is constant with depth at each site and averaged the measurements to obtain a mean value for supported ^{210}Pb. The two northern sites (1 and 3) have indistinguishable values of ^{226}Ra (Table 4), as well as similar lithologies and similar high concentrations of organic carbon and nitrogen.

Excess ^{210}Pb was calculated as the difference between measured ^{210}Pb (total ^{210}Pb) and average ^{226}Ra, and it is plotted versus depth in Figure 4. Profiles approach zero at depth in each of the cores, which indicates internal consistency between the radium and lead measurements. Both the background concentrations of ^{226}Ra and excess ^{210}Pb at the two stations furthest from the river are substantially larger than that at the southern site.

Mass accumulation rates were calculated from excess ^{210}Pb and cumulative density data; the latter was calculated as the integral of dry density versus depth. Two methods, discussed in APPLEBY & OLDFIELD (1983), were used to calculate accumulation rates. The first method (CIC) assumes ^{210}Pb in sedimenting material is constant with time, accumulation rates are constant with time, and no bioturbation occurs in the sediment column. The last assumption is critical, and fits to the data provide a partial test of its validity. The potential for bioturbation is limited by the presence of anoxic bottom waters at these sites during the majority of the year. Given the above assumptions, the unsupported ^{210}Pb in the sediments (P, dpm g^{-1}) should be described by the equation:

$$P = P_o \exp(-\lambda d S^{-1}) \qquad (2)$$

where P_o = unsupported ^{210}Pb at the sediment-water interface (dpm g^{-1})
d = cumulative density (g cm^{-2})
λ = ^{210}Pb decay constant (0.0311 yr^{-1})
S = accumulation rate (g cm^{-2} yr^{-1})

The equation was fit to the data to derive S and P_o using a least squares technique that weights each point equally (WOLBERG 1967). The integral of equation 2 with respect to the cumulative density (d) yields an estimate for the flux of ^{210}Pb to the sediment-water interface. Fits of the model to the data are shown in Figure 4, with the calculated fit converted to the linear depth scale. Most calculated fits are close to the measured data, although it is clear that this model does not fit well in all cases. A problem is apparent in the 1982 core of site 3. While the data in the top 25 cm follow one trend, the final data point is substantially lower. Apparently some spatial heterogeneity must exist, as the 1984 core shows no evidence of a change in slope and has lower concentrations of excess ^{210}Pb in the 10-25 cm region. It appears that either bioturbation has influenced the 1982 core, or the accumulation rate at site 3 is heterogeneous and may have increased in recent years. Otherwise, there is no obvious trend toward small gradients in the upper few centimeters and steeper ones below, and we conclude that bioturbation is not a serious problem at any of our sites. Results of the fits are listed in Table 5 and indicate that for sites 1 and 4, the mean of replicate cores lies within the 20-30 % uncertainty of each individual fit.

The second method (CRS) assumes that the supply of ^{210}Pb to each site is constant and no bioturbation occurs, but accumulation rates may vary with time. In this case, minima in profiles might appear during periods of rapid sedimentation, and maxima during periods of low sedimentation. The accumulation rate may be calculated by integrating the inventory of excess ^{210}Pb from the surface to a given horizon, calculating the age of the horizon, and finding the slope of a plot of cumulative density versus age. The age of the horizon (T) is calculated from the equation:

$$I = I_o (1 - \exp(- qT)) \quad (3)$$

where I = inventory of unsupported ^{210}Pb in the sediment column above a given horizon (dpm cm^{-2})

I_o = inventory of unsupported ^{210}Pb in the sediment column to infinite depth (dpm cm^{-2})

T = age of horizon (yr)

q = ^{210}Pb decay constant (0.0311 yr^{-1}).

Two assumptions were necessary to make this calculation. First, linear interpolations were made to calculate the concentrations of horizons not measured. Second, on the basis of the shapes of the profiles, we assumed negligible ^{210}Pb present below 40 cm at sites 1 and 3, and 30 cm at site 4. These assumptions introduce an estimated uncertainty of about 20 % into the estimate of I_o and will introduce a corresponding systematic error in age (and thus accumulation rate) for horizons near the upper part of the sediment column. Accumulation rates are derived from fits to data in Figure 5 and listed in Table 5. The uncertainty in age increases with depth and may become quite large for deep horizons; consequently the bottom point in each profile was excluded from this calculation. With the possible exception of the 1982 core at site 3, there is no obvious change in accumulation rate at any site during the past 40-60 years. The CRS model predicts an accumulation rate 3 times smaller than the CIC model for 1982 at site 3. This difference could be explained by bioturbation or non-constant accumulation rates of ^{210}Pb. The similarity in excess ^{210}Pb inventory between the two cores from this site (Table 4) suggests that the former is a more likely explanation. The fitting uncertainty for the CRS approach suggests a high precision for age and accumulation rate, but the systematic error in finding I_o for each profile limits the accuracy in accumulation rate to about 20 %, an estimate compatible with the differences in I_o for replicate cores from the same site.

Results of these two approaches are compared in Table 5. In most cases, the two models indicate consistent accumulation rates. The CRS approach provides a mechanism to explain minima and maxima in the ^{210}Pb profiles, and the precision in estimates of the replicate cores is better. Consequently, we adopt the estimates of sediment accumulation derived from the CRS model, acknowledging that the choice of model adds an additional uncertainty to any budget calculation. Accumulation rates decrease in a significant linear fashion ($r^2 = 0.86$, $n = 6$, $p < 0.05$) with distance from the river.

Burial rates of carbon, nitrogen and phosphorus across the 25 cm horizon were calculated as the product of the elemental content in the sediments between 20 and 30 cm and the sediment accumulation rate derived from the CRS model (Table 6). Pore water ammonia profiles measured at each site were used to calculate upward diffusional fluxes (SMITH-MORRILL 1987) and demonstrate that diagenesis of N below 25 cm degrades about 15 % of the solid phase N buried below 25 cm; the solid phase accumulation rates were reduced to account for this effect. The relative constancy of C:N and N:P downcore (Fig. 3) suggests that diagenesis has similar influences on all three of these elements, and results in Table 6 should approximate the average long-term burial rates at sites 3 and 4. The change in solid phase composition at site 1 makes the results more difficult to interpret.

Burial rates of carbon and nitrogen were significantly greater at sites 1 and 3 compared to the southern lake site (ANOVA: $p < 0.05$; $n = 6$). Although site 4 had higher phosphorus burial rates (mean = 0.0025 mmol cm^{-2} yr^{-1}) than the other sites, burial rates at the three sites were statistically indistinguishable ($p > 0.05$). Our results indicate that carbon burial rates within L. Calado are variable, but they bracket those rates reported for nearby floodplain lakes Cristalino and Jacaretinga, which range from 0.23 to 0.36 mmol C cm^{-2} yr^{-1}, respectively (DEVOL et al. 1984).

Discussion

Sediment composition: The physical composition of the sediments reflects the influence of the different parts of the catchment. The streams draining into L. Calado have sandy substrata, and we observed that the highest percentage of sand was in the northern and middle reaches where stream inputs dominate. In contrast, the Solimões River carries silts and clays (MEADE 1985), hence little sand was found at the southern site. We observed higher levels of ^{226}Ra where sandy substratum was more common (sites 1 and 3).

The chemical composition of the lacustrine sediments reflects the sources of inputs, and it is likely that the distribution of C, N, and P in L. Calado reflects a combination of inputs from the inflowing streams draining upland forests, influenced increasingly by clearing for crops and homes, autochthonous production (phytoplankton, periphyton, and aquatic macrophytes), and the Solimões River. The C:N and N:P ratios of the northern site 1 and the stream (site 10) are nearly identical (Table 2). At site 1, the sediment cores consisted primarily of partially decomposed leaf litter that is carried by streams or wind. The high C:N ratio, compared to the other lake sites, reflects the importance of carbon-rich allochthonous inputs to the northern portions of the lake, such as leaf litter which has average C:N value of 28.1 ± 6.0 (HEDGES et al. 1986). In addition to leaf litter, seston settling out of the epilimnion contributes carbon and nitrogen to the lake sediments. Sedimentation of epilimnetic seston, which probably consists primarily of phytoplankton, will dilute the high C:N ratio of leaf litter. Assuming a 50:50 contribution of leaf litter (28.1) and seston (7.8; Table 3) in the northern reaches of the lake, the resulting C:N ratio of the sediment is 18.0, the average C:N value measured at site 1. Given the fact that leaf material was present throughout the sediment cores collected at this site, it is likely that leaf litter is the major contributor of C and N, but the importance of phytoplankton inputs to the sediments cannot be discounted.

The sediments in the southern basin of L. Calado are carbon-poor, compared to the northern portion, because this region is more strongly influenced by inputs from the Solimões River, which are organic-poor (1.01-1.19 % organic carbon; HEDGES et al. 1986). The sediments in this region will consist of a combination of macrophyte inputs, which are carbon-rich (C:N of macrophytes = 46.0 ± 2.5; HEDGES et al. 1986), and epilimnetic seston (8.2; Table 3). When the river inundates the floodplain, the suspended load of inorganic material from the river will dilute the organic material that is produced within L. Calado. This is consistent with our observation that the C:N ratio and the percent organic carbon in the southern basin of the lake (1.15-2.69 % organic carbon) is lower than that of the northern portion of the lake. The C:N ratio of station 3 is intermediate to those of sites 1 and 4, which suggests that the mid-lake region is influenced by inputs from streams and the Solimões River.

Macrophytes of the Amazon floodplain are carbon-rich (average C:N of macrophytes = 46.0 ± 2.5; HEDGES et al. 1986), therefore we would expect the sediments found below stands of floating aquatic macrophytes to have higher C:N ratios than neighboring open water areas. We observed that sediments collected from below floating emergent macrophytes (site 11) are enriched in C and N compared to sediments collected from the nearby open water sites (4, 5, 6) of the southern basin (C:N and N:P for macrophyte site 11 = 17.4 ± 0.2 and 24.0 ± 4.6, respectively; average C:N and N:P for sites 4-6 = 9.4 ± 0.3 and 7.9 ± 2.1). However, relative to the C:N composition of the major species of macrophytes found on the Amazon floodplain, the sediments of site 11 are carbon-poor, perhaps because the floating macrophytes consist of a melange of macrophyte and periphyton biomass (ENGLE & MELACK 1993). Periphyton associated with the root clusters of macrophytes is relatively low in carbon (C:N = 10.4 ± 1.3, FISHER & MELACK, unpubl. data), and will tend to dilute the carbon input from macrophytes.

Sediment accumulation rates: Lake-wide accumulation rates in small lakes have often been inferred from one core collected in the deepest part of a lake (e.g., DAVIS 1969; KERFOOT 1974; LIKENS & DAVIS 1975). However, the heterogeneous nature of sedimentation compromises the validity of extrapolation of sediment accumulation rates derived from one core to an entire lake basin. For example, sediment accumulation rates may have a positive relationship with depth (DAVIS & FORD 1982; EVANS & RIGLER 1980) and slope (KIMMEL 1978; HILTON 1985). Furthermore, DOWNING & RATH (1988) demonstrated that even in lakes with bathymetrically uniform basins, patchiness in sediment chemistry can be significant. In order to derive accurate, lake-wide accumulation rates, it is therefore necessary to collect cores from a number of sites.

In L. Calado, a series of cores were collected along the north to south axis of the lake, and the data indicate regional differences in depositional processes. For example, the ^{210}Pb fluxes to the sediment-water interface are similar at sites 1 and 4, but the fluxes at site 3 are about two times greater. If we assume: (1) the delivery rate of ^{210}Pb to the sediments is equivalent to the ^{210}Pb fallout rate (atmospheric deposition), and (2) there is no alteration of ^{210}Pb activity after deposition, then we would expect the flux of ^{210}Pb to the sediments to be roughly equivalent to the average global atmospheric fallout rate of 1.11 dpm cm^{-2} yr^{-1} (NOZAKI et al. 1979). This is the case for sites 1 and 4 where the ^{210}Pb fluxes ranged from 0.85-1.07 dpm cm^{-2} yr^{-1} (CRS model). However, the average ^{210}Pb flux at site 3 is about two times higher than the global fallout rate, which suggests that something is affecting the ^{210}Pb delivery rates to the sediment-water interface at this site.

Direct atmospheric fallout is the main source of ^{210}Pb to lake sediments. However, other factors, such as indirect atmospheric fallout (^{210}Pb entering the lake indirectly via the catchment basin), or post-depositional redistribution of sediments will increase the rate of ^{210}Pb delivery to the sediments (OLDFIELD & APPLEBY 1984). It is possible that ^{210}Pb enters the lake indirectly at the middle section of the lake. For example, during the rising water period this section receives inputs from neighboring L. Miriti, a possible external source of organic-bound ^{210}Pb. In addition, sediment focusing may occur in this area. At site 3, the shoreline contains short segments where the slope is steep (approximately 13 %). This may cause sediment re-distribution, as re-distribution will occur when slopes are ≥14 % (HILTON 1985). At this time we do not know what processes increase the ^{210}Pb fluxes to the sediment/water interface at this mid-lake site.

As a cross-check of the estimated accumulation rates of site 3, we can compare our results with those of IRION (1982), who ^{14}C-dated a core collected from approximately the same site in L. Calado (Fig. 1). IRION (1982) reports linear accumulation rates of 0.76-1.94 mm yr^{-1} for three different sections of his sediment core. If we assume a sediment density of 2.2 g cm^{-3} and a porosity of 0.7 at depth (IRION, pers. commun.), IRION's sediment accumulation rates range from 50 mg cm^{-2} yr^{-1} to 128 mg $cm^{-2}yr^{-1}$, which spans our estimated average accumulation rate of 84 mg cm^{-2} yr^{-1} for site 3. We assume, therefore, that our sediment accumulation rates are accurate for L. Calado, and we acknowledge that the accumulation rates may be somewhat overestimated for the mid-lake region, as neither ^{210}Pb-dating nor ^{14}C-dating of sediment cores can identify the effects of sediment focusing.

Sediment accumulation rates for floodplain lakes located in the Amazon Basin are not common in the literature. However, the few published studies of ^{210}Pb-dated sediment cores collected from the region suggest that the rates are similar when compared across lakes. FORSBERG et al. (1989) report accumulation rates of 120 mg cm^{-2} yr^{-1} for the undisturbed (pre-deforestation) portion of a core collected from Lake Paca, a floodplain lake of the Jamarí River, Rondonia. Based on the linear accumulation rates of 0.41 cm yr^{-1} and 0.17 cm yr-1 for the two Amazon floodplain lakes, Jacaretinga and Cristalino (DEVOL et al. 1984), we estimate their accumulation rates to be roughly 270 mg cm^{-2} yr^{-1} and 110 mg cm^{-2} yr^{-1}, respectively (again we assume a density of 2.2 g cm^{-3} and a porosity of 0.7). The accumulation rates of Lake Calado, 40 to 120 mg cm^{-2} yr^{-1}, bound the lower end of the range of the reported accumulation rates for these two lakes.

Whole-Lake Burial Rates: To derive whole-lake burial rates of C, N and P, we will consider only the zone of lacustrine sediments, i.e., zone of the lake which remains flooded throughout the year (Fig. 1). The periodically inundated soils do receive particulate inputs from the water column while flooded (SMITH-MORRILL 1987), and some macrophytic material is most likely incorporated into these soils, as SMITH-MORRILL (1987) demonstrated that sedimentation rates are greater under macrophyte beds than in neighboring open-water regions. However, the sediment survey (Table 2) indicates that this material is not carried very far into the pelagic zone. We assume, therefore, that most of the sedimenting material is rapidly oxidized or consumed by grazers once it becomes exposed to the atmosphere and that the bulk of organic accumulation occurs within the lacustrine sediments principally from non-macrophyte-covered regions of the lake.

The area corresponding to the lacustrine zone can be determined from the bathymetric map prepared by LESACK (1988). LESACK (1988) correlated lake depth with the stage height of the Solimões River recorded at Manacaparu, a small town located approximately 10 km upriver from L. Calado. Fifteen years of stage height data indicate that a depth of 4 m is the average stage at which the lake is inundated during the low water period; only during very dry years does the lake fall below this depth. In order to calculate lake-wide accumulation rates, the average burial rates derived from the cores collected in 1982 and 1984 (Table 6) were multiplied by the area representative of each station at a stage of 4 m. On a lake-wide basis, we estimate that 3.5 mol C m^{-2}, 0.28 mol N m^{-2}, and 0.016 mol P m^{-2} are permanently buried in L. Calado on an annual basis.

The Role of the Floodplain in Particulate Nutrient Retention: According to LESACK (1988), total N import balances total N export to the Solimões River, and his data indicate that no storage of N and P within the lacustrine sediments occurred in the 1983/1984 water year. If our estimates of burial rates are included in the particulate N and P budget for L. Calado, the quantity of both N and P sequestered by the sediments is approximately equivalent to 50 % of the total N and P exported to the Solimões River.

Several factors may explain the apparent discrepancy between the balance of N and P import and export, and the quantity of N and P buried in L. Calado. First, there may be an internal source of N and P, which has not been accounted for in Lesack's budget. Measurements of nitrogen fixation by phytoplankton and intact periphyton and macrophyte roots indicate that fixation occurs both within the phytoplankton and the periphyton/grass assemblages (DOYLE & FISHER 1994; MELACK & FISHER, 1988). Furthermore, detrital inputs from the flooded forest and macrophyte beds may contribute both N and P.

Second, there may be a partially unmeasured external input of P to L. Calado from streams and the river. LESACK (1988) under-estimated the total P inputs because he used a milder persulfate digestion to assay for total P in contrast to high temperature-strong acid digestion used here to measure the particulate P fraction. GROBBELAAR (1983) and ENGLE & SARNELLE (1990) have demonstrated that the P adsorbed onto clay particles found in suspension in the Solimões River can be used by phytoplankton, and this fraction is not well determined by persulfate digestion.

Third, interannual variability in the inputs of P from streams and the river are likely and would not be captured with only one year of data. In contrast, ^{210}Pb derived burial rates average several years. As a result, a strict comparison between inputs and outputs determined for one year and ^{210}Pb-derived burial rates may not be possible.

Finally, LESACK's (1988) analysis of the errors associated with his measurements indicates that agreement between terms within a factor of two is reasonable. If we take into account both the errors associated with the burial rates and LESACK's data, there is a reasonable balance between inputs (rain, runoff, river, groundwater seepage), export to the river, and storage within the lacustrine sediments of L. Calado.

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Table 1: The percentage of sand, silt, and clay in the 0-2 and 10-12 cm intervals, and surface porosity (A), and surficial particulate carbon, nitrogen, and phosphorus content (mol mg^{-1} dry weight) in sediment cores (B) collected in Lake Calado. The values in parentheses represent the standard deviation of the mean (n=2). If no parentheses are shown only one measurement was made.

A		**Sand**		**Silt**		**Clay**		
Site	**Date**	**0-2**	**10-12**	**0-2**	**10-12**	**0-2**	**10-12**	**Porosity**
1	1982	-	-	-	-	-	-	0.952
1	1984	9	9	10	13	81	79	0.941
			(0.4)		(4)		(0.3)	(0.001)
3	1982	-	-	-	-	-	-	0.965
3	1984	24	4	13	10	63	86	0.897
		(0.8)	(0.3)	(0.6)	(0.7)	(0.4)	(0.8)	
4	1982	-	-	-	-	-	-	0.868
4	1984	1	<1	35	12	64	87	0.871
		(0)	(0)	(7)	(1)	(7)	(1)	(0.005)

B				
Site	**Date**	**C**	**N**	**P**
1	1982	12.6	0.84	0.027
1	1984	12.5	0.80	0.035
		(0.1)	(0.02)	(0.0003)
3	1982	6.8	0.59	0.030
3	1984	6.7	0.57	0.034
		(0.2)	(0)	(0.0001)
4	1982	2.2	0.21	0.019
4	1984	2.3	0.22	0.023
		(0.02)	(0)	(0.0001)

Table 2: Carbon, nitrogen and phosphorus content (mol mg^{-1} dry weight) and molar C:N and N:P ratios of surficial sediments collected throughout L. Calado. Values within parentheses represent the standard deviation of two samples. Refer to Figure 1 for location of site numbers. Type indicates where the samples were collected: open water (open), streambed (stream), or below macrophytes (macro).

Site	Type	C	N	P	C:N	N:P
1	open	13.4 (0.69)	0.743 (0.057)	0.0244 (0.0160)	18.0 (0.9)	30.4 (2.3)
2	open	13.0 (0.28)	0.879 (0.007)	0.0305 (0.0011)	14.8 (0.3)	28.8 (0.2)
3	open	6.68 (0.11)	0.571 (0.030)	0.0269 (0.0007)	11.7 (0.2)	21.2 (1.1)
4	open	2.24 (0.03)	0.229 (0.007)	0.0224 (0.0008)	9.8 (0.1)	10.2 (0.3)
5	open	1.40 (0.08)	0.150 (0.007)	0.0206 (0.0007)	9.3 (0.5)	7.3 (0.3)
6	open	1.31 (0.03)	0.143 (0.007)	0.0231 (0.0016)	9.2 (0.2)	6.2 (0.3)
7	open	1.84 (0.08)	0.207 (0.021)	0.0191 (0.0001)	8.9 (0.4)	10.8 (1.1)
8	open	0.96 (0.16)	0.100 (0.007)	0.0201 -	9.6 (1.6)	5.0 (0.3)
9	open	1.05 (0.06)	0.100 (0.007)	0.0206 (0.0003)	10.5 (0.6)	4.8 (0.3)
10	stream	17.7 (1.8)	0.957 (0.037)	0.0304 (0.0016)	18.5 (1.9)	31.5 (1.2)
11	macro	9.68 (0.12)	0.557 (0.107)	0.0232 (0.0008)	17.4 (0.2)	24.0 (4.6)

Table 3: Epilimnetic seston composition (μM) during the stratified period in Lake Calado. The values represent the mean of two samples collected at the sub-surface and above the hypolimnion. See Figure 1 for location of site numbers.

Site	Month	Carbon	Nitrogen	C:N
1	Feb.	44.6	5.4	8.3
	Mar.	61.6	8.7	7.2
	Apr.	68.7	9.1	7.6
	Jul.	51.6	6.4	8.1
	Aug.	54.7	7.0	7.8
Average:		56.2	7.3	7.8
3	Feb.	59.3	8.2	7.2
	Mar.	77.6	10.8	7.2
	Apr.	105	15.5	6.6
	Jul.	77.7	9.8	8.1
	Aug.	59.2	8.0	7.4
Average:		75.8	10.4	7.3
4	Feb.	36.8	4.3	7.8
	Mar.	73.6	10.0	7.4
	Apr.	74.8	9.4	8.8
	Jul.	73.8	8.3	9.0
	Aug.	61.6	7.6	7.6
Average:		64.1	7.9	8.2

Table 4: Summary of ^{210}Pb data for cores collected at Lake Calado.

Site	Date	Interval (cm)	Cumulative Density (g cm^{-2})	Total ^{210}Pb (dpm g^{-1})
1	1982	2-3	0.25	32.8 ± 1.4
		3-4[a]	0.36	29.0 ± 1.0
		6-7	0.70	25.9 ± 0.7
		7-8[a]	0.85	24.0 ± 1.0
		11-12	1.37	20.4 ± 1.0
		16-17[a]	2.01	17.2 ± 1.0
		20-21[a]	2.52	14.7 ± 0.9
		25-26	3.24	15.0 ± 0.5
1	1984	0-1[a]	0.065	27.8 ± 0.8
		1-2[a]	0.205	31.8 ± 0.7
		2-4[a]	0.44	27.3 ± 1.2
		6-8[a]	1.05	27.0 ± 1.1
		12-14[a]	1.97	17.3 ± 0.5
		20-22	3.23	13.9 ± 0.4
		30-32	5.06	14.0 ± 0.4
		40-42	6.97	12.5 ± 0.4
3	1982	1-2[a]	0.13	30.6 ± 1.2
		2-3[a]	0.24	33.3 ± 1.0
		4-5[a]	0.48	33.1 ± 1.0
		6-7[a]	0.78	31.8 ± 1.4
		13-14	1.94	28.9 ± 0.4
		18-19	2.89	27.3 ± 0.7
		19-20[a]	3.09	27.4 ± 0.7
		23-24	3.90	26.8 ± 0.6
		26-27[a]	4.59	17.4 ± 0.5
3	1984	0-1[a]	0.12	37.2 ± 1.3
		1-2[a]	0.38	34.4 ± 1.2
		2-3[a]	0.68	31.9 ± 1.0
		12-14[a]	4.33	20.8 ± 0.7
		20-22	7.20	18.5 ± 0.5
		28-30	10.40	15.4 ± 0.4
4	1982	0-1	0.15	12.1 ± 0.4
		1-2[a]	0.49	11.5 ± 0.3
		2-3	0.88	12.9 ± 0.4
		3-4[a]	1.33	7.9 ± 0.3
		4-5	1.78	10.6 ± 0.4
		6-7[a]	2.59	9.6 ± 0.4
		8-9[a]	3.31	10.3 ± 0.3
		13-14	5.31	7.4 ± 0.4
		18-19	7.28	7.8 ± 0.2

Table 4: ^{210}Pb data summary (continued).

Site	**Date**	**Interval (cm)**	**Cumulative Density ($g\ cm^{-2}$)**	**Total ^{210}Pb ($dpm\ g^{-1}$)**
4	1984	0-1[a]	0.15	12.6 ± 0.5
		1-2	0.46	11.4 ± 0.5
		2-4[a]	1.02	11.4 ± 0.5
		4-6	1.75	13.5 ± 0.5
		8-10[a]	3.21	10.8 ± 0.4
		14-16	5.84	7.8 ± 0.4
		18-20[a]	8.16	5.7 ± 0.3

[a] Used for ^{226}Ra composite.

Table 5: Measurements of ^{210}Pb from cores collected in Lake Calado. ^{226}Ra indicates the background level of radium used to estimate supported ^{210}Pb. Excess ^{210}Pb is the quantity of unsupported ^{210}Pb within the surficial sediments. Accumulation rates of total dry weight ($mg\ cm^{-2}\ yr^{-1}$), which were derived from two models (CIC and CRS; APPLEBY & OLDFIELD, 1983), are also compared. ^{210}Pb flux is the flux of ^{210}Pb at the sediment-water interface ($dpm\ cm^{-2}\ yr^{-1}$). Uncertainties are given as ± 1 standard deviation, unless otherwise indicated.

		Accumulation Rate		**^{210}Pb Flux**		**^{210}Pb Flux**	
Site	**Year**	**^{226}Ra ($dpm\ g^{-1}$)**	**excess ^{210}Pb ($dpm\ g^{-1}$)**	**CIC**	**CRS[b]**	**CIC**	**CRS[c]**
	1982	10.9	24.0 ± 1.0	40 ± 3	45 ± 9	0.97 ± 0.08	1.00
1	1984	13.6	19.4 ± 1.7	62 ± 15	37 ± 8	1.21 ± 0.30	0.69
	mean[a]	12.2 ± 1.9	21.7 ± 3.2	51 ± 6	41 ± 6	1.09 ± 0.12	0.85 ± 0.15
3	1982	9.4	21.7 ± 1.6	211 ± 54	75 ± 15	4.58 ± 1.22	2.64
3	1984	15.2	24.6 ± 0.8	97 ± 9	92 ± 18	2.39 ± 0.24	2.30
	mean[a]	12.3 ± 4.1	23.2 ± 2.1	154 ± 23	84 ± 12	3.49 ± 1.10	2.47 ± 0.17
4	1982	4.8	5.7 ± 1.0	133 ± 23	137 ± 27	0.76 ± 0.34	1.05
4	1984	5.7	6.6 ± 1.1	146 ± 67	98 ± 20	0.97 ± 0.47	1.08
	mean[a]	5.2 ± 0.6	6.2 ± 0.6	140 ± 44	117 ± 16	0.87 ± 0.11	1.07 ± 0.02

[a] Uncertainty calculated as mean standard error for each profile/sample size (n).
[b] Fitting uncertainties were all <10 %; an uncertainty of 20 % is assigned for each profile and 14 % for the mean.
[c] The uncertainty of integrating an individual profile was estimated to be 15 %.

Table 6: Burial rates of carbon, nitrogen and phosphorus (mmol cm^{-2} yr^{-1}) for Lake Calado. See text for explanation of how burial rates were calculated.

Site	Date	Burial Rate C	N	P
1	1982	0.58 ± 0.12[a]	0.036 ± 0.008	0.0011 ± 0.0006
1	1984	0.46 ± 0.10	0.025 ± 0.005	0.0008 ± 0.0002
	mean	0.52 ± 0.08	0.031 ± 0.008	0.0010 ± 0.0002
3	1982	0.41 ± 0.09	0.035 ± 0.009	0.0012 ± 0.0006
3	1984	0.47 ± 0.09	0.037 ± 0.008	0.0017 ± 0.0003
	mean	0.44 ± 0.04	0.036 ± 0.0001	0.0015 ± 0.0004
4	1982	0.21 ± 0.04	0.019 ± 0.005	0.0017 ± 0.0008
4	1984	0.09 ± 0.02	0.009 ± 0.002	0.0021 ± 0.0004
	mean	0.15 ± 0.08	0.014 ± 0.007	0.0019 ± 0.0003

[a] Errors for individual cores were calculated as: $SD = (AX)^{0.5}$ (BEVINGTON, 1969), where $A = (SQ)^2$ and $X = [(sd_s)^2 / S^2] + [(sd_q)^2 / Q^2]$; SD is the standard deviation of the burial rates; S is the sediment accumulation rate (CRS model; Table 5); Q is the quantity of C, N, or P in the surficial sediments, sd_s is the standard deviation of the sediment accumulation rate (S), and sd_q is the standard deviation of the quantity of C, N, or P in the surficial sediments (Q).

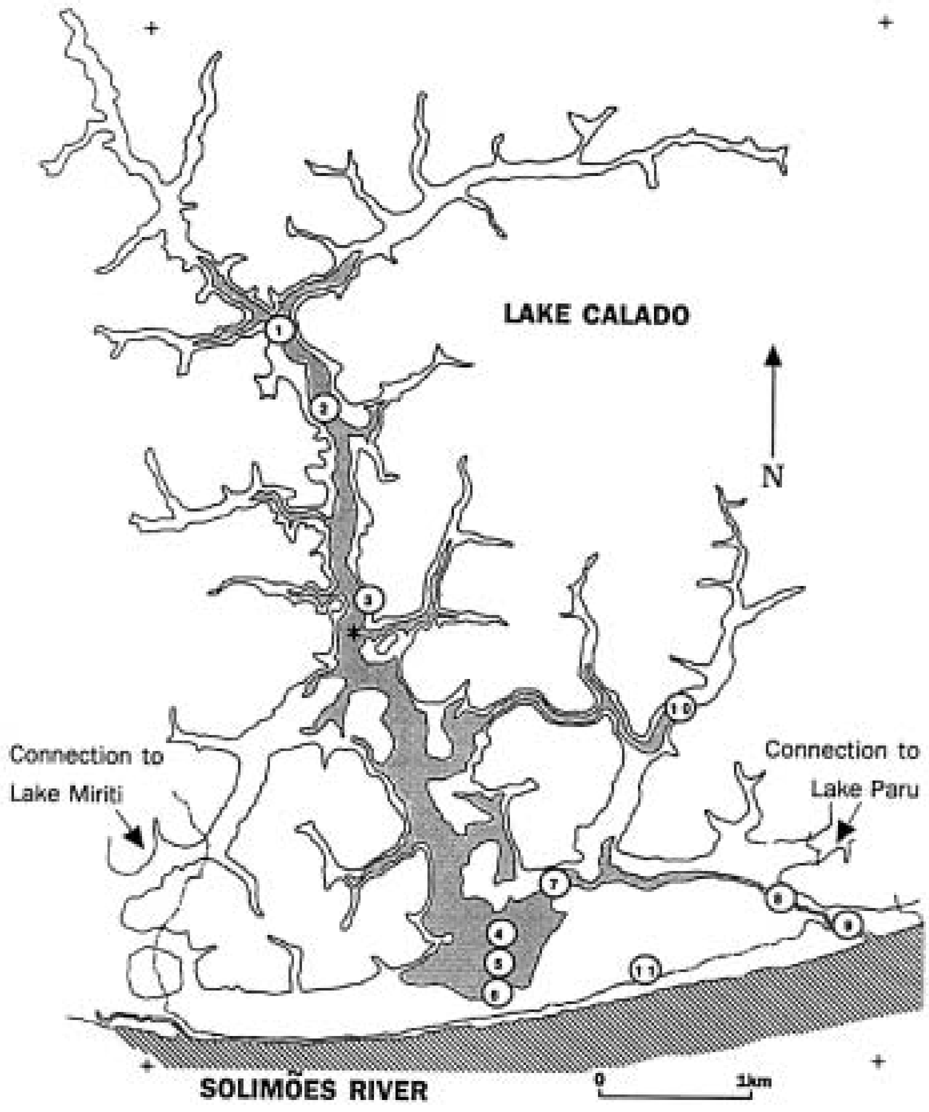

Fig. 1:
Map of Lake Calado located in Amazonas, Brazil (3°5'S, 60°34'W). The numbers on the map indicate the sampling sites of the sediment survey described in Table 2. Two sets of sediment cores were collected at sites 1, 3, and 4. The limit of the lake during the low water period lake is indicated by stippling, and the high-water extent of the lake is indicated by solid lines. Asterisk indicates site where IRION (1982) collected a sediment core.

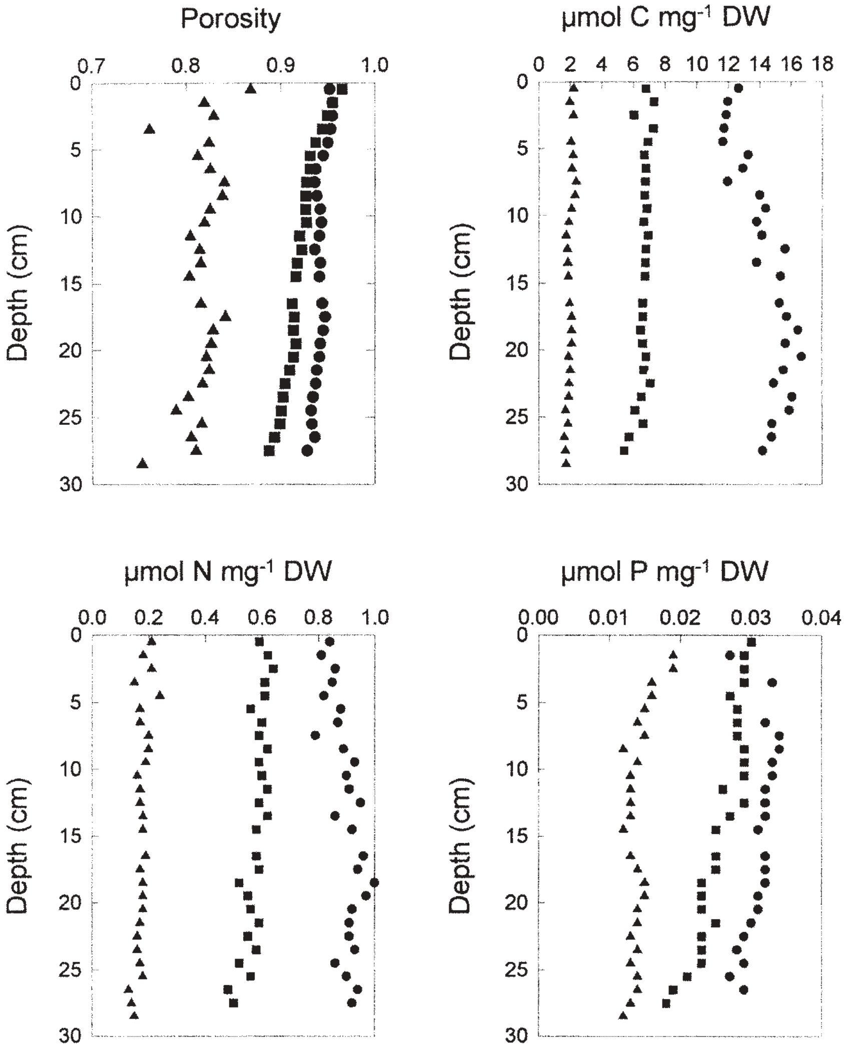

Fig. 2:
Depth profiles of sediment porosity and C, N, and P content of cores collected in 1982 at sites 1 (circle), 3 (square), and 4 (triangle).

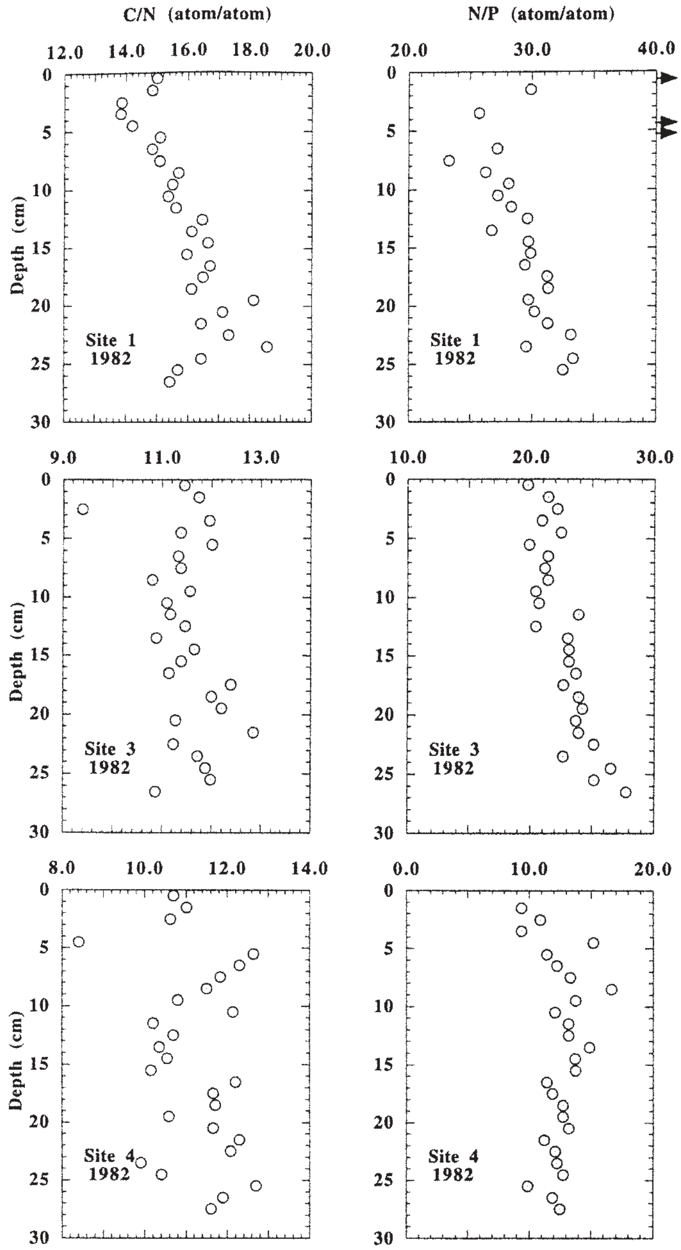

Fig. 3:
Depth profiles of C:N and N:P ratios (molar) of cores collected in 1982 at sites 1, 3, and 4. Arrows indicate data points that are off-scale.

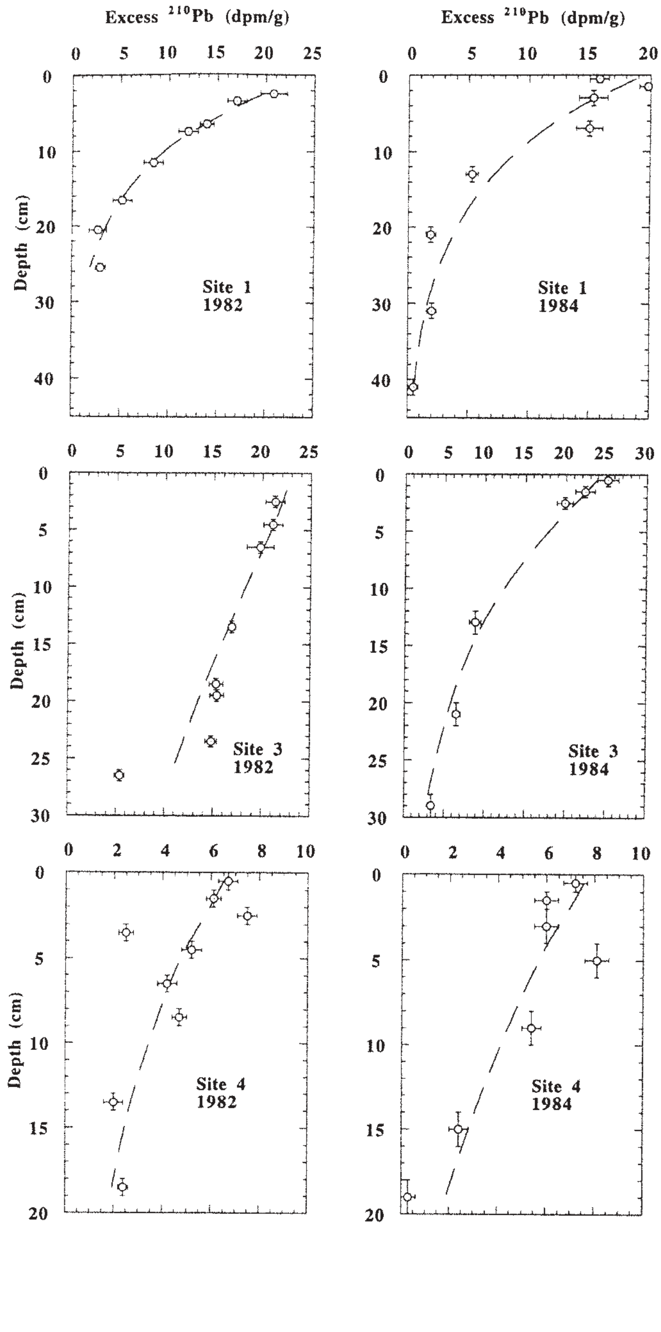

Fig. 4:
Excess ^{210}Pb versus depth profiles from the cores collected in 1982 and 1984. Vertical bars indicate the length of the sample interval, and horizontal errors indicate the uncertainty in the analysis. A supported activity of 12 dpm g^{-1} was subtracted at sites 1 and 3, and 5.4 dpm g^{-1} at site 4. The dashed lines show fits of the CIC model to profiles of excess ^{210}Pb versus integrated density, and the calculated fit has been transformed back into depth coordinates for plotting.

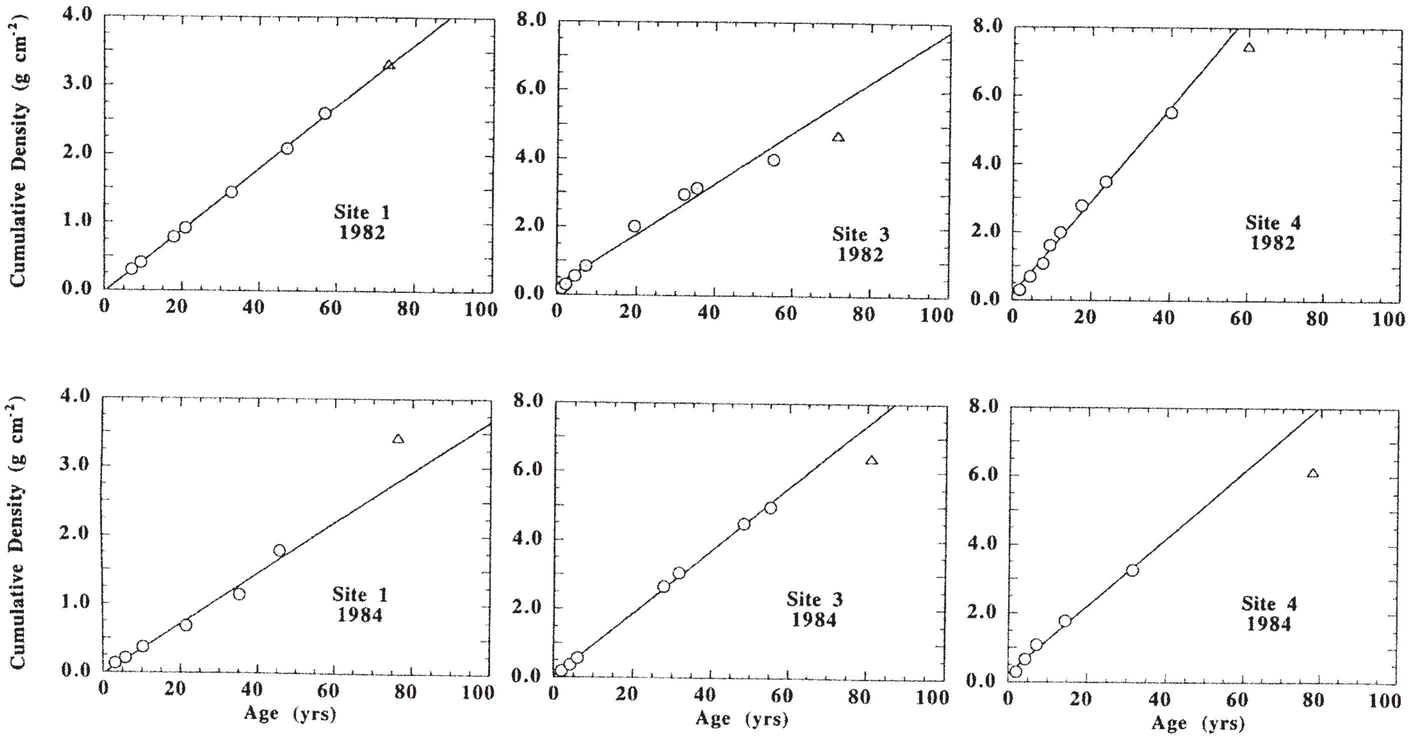

Fig. 5:
Cumulative density versus age calculated from the CRS model. Solid lines are linear regressions from least square fits to the circles, and the derived slope is the sediment accumulation rate. Because of large uncertainties in the age calculation for deep data points, the deepest sample in each profile (triangles) was excluded from the fit.