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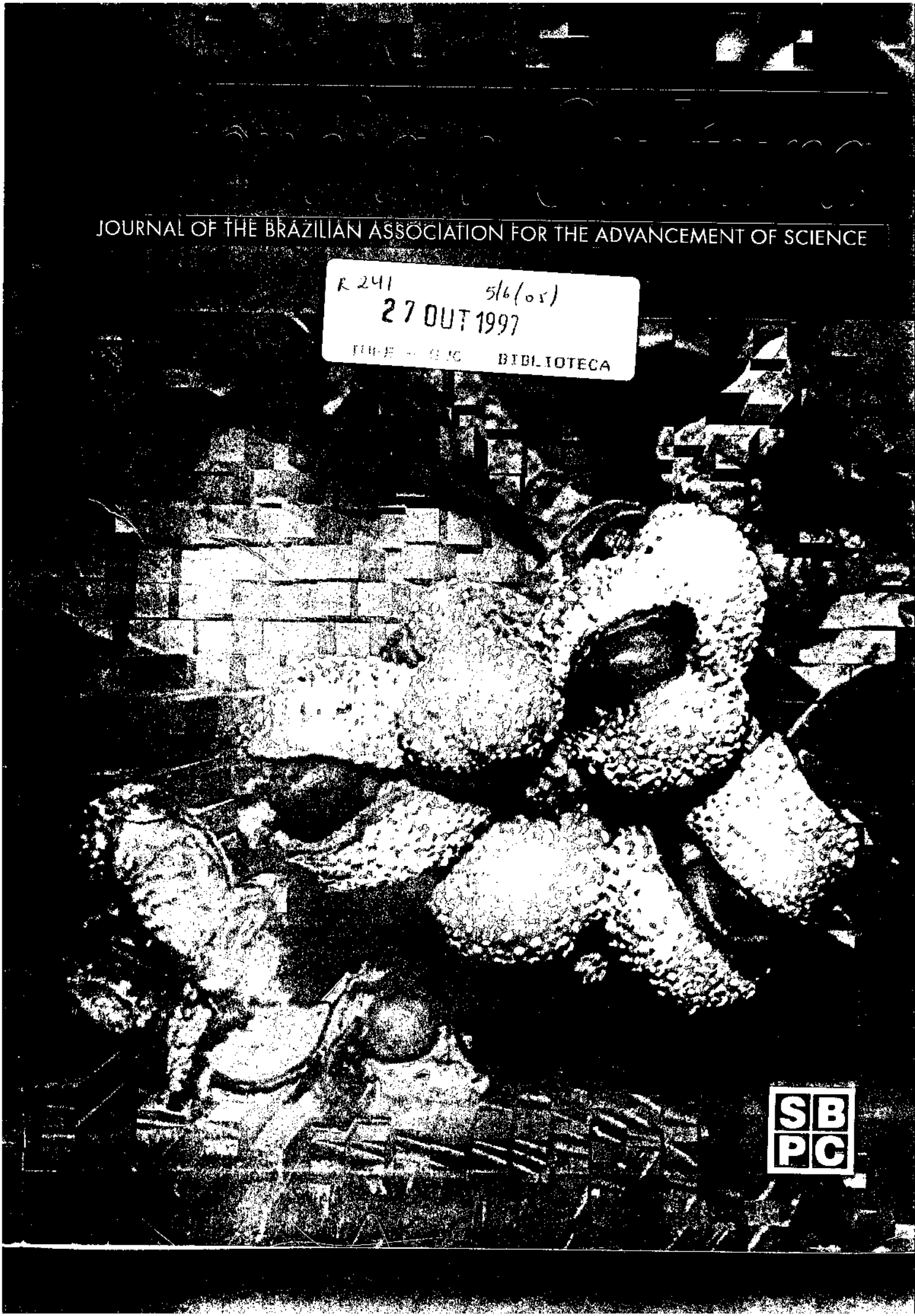

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Assessment of Amazon floodplain habitats using TM/Landsat data

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The size and diversity of the Amazon region make it difficult to know the area and the spatial distribution of its habitats. The use of satellite imagery can help to map those habitats. In this study, images acquired by the Thematic Mapper sensor on board of the American satellite Landsat-5 were used to map floodplain habitats within reach of the Amazon river between Parintins and Óbidos. The following habitats were mapped: Turbid water lakes and rivers, clear/black water lakes and rivers, mixed water lakes and rivers, aquatic vegetation stands, flooded nonforest vegetation and flooded forest vegetation. The extent of each habitat is an essential information to determine the contribution of the Amazon floodplain to the global methane budget.

O tamanho e a diversidade da Amazônia tornam difíceis conhecer a área e a distribuição espacial de seus habitats. O uso de imagens de satélite pode auxiliar o mapeamento destes habitats. Neste estudo, imagens do sensor Thematic Mapper (TM) a bordo do satélite americano Landsat-5 foram utilizadas para mapear habitats da planície de inundação do rio Amazonas entre Parintins e Óbidos. Os habitats mapeados foram: Lagos e rios de águas túrbidas, rios e lagos de águas claras e/ou negras, rios e lagos de águas mistas, bancos de vegetação aquática, vegetação não-florestal inundável e floresta inundável. A determinação da área ocupada por estes habitats é uma informação fundamental para se avaliar a contribuição da planície amazônica para o balanço global de metano

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In recent years several attempts have been made to estimate the methane flux (CH_4) from the Amazon river floodplain based upon ground-level measurements at a series of sites along the Amazon main stem, approximately from Tefé to Óbidos (1-5). The measurements were performed during the wet and dry seasons to account for the seasonality of the methane flux in three broad floodplain habitats: Open water, floating aquatic vegetation stands and flooded forests. A total of 600 measurements consistently showed that there are significant differences among these three habitats as sources of methane flux and that emissions from floating aquatic vegetation were higher and more variable than those from flooded forests (5). They also showed little consistent upriver to downriver trend, either for all data grouped together, or stratified by habitat type (5).

The extent of each habitat, however, is poorly known and is critical to the estimate of the overall contribution of the Amazon floodplain. The first unknown issues in this respect are the floodplain area and the temporal variation of the inundated area. Various estimates of the extent of the Amazon floodplain vary from 100,000 to 500,000 km^2 (3,5,6,7). The habitat area has been estimated in selected test sites along the Amazon main stem. Remote sensing data have been used to improve those estimates. The area occupied by open lakes was computed from 1:250,000 scale Side Looking Airborne Radar (SLAR) mosaics as 13% of the floodplain reach between the Purus and Negro rivers (8). A more recent study has used Thematic Mapper/Landsat data at two dates (high and low water) to estimate the proportion of the each floodplain habitat in the same reach. The figures are: 23 to 27% of open lakes, 10% of floating macrophyte stands and 64% of flooded forest.

Geomorphological studies (9) have shown that the Amazon main stem floodplain can be divided into five reaches according to features such as sinuosity, floodplain width, channel width and island area. At least three of these features are fundamental to the proportion of floodplain habitats: The floodplain width, the channel width and the island area. The channel width in relation to the floodplain width can give a rough idea of the proportion of open riverwater in the various reaches. As would be expected, the channel width increases steadily downstream except in the reach between Manacapuru and São José do Amariti where it decreases sharply. The same trend is observed for the number of islands. The average floodplain width, on the other hand, varies more erratically from an average of approximately 60 km near Jutica to a values as low as 20 km near Manaus. These results have at least two implications: The habitat proportions estimated for the Manacapuru reach may not be typical for the entire Amazon river main stem because this reach presents an anomalous geomorphology when compared to the other reaches; the geomorphological pattern of the reaches should guide the sampling site selection.

This paper reports an assessment of the proportion of the various floodplain habitats in a reach of the Amazon main stem between Parintins and Óbidos based on the visual interpretation of TM/Landsat color composition at the scale 1:250,000 from June to July 1992 (high water stage).

The floodplain limit in this study is geomorphological: A strip of relatively smooth land bordering a stream and overflowed at time of high water (10) and characterized by morphological features. There is a broader concept of floodplain (11) as being areas periodically inundated by the lateral overflow of rivers or lakes, and/or by direct precipitation. In this concept the floodplain area is an aquatic/terrestrial transition zone (ATTZ) because it alternates between aquatic and terrestrial environments. The floodplain conceived as a geomorphological unit shares some of the features of the ATTZ but comprises permanent lotic habitats (main channel), permanent lentic habitats (lakes) and the ATTZ. It does not include, however, areas outside the topographical unit of lowlands where the origin of the wetlands is related to processes other than river overflow.

The test site covers approximately 300 km of the Amazon river (Fig. 1) from Parintins (56°47'00"W and 2°45'00"S) to 50 km west of the Tapajós river mouth (54°52'30"W and 1°45'00"S). The average floodplain width varies from 30 to 35 km. The annual rate of channel change is less then 0.5% and much lower than those found in upstream reaches. The islands and lakes in this section are larger and rounder than in the upstream sections. Because the levee system in this reach is less continuous than in other reaches, water from the main stem can carry sediment onto the floodplain more frequently (9).

The Amazon river is a whitewater river, characterized by very large inputs of dissolved and particle-associated nutrients to the floodplain (12,13). This nutrient input results in dense forest on the levees, and a luxuriant herbaceous vegetation at low water on the mud flats and bars, and algal blooms and aquatic macrophytes in the lakes at high water (14).

Studies performed near Manaus showed the great species diversity of the herbaceous floodplain vegetation. The herbaceous plants were surveyed in a range 100 km upstream and downstream from Manaus (15). The authors collected 388 different herbaceous species in this region and classified them according their habitats, frequency and mode of existence (aquatic, aquatic with terrestrial phase, palustral etc). The results showed that only 12 species covering 3% of the total area were very abundant and 5 species were able to form large monospecific stands. Of the 17 abundant, dominant species, four are classified as aquatic macrophytes: *Pistia stratiotes*, *Scirpus cubensis*, *Eicchornia crassipes* and *Salvinia auriculata*. Six species are aquatic with a clearly evident terrestrial phase: *Echinochloa polystachya*, *Hymenachne amplexicaulis*, *Leersia hexandra*, *Oryzia perennis*, *Paspalum repens* and *Montrichardia arborecens*. Two species were classified as terrestrial but enduring long periods of submergence: *Cynodon dactylon* and *Paspalum fasciculatum*. Only five species are dominant in terrestrial habitats: *Alternanthera pilosa*, *A. brasili-*

Table 2 - Interpretation key used to characterize the floodplain boundary and floodplain habitats.

Mapping Unit	*Image features*	*Ground features*
Turbid water	Water bodies presenting cyan color in the TM composition	Corresponds to the whitewater rivers and lakes
Clear/black water	Water bodies presenting black color in the TM composition	Corresponds to both clear water and black water rivers which are not spectrally distinct in the TM images
Mixed water	Water bodies presenting a very subtle pattern of cyan mixed to the clear/black water bodies	Corresponds to lakes where the overflow of the Amazon river introduces water with high concentration of inorganic matter
Aquatic vegetation	Small elongated features located near the islands and border of lakes and rivers; characterized by light green and light cyan colors	Corresponds to the aquatic macrophytes mainly without a terrestrial phase
Flooded nonforest vegetation	A mixture of colors ranging from dark cyan, pink, magenta, dark magenta and yellowish. Floodplain patterns such as scroll bars, small round lakes, elongated lakes etc	This class encompasses the herbaceous vegetation present in the ATTZ as described by Junk and Piedade (15), including species with terrestrial phase, palustral habitats etc
Flooded forest vegetation	Green color, elongated shape following the river levees	This class corresponds to the areas of floodplain forest
Floodplain boundary	Geomorphological features typical of the floodplain	Geomorphological limit of the Amazon main stem floodplain

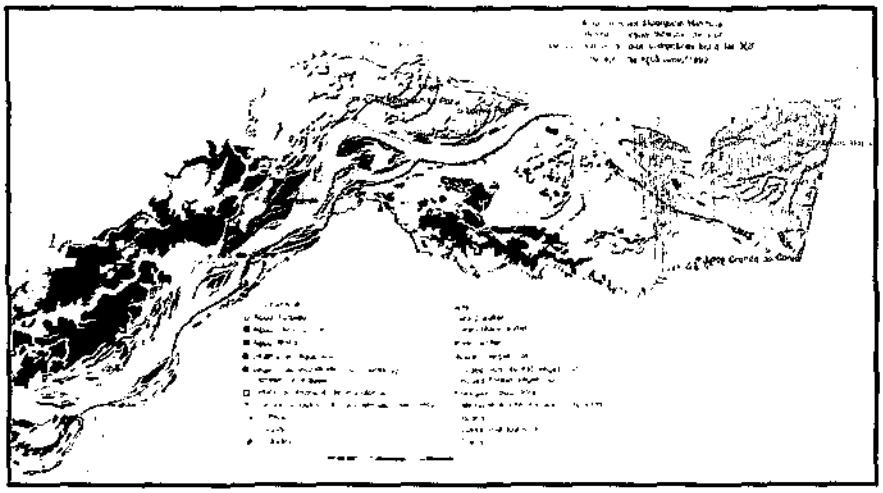

Figure 2. Amazon river floodplain habitats: Based on visual interpretation of TM/Landsat data color composites band TM 3(B), TM 4(R) and TM 4(G), June 1992.

habitats identified were: Turbid water, which corresponds to the whitewater rivers and lakes (12); clear/black water, which corresponds to both distinct types of water on the ground but which can not be separated on the basis of their spectral reflectance using broad band sensors (for discussions see References 18,19,20,21); mixed water which corresponds to the clear and/or black lake water receiving the overflow of whitewater from the Amazon river (for discussion see Reference 13); aquatic vegetation, which corresponds to the floating species; flooded nonforest vegetation includes all those species ranging from terrestrial herbaceous to aquatic species with a terrestrial phase (15); flooded forest, corresponding to the areas of forest which are periodically inundated during the high water stage.

The area occupied by each floodplain habitat and its proportion in relation to this floodplain reach can be seen in Table 3. The area occupied by the flooded nonforest vegetation is the largest and represents 45.5%. It presents an important difference in relation to the Purus-Negro reach (22) where the flooded forest vegetation makes up 67% of the floodplain.

Another important difference between the reaches regards the "open water" habitat, which in most of the methane estimations includes only the "lake open water". In Table 3, however, the turbid water habitat which is consists mainly of main stem water, represents 31% of the floodplain area at the high water stage. If the river open water and lake open water are taken into consideration in deriving the "open water habitat" contribution to the methane flux, the fraction of this habitat would be larger then that assumed in (5), representing 49.5% of the floodplain in this reach. If the river open water is neglected, the proportion of open water would drop to only 18.5%. The inclusion or not of river water as "open water habitat" may be, therefore, another important source of error in the estimation of methane flux from the floodplain. Low but measurable methane fluxes were determined from the central channel of the Amazon main stem, with an increased concentration towards the river banks (5).

Table 3 - Distribution of the floodplain habitats in the Parintins-Santarém reach.

Floodplain habitat	*Area (km²)*	*Percentage of the floodplain reach*
Turbid water	2471	31
Clear/black water	118	1.5
Mixed water	1356	17
Aquatic vegetation	312	3.9
Flooded nonforest vegetation	3630	45.5
Flooded forest vegetation	133	1.7
Floodplain	8020	100

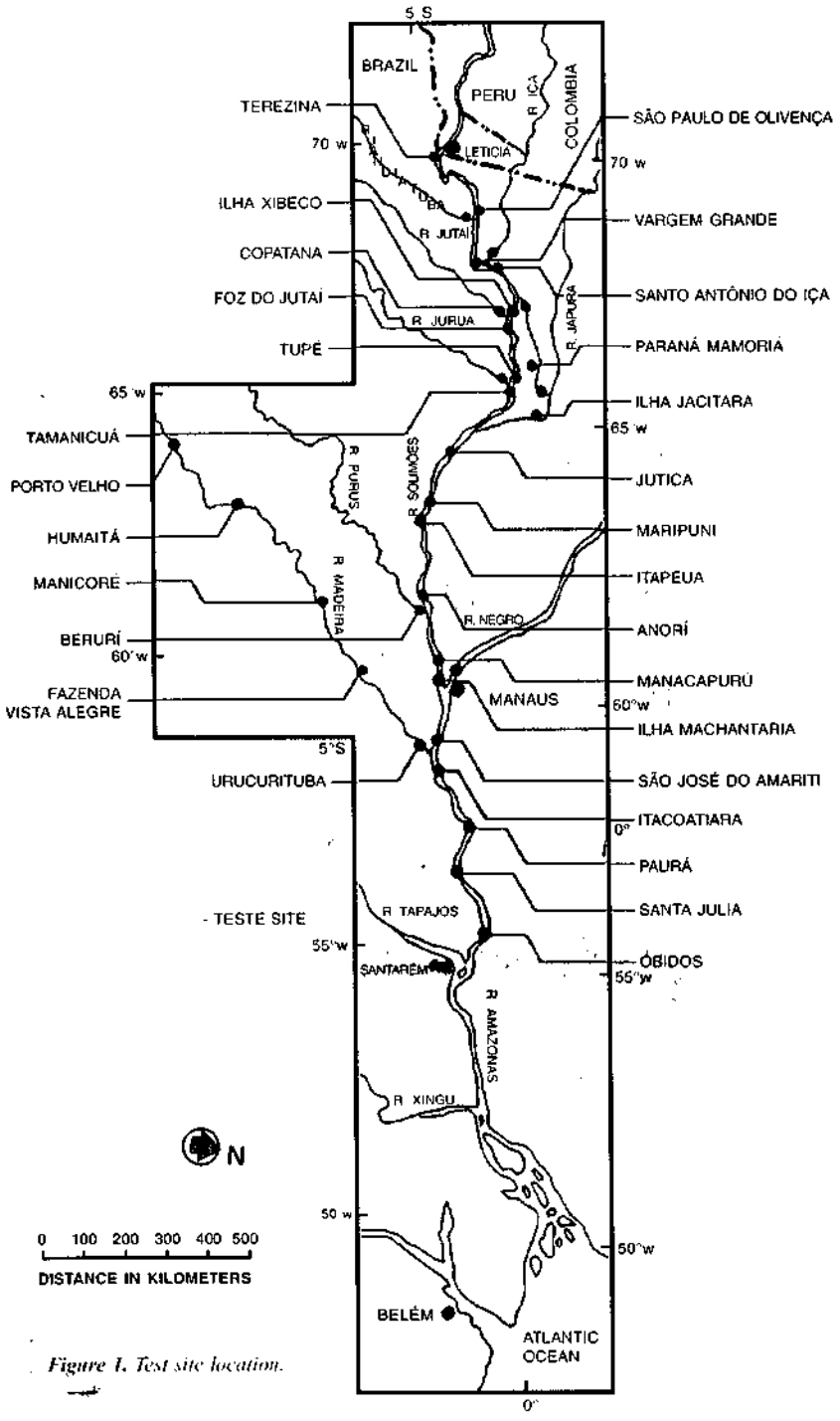

Figure 1. Test site location.

Table 1 - Landsat images used to derive the Amazon river floodplain habitats.

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ana, Paspalum conjugatum, Ludwigia densiflora and *Sorghum aundinaceum*.

Landsat Thematic Mapper (TM) images (Table 1) at the scale of 1:250,000 were obtained as color composites of bands TM3 (blue), TM4 (green) and TM5 (red). These images were visually interpreted in order to identify: The floodplain boundary and six different floodplain habitats. Table 2 describes the interpretation key used to identify those habitats.

The first step in the visual interpretation was to set the floodplain boundary on basis of the geomorphological features observed in the TM color prints such as: Point bars, depressions, floodplain channels (paranás), overbank deposits, scroll bars, ancient channel scars, terraces etc. The boundary identified using Landsat TM images was compared to the 1:250,000 RADAMBRASIL set and the differences were considered negligible. The boundaries were also checked against 1:250,000 topographical sheets.

The second step was to define the habitats which could be identified in the TM images. The classes identified can be grouped according to the classification used to produce estimates of the proportion of the habitats in this floodplain reach (5). The scheme could be expanded into a more complete habitat classification (16) when seasonal information derived from microwave active sensors become available.

The third step in the study was to prepare the maps to be inserted into a georeferenced data base (17). This step consisted in locating control points in the floodplain maps and in the topographical sheets. The area is partially covered by the following 1:250,000 topographical sheets: Parintins, Óbidos, Alenquer and Santarém. After the calibration phase, the maps were keyboarded and manipulated with the aid of a software developed by the Image Processing Division at the National Institute for Space Research. The fourth step involved the determination of the coordinates of the methane sampling sites (5) and their incorporation as an information layer in the data base. The area and the proportion of each floodplain habitat were determined. The spatial distribution of the methane samples were also analyzed.

Spatial distribution of floodplain habitats

Figure 2 shows the spatial distribution of the floodplain habitats in the reach between Parintins and Óbidos. The

Floating aquatic vegetation represents 3.9% of the floodplain and this is a much smaller percentage then that estimated (22) for the Purus-Negro reach (20%). As many species found in the flooded nonforest vegetation represent a gradient from rooted aquatic vegetation to terrestrial vegetation, one could assume that half of this area can be considered as a macrophyte-like vegetation. In this case, the fraction of floating mats would reach 26% in this reach, a proportion similar to that assumed in (5).

The spatial distribution of the methane flux sampling sites

The spatial distribution of some methane sampling sites can be observed in Figure 1. It does not represent all sampling sites, but includes the location of lakes and reaches where several sites were sampled. It is important to point out that sampling was peformed before ground position systems were available and the sites were located on topographical sheets and could not be recovered. In spite of these problems it is interesting to observe the following aspects: *1)* Some of the samples sites are not located in the Amazon main stem stricto sensu; *2)* the spatial distribution is very sparse.

Figure 2 shows that the number of sample sites is limited in relation to the extent and variability of the habitats. Although statistical analysis (5) has shown that the number of methane flux samples was sufficient to provide a standard error of the mean around 20%, that analysis does not account for the diversity of environmental conditions in the floodplain.

Conclusions

The analysis of the results of this study shows that TM/Landsat color composites can be used to map the Amazon floodplain habitats during high water level. Although the classes identified are limited to the spectral information content of TM data, one can classify the aquatic environment into at least three classes of water which might influence in the methane flux: Turbid, mixed and "nonturbid clear and/or black water". The first two types of water hosts a much more productive floating vegetation, and therefore play a more important role in the methane flux.

Finally, the analysis of the spatial distribution of the sampling sites in the floodplain points to the need for more in situ measurements of methane emission. The spatial distribution shows that in spite of the sampling effort this reach as a whole is largely undersampled. ■

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