Spatial and Temporal Variations in Soil Chemistry on the Amazon Floodplain

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ABSTRACT: Soil samples were collected on the floodplains of the Amazon River and its principal Brazilian tributaries during dry, early rising water, and early falling water periods. The concentrations of basic cations and pH in these alluvial soils were always higher than those in the more common “terra firme” soils while the concentrations of aluminum were generally lower. Among the alluvial soils, those from the main channel floodplain were generally higher in basic cations and pH, and lower in aluminum than those from the tributary floodplains. The concentrations of basic cations in soils along the main channel floodplain decreased downstream. No significant difference was found in the levels of basic cations, pH, or aluminum between sampling periods.

Introduction

The Amazon floodplain (“varzea”), a region of over 60,000 km², is noted for its fertile soils and nutrient-rich waters (Sioli 1975; Junk 1984; Furch 1984). The fertility of the region is sustained by the Amazon river which, each year, deposits a significant part of its nutrient and sediment load in the area during seasonal floods (Sioli 1984). In turn, bank erosion and the growth-decomposition cycle of the varzea plant community influence the chemical and biological characteristics of the main channel (Forsberg et al. 1988). The high fertility is reflected in the high levels of primary production (Schmidt 1973) and fish production (Goulding 1986) encountered in Amazon floodplain lakes and the high agricultural yields obtained on floodplain soils. Due to their productivity, the floodplains are among the most densely populated and developed areas in the Amazon (Meggers 1986).

Because of their importance to the ecology and economy of the Amazon region, the floodplains have been the subject of intensive study. Most of these studies, however, have focused on the central part of the basin, with relatively few quantitative studies of soil chemistry (Irion 1978; Martinelli 1986).

Here we investigate the spatial and temporal variability of floodplain soil chemistry along a 1,700 km stretch of the Amazon/Solimões river between Vargem Grande (3° 16.3’ S, 67° 55.2’ W) and Obidos (1° 55.9’ S, 55° 30.4’ W) (Fig 1). Samples were collected in three surveys between October 1983 and July 1984, as part of the Carbon in the Amazon River Experiment (CAMREX, Richey et al. 1986). This information is important as a basic data set for biogeochemistry and for better planning of agricultural development in the region.

The Amazon River-Floodplain System

The Amazon basin, with a drainage area of approximately 6 million km², can be divided into physiographical zones. To the W is the Andes Cordillera (Tertiary) characterized by the highest elevations, with the less elevated Subandean region to the E. To the N and S are the Pre-Cambrian crystalline shields. The Amazon
depression, with the main channel and floodplain, lies in the center part of the basin (Klammer 1985). Minimum and maximum discharge measured at Obidos average 100,000 m$^3$/s and 220,000 m$^3$/s, respectively (Richey et al. 1986).

Between Vargem Grande and Obidos (the sampling reach), the Amazon river receives seven of its major tributaries (Fig 1). Chemical characteristics of each tributary are determined primarily by the location of headwaters and the distance travelled through the Amazon depression before reaching the main channel (Sioli 1975). The main channel at Vargem Grande is composed primarily of Andean water, and has high sediment and nutrient concentrations. The Rio Madeira begins in the Bolivian Andes, and passes across the Brazilian Shield and the central Amazon plain, with high sediment and moderate nutrient levels. The Rios Iça and Japurá have Andean origins with mostly lowland drainages, while the Rios Jutai, Jurua, and Purus drain the sediments of the Subandean Trough and central plain, with intermediate levels of sediments and nutrients. The Rio Negro drains primarily the caatinga forest on the Guyana Shield, though its major tributary, the Rio Branco, drains a drier savannah region, and is depleted in sediments and nutrients.

The floodplains along the main channel form a highly dynamic system, both from the geomorphic (Mertes 1985) and biological and chemical (Junk 1984) points of view. The active varzea can be divided into several geomorphologically distinct reaches (Mertes 1985). The upstream reaches (Vargem Grande to Itapeua) are characterized by deposition of sand in the main channel and floodplain channels, with subsequent rapid migration of these channels to produce an intricate scroll-bar topography with hundreds of long, narrow lakes. The middle reaches of the river (Itapeua to Sao Jose do Amatari) are controlled by structural features that tend to constrain the river and allow almost no morphological change. The floodplain is narrow and lakes less numerous. Finally, in the downstream reaches (Sao Jose do Amatari to Obidos), an incomplete levee system provides free access for overbank flows to a wide floodplain of relatively flat-lying topography and a patchwork of wide, shallow lakes. Differences in the degree of annual sediment deposition in the downstream reaches seem to control the location of the lakes.

### Materials and Methods

Sampling was conducted at 18 stations along the main channel and at 1 station on each of 6 tributaries, on cruises 6, 7, and 8 of CAMREX, aboard the Brazilian research vessel LM Amanai. Cruise 6 occurred during the dry period (October-November) of 1983, cruise 7 fell during the early rising water period (January-February) of 1984, and cruise 8 took place during the early falling water period (June-July) of 1984.
Soil samples were collected with a corer within 100 m of the river's edge from recent alluvial deposits. Geologically, these deposits are classified as Holocene (Irion 1976, 1978, 1984). Tropical grasses (Echinochloa polystachya and Paspalum sp.) dominated the vegetation at most sites. During cruise 6 samples were obtained by integrating the first 60 cm of the soil column at three points within 50 m of each other. Subsamples from these three points were then combined to provide a single composite sample for each station. During cruises 7 and 8 samples were collected at 20 cm intervals to a depth of 60 cm at three points within 50 m of each other and then mixed to provide a composite sample for each depth interval. Samples were air dried aboard ship and then sent to the Centro de Energia Nuclear na Agricultura (CENA) for analysis.

At CENA the dried samples were passed through a 2 mm sieve. The levels of Ca, Mg, K, and Na in the samples were determined by extracting 5 g of dry sediment in 50 ml of 0.05 N HC1 and then analyzing the extract in a Varian Series 634 atomic absorption spectrophotometer. Aluminum and hydrogen content were determined by titration after extracting 5 g of dry sediment in 50 ml of 1 N KC1 (Catani and Jacintho 1974). The pH of the samples was determined potentiometrically after equilibration of 10 g of sediment with 25 ml of distilled water (Catani and Jacintho 1974).

Since the resulting data were not normally distributed, nonparametric statistics were used for analysis. The Spearman Rank Test (SRT) was used to test for significant differences within groups, while the Wilcoxon Test (WT) was used for differences between groups. In the text, means (x) are presented together with the corresponding standard deviation, (s) and number of observations (n) in the form x ± s (n = ). The test statistics abbreviated as SRT and WT and their levels of significance in parentheses. During cruises 7 and 8 samples were collected at three different depths in the soil column. However, as no significant difference were found between depths for any of the parameters measured; only the means of all depths will be presented.

Chemistry of Mainstem and Tributary Floodplain Soils

The levels of exchangeable Ca in soils collected on the main channel floodplain varied from 7.4–15.7 meq/100 g, with a mean of 10.7 ± 0.3 meq/100 g (n = 40) (Tab 1). Calcium dominated the exchange complex in the main channel soils representing, on average, 79% of total exchangeable bases.

The concentrations of calcium in soils from the tributary floodplains were significantly lower than those in soils from the mainchannel floodplains (WT, p = 0.0025). The values ranged from 3.3–11.9 meq Ca/100 g (Tab 1) with a mean of 6.7 ± 0.8 meq Ca/100 g (n = 16). While the Rios Ica and Japura both have headwaters in the northern Andes and are considered geochemically similar (Stallard and Edmond 1983), the calcium levels in their floodplain soils were significantly different (WT, p = 0.005), averaging 4.5 ± 1.2 meq/100 g (n = 3) and 8.2 ± 1.4 meq/100 g (n = 3) respectively. During cruises 6 and 7 soils from the Japura floodplain were collected near the confluence with the Aranapu Parana, which transports water and sediments from the Solimões River to the Japura. Consequently, the differences between the Japura and Ica soils may have been derived from lateral inputs from the Solimões and not differences in headwater geochemistry. During cruise 8 soil samples were collected upstream from the confluence with the Aranapu Parana. As expected, the calcium concentrations in these soils were similar to those encountered in soils from the Ica floodplain (Tab 1).

The Ca levels in soils collected from the floodplain of the Rio Jutai were also surprisingly high for a river with predominantly lowland drainage. These results also suggest a significant input of non-Jutai material, possibly from the Copetana Parana, which carries some water from the Solimões river and centers the Jutai near the sampling site. River Purus Ca concentrations were on average slightly higher than in the other tributaries. Surprisingly, samples from the Rio Jurua, with headwaters in the same region as the Rio Purus, showed Ca concentrations similar to the varzea of the main channel (Tab 1). The soil samples collected from the floodplain of the Rio Madeira had Ca concentrations similar to those in soils from the Rio Ica floodplain, despite differences in the geology of the headwater regions (Irion 1976, 1984; Stallard and Edmond 1983). As in the main channel soils, Ca dominated the exchange complex in soils from the tributary floodplains, although its average contribution to total exchangeable bases, 73%, was significantly lower (WT, p = 0.006).

The concentration of magnesium in soils collected along the main channel floodplain ranged from 1.1–3.8 meq/100 g, with an average value of 2.6 ± 0.1 meq/100 g (n = 40). Magnesium accounted for an average of 19% of the exchangeable bases in these soils. The magnesium content of soils collected from the tributary floodplains was significantly lower (WT, p = 0.05) than the main channel soils. The average concentration was 2.0 ± 0.2 meq/100 g (n = 16) with a range of 0.97–4.10 meq/100 g (Tab 1). Magnesium accounted for an average of 24% of the exchangeable bases in these soils, significantly more than in the main channel (WT, p = 0.006). The large ranges of values encountered for the Ica and Japura rivers indicate differences between sample sites. These differences may reflect different sources for the material or may be due to the differential action of diagenetic processes.

Potassium concentrations in the main channel samples ranged from 0.05–0.33 meq/100 g (Tab 2) with an average of 0.17 ± 0.01 meq/100 g (n = 40). The mean concentration for the tributary soils, 0.14 ± 0.01 meq/100 g (n = 16), was significantly lower (WT, p = 0.02) with a range of 0.07–0.27 meq/100 g. Potassium ac-
Tab 1

Concentration of exchangeable basic cations, sum of bases (S), aluminium (all expressed in meq/100 g), and pH of varzea sediment samples collected in the main channel and tributaries. (The sampling point distance in relation to Vargem Grande is expressed in kilometers)

<table>
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<tr>
<th>Local</th>
<th>d (Km)</th>
<th>Ca</th>
<th>Mg</th>
<th>K</th>
<th>Na</th>
<th>S</th>
<th>Al</th>
<th>pH</th>
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<td>6</td>
<td>7</td>
<td>8</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>V. Grande</td>
<td>0</td>
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<td>9.4</td>
<td>13.0</td>
<td>1.8</td>
<td>2.0</td>
<td>3.6</td>
<td>0.05</td>
</tr>
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<td>S.A. Iça</td>
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<td>11.8</td>
<td>13.0</td>
<td>15.7</td>
<td>2.4</td>
<td>3.6</td>
<td>3.8</td>
<td>0.22</td>
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<td>2.7</td>
<td>0.15</td>
<td>0.15</td>
<td>0.10</td>
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<td>15.2</td>
<td>1.8</td>
<td>3.6</td>
<td>3.7</td>
<td>0.15</td>
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<td>2.9</td>
<td>0.16</td>
<td>0.09</td>
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<tr>
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<td>2.2</td>
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<td>8.1</td>
<td>1.9</td>
<td>2.0</td>
<td>0.11</td>
<td>0.15</td>
<td>0.10</td>
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<td>2.0</td>
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<td>0.07</td>
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<td>2.6</td>
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<td>0.07</td>
<td>12.1</td>
<td></td>
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<tr>
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<td>1696</td>
<td>12.0</td>
<td>9.7</td>
<td>2.5</td>
<td>2.4</td>
<td>0.18</td>
<td>0.33</td>
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<table>
<thead>
<tr>
<th>Tributários</th>
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<tr>
<td></td>
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<tr>
<td>Iça</td>
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<tr>
<td>Jutal</td>
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<tr>
<td>Jurujá</td>
</tr>
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<td>Japurá</td>
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<tr>
<td>Purus</td>
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<td>Madeira</td>
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</table>
counted for an average of 1.7% of the total exchangeable bases with no significant difference between the tributary and main channel samples.

Sodium generally accounts for only a small fraction of the exchangeable bases encountered in soils. The average level of Na encountered in the mainstem soils was 0.10 ± 0.01 meq/100 g (n = 40) with a range of 0.04–0.25 meq/100 g (Tab 1) and a relative contribution of only 0.8% to the total base sum. The average concentration of Na in the tributary soils, 0.09 ± 0.01 meq/100 g, was significantly lower than in the main channel soils (WT, p = 0.05) with values ranging from 0.06–0.13 meq/100 g (Tab 1) and an average contribution of 1.6% to the total exchangeable base sum.

The pH and Al content of soils were generally closely correlated (Van Raij 1983). The more acid the soils the greater the dissolution of aluminum minerals and the higher the concentration of exchangeable Al. The pH-Al correlation is also evident in Tab 1. The average concentration of exchangeable aluminum in the main channel samples, which had pH's near neutrality, was low (0.06 ± 0.01 meq/100 g, n = 40). As a consequence the base saturation (V%) was high (97±2%). The pH in soils from the tributary floodplains was significantly lower (WT, p = 0.0004) with a much higher average concentration of aluminum and a lower base saturation. The samples from the Rio Jutai floodplain were more acid and higher in exchangeable aluminum than those from the main channel floodplain. This difference is surprising given that the soils sampled were composed primarily of sediments derived from the Rio Solimões. The greater acidity and lower aluminum content in the Jutai soils may be due to the seasonal inundation of the soils by acidic Jutai river water.

The average cation exchange capacity (CEC) of samples from the main channel floodplain was 13.9 ± 0.43 meq/100 g (n = 40) with a range of 8.8–20.1 meq/100 g. Due to the low levels of H and Al in these samples, their cation exchange capacities were not significantly different from their total base sums. The average cation exchange capacities for samples from the tributary floodplains were all significantly lower than that for the main channel samples (WT, p=0.35). The only values which were close to the main channel average were those for the Jurua (18.6 meq/100 g, n = 2) and Iça (11.7 ± 0.27 meq/100 g, n = 3).

The chemical and mineralogical characteristics of a river's suspended load generally depend on the composition of the weathering horizons within its drainage basin. The geology of weathering horizons varies considerably among the major subbasins of the Amazon (Stallard and Edmond 1983). Irion (1976) showed that the concentration of basic cations in the fine fraction of the suspended load is higher in the tributaries of the Amazon with Andean drainage than those draining the lowland areas. To determine how these properties are reflected in floodplain soil chemistry, we examined the variations between the mainstem and terra firme, along the floodplain of the Amazon main channel on an E-W or downstream axis between Vargem Grande (0 km) and Obidos, and between cruises. The results of statistical tests are summarized in Tab 2.

### Floodplain – Terra Firme

Values of Ca were much higher than the values encountered in yellow latosols (oxisols) of terra firme areas in the lowland Amazon. Vieira (1975) found an average calcium content of 0.38 ± 0.04 meq Ca/100 g for three representative latosol profiles, or about 28 times less calcium than in the floodplain soils. Though lower than the main channel, tributary Ca values were still high when compared with the Amazon latosols. The predominance of calcium is due, in part, to the selective weathering of dolomite and calcite deposits in the Andean headwater region (Gibbs 1964; Stallard and Edmond 1983) and, also, to the small size of the calcium ion relative to its charge which leads to greater absorption by clay particles and organic matter in the soils (Van Raij 1983).

Magnesium concentrations in the floodplain were 18 times higher than the average value encountered by Vieira (1975) for Amazonian yellow latosols. Potassium concentrations were within the range found for fertile soils. Compared with calcium and magnesium, though, these levels are low and K could eventually limit agricultural production if the soils are not effectively
managed. Despite the differences between the main stem and tributary areas, all of the soils collected were less acid and lower in aluminum then the yellow latosols of Amazonia.

Spatial Variations along the Mainstem

During the low water period (C6) the concentration of exchangeable cations did not vary significantly along the E-W axis (Fig 2a and 2b). In contrast, during cruises 7 and 8 the concentration of basic cations, pH and Al along the main channel varied considerably (Fig 3 and 4). During the early rising water period (C7) the concentration of basic cations and pH declined significantly (SRT, Tab 2) downstream. Due to its inverse relationship with pH, the concentration of aluminum showed the opposite trend, increasing significantly downstream (Fig 3).

The spatial patterns observed during cruise 7 were repeated during the early falling water cruise (C8), except for Al and K which showed no significant spatial trends (Fig 4). As a consequence of these variations the total base sum (S) and CEC also showed significant downstream trends only during cruises 7 and 8.

Since the floodplains are formed almost exclusively of river sediment, a strong correlation is expected between the chemical composition of river suspended sediments and floodplain soils. Irion (1976) determined the concentrations of total and exchangeable cations in the fine fraction of suspended sediments from the Amazon main channel and demonstrated that both parameters decreased in the downstream direction.
Samples of fine suspended sediment (< 63 microns) collected by Martinelli (1986) from the Amazon main channel during July-August in 1985 showed a similar trend. The concentrations of Ca and Mg declined significantly (SRT, p = 0.09), K remained unchanged and the concentration of Na increased significantly (SRT, p = 0.05) in the downstream direction. These results suggest that the downstream decline in Ca and Mg concentrations in soils from the main channel floodplain may have been due to a change in the chemical composition of the river sediments. Another hypothesis for the observed variations in soil chemistry is that they reflect diagenetic changes in the soils, perhaps representing different stages of physical and chemical weathering.

Irion (1976) has suggested that the downstream reduction in cation concentrations is due, in part, to the reduction in montmorillonite in the clay fraction of the suspended sediments. In addition, the percent saturation of calcium adsorption sites of montmorillonite also declines downstream. Both of these changes result from the downstream dilution of suspended sediment and dissolved constituents by dilute water from lowland tributaries.

The lack of significant downstream trends for K during cruises 6 and 8 reflects an increase in K concentration due to the input of the Rio Madeira which tends to be rich in K. Once they enter the main channel the Madeira sediments undergo a seasonal cycle of deposition and resuspension associated with variations in the surface slope of the main channel. As a consequence, the supply of these sediments to the floodplain below the confluence of the Madeira is likely to vary.

Temporal Variations

Although a difference between sampling periods of only 3 months would not seem to be long enough to generate chemical differences for soils in normal conditions, it may be sufficient along the Amazon floodplain. It may be hypothesized that during the annual floodplain the "new rich" deposited sediment that comes from the Andes alters the soil chemistry.

Of the parameters considered, only magnesium and potassium varied significantly between cruises. The concentration of K in samples collected during the early falling water cruise (C8) was significantly higher (WT, p = 0.01) than those encountered during the other cruises while the concentration of Mg was highest during the early rising water cruise (C7). This suggests that the composition of river sediments was also relatively constant between cruises. The stability of floodplain soil chemistry may be due, in part, to the influence of the associated plant community, principally Gramineae (Junk and Howard-Williams 1983).

Many of these plants undergo a seasonal growth cycle with high levels of production as pointed out by Junk (1984), (e.g. 40 mt/ha/8 months of Paspalum repens) followed by rapid decomposition. Large quantities of cations are presumably taken up from the floodplain soils during the growth period and then returned when the plants decompose. By temporarily storing nutrients, the plants may act to equilibrate the gains (during high water) and losses (during low water) which would otherwise alter floodplain soil chemistry.

Conclusions

It is clear from these data that the chemistry of soils on the main channel and tributary floodplains are distinctly different. The Amazon main channel, which has extensive drainage in the Andes, has floodplain soils much richer in cations than its tributaries which have a larger proportion of lowland drainage. Soils from both the main channel and tributaries were higher than the
concentrations found for high-land (terra firme) soils. The main channel samples showed a decrease in cation concentration downstream.

From the point of view of soil fertility, the Amazonian várzea show a high potential for agricultural development. Soils are fertile and with no major problems in relation to availability of major nutrients for plants, but physical conditions such as porosity and moisture with consequent low aeration will definitely require management efforts for good agricultural production. This contrasts with the terra firme soils which posses better physical characteristics (good aeration and humidity) but are generally deficient in nutrients.

Acknowledgements

The authors are indebted to the skill of the crew of the L. M. Amanai, especially Miguel Rodrigues de Souza, Adamor Mendonca, and Pedro Inacio da Silva. Megumi Yamakoshi, John Hedges, and Robert Meade helped with field collections. Financial support for this work came from the Conselho Nacional de Desenvolvimento Cientifico e Tecnologico, Fundação de Amparo a Pesquisa do Estado de São Paulo, International Atomic Energy Agency Project BRA/OIO and National Science Foundation grant DEB 81-07522. Contribution number 29 of the CAMREX Project.

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