Regionalization of methane emissions in the Amazon Basin with microwave remote sensing

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Abstract

Wetlands of the Amazon River basin are globally significant sources of atmospheric methane. Satellite remote sensing (passive and active microwave) of the temporally varying extent of inundation and vegetation was combined with field measurements to calculate regional rates of methane emission for Amazonian wetlands. Monthly inundation areas for the fringing floodplains of the mainstem Solimões/Amazon River were derived from analysis of the 37 GHz polarization difference observed by the Scanning Multichannel Microwave Radiometer from 1979 to 1987. L-band synthetic aperture radar data (Japanese Earth Resources Satellite-1) were used to determine inundation and wetland vegetation for the Amazon basin (< 500 m elevation) at high (May–June 1996) and low water (October 1995). An extensive set of measurements of methane emission is available from the literature for the fringing floodplains of the central Amazon, segregated into open water, flooded forest and floating macrophyte habitats. Uncertainties in the regional emission rates were determined by Monte Carlo error analyses that combined error estimates for the measurements of emission and for calculations of inundation and habitat areas. The mainstem Solimões/Amazon floodplain (54–70 W) emitted methane at a mean annual rate of 1.3 Tg C yr⁻¹, with a standard deviation (SD) of the mean of 0.3 Tg C yr⁻¹; 67% of this range in uncertainty is owed to the range in rates of methane emission and 33% is owed to uncertainty in the areal estimates of inundation and vegetative cover. Methane emission from a 1.77 million square kilometers area in the central basin had a mean of 6.8 Tg C yr⁻¹ with a SD of 1.3 Tg C yr⁻¹. If extrapolated to the whole basin below the 500 m contour, approximately 22 Tg C yr⁻¹ is emitted; this mean flux has a greenhouse warming potential of about 0.5 Pg C as CO₂. Improvement of these regional estimates will require many more field measurements of methane emission, further examination of remotely sensed data for types of wetlands not represented in the central basin, and process-based models of methane production and emission.

Keywords: Amazon, biogeochemistry, carbon, methane, microwave remote sensing, wetlands

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Introduction

Tropical wetlands are known to be a major source of methane to the atmosphere and are estimated to comprise about 60% of the flux from all natural wetlands (Bartlett & Harriss, 1993). However, regional and global estimates of methane emission vary considerably and have large uncertainties (Matthews & Fung, 1987; Aselmann & Crutzen, 1989; Schlesinger, 1997). Much of the uncertainty stems from few measurements of fluxes, especially in remote regions (Bartlett & Harriss, 1993). Even for locations with numerous field measurements of fluxes, extrapolation...
Our purpose is to combine previously published field measurements of methane fluxes with information on the temporally varying extent of inundation and vegetation of Amazonian wetlands, derived from microwave remote sensing, to calculate regional rates of methane emission from Amazonian wetlands to the atmosphere. The majority of field measurements of emission and the most thorough analyses of inundation and vegetation are available for the floodplains and rivers of the central basin within Brazil. Hence, we provide a detailed analysis for the mainstem Solimões/Amazon floodplain from 54 to 70°W, extend our analyses to major tributaries within a 1.77 million square kilometers quadrat in the central basin, and offer an extrapolation to the whole basin below the 500 m contour. We also discuss recent estimates for tributaries of the Negro River and summarize results from reservoirs in the Amazon. In addition, we provide estimates for large tropical savanna floodplains within and outside of the Amazon basin in South America.

Habitat descriptions

Overview of wetlands within the Amazon basin

Vegetative cover of wetlands within the Amazon basin varies as a function of hydrologic regime and solute and sediment content of the waters (Klinge et al., 1990; Junk, 1993, 1997; Junk & Furch, 1993). The large rivers usually have unimodal annual floods that last for several months and inundate extensive floodplains covered by open water, flooded forests and aquatic macrophytes. The waters vary from sediment-laden, whitewater rivers (e.g. Amazon, Madeira, Purus, Jurú and Jagurá) rich in dissolved nutrients to the relatively sediment-free blackwater rivers (e.g. Negro) with high dissolved organic carbon and low levels of nutrients and other solutes, to clearwater rivers (e.g. Tapajós and Xingu) that tend to be intermediate in sediment load and solute content. Smaller rivers and streams display polymodal inundation of their narrow fringing floodplains, but the many thousands of kilometers of these habitats lead to their regional importance. In portions of the basin with a pronounced dry season, savannas occur and are exposed to seasonal flooding from local rain and rivers (e.g. Roraima in Brazil and Llanos de Mojos in Bolivia). Poorly drained podzolic sands cover considerable areas, and their acidic and nutrient-poor waters can support flooded caatinga vegetation. Extensive wetlands covered by nearly monospecific stands of palms, such as Mauritia flexuosa, occur in regions including the upper Negro River in Colombia, the upper Amazon in Peru, and the Amazon estuary.

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of these results to regional scales suffers from the lack of quantitative information on seasonal and interannual variations in vegetative cover and inundation (Devol et al., 1990). Recent advances in remote sensing of land cover and inundation offer the basis to improve regional estimates (Melack & Hess, 1998; Prigent et al., 2001).

Methane is generated by anaerobic degradation of organic matter under conditions where anaerobic respiration by bacteria is limited by the paucity of alternate electron acceptors (Fenchel et al., 1998). The inundation of organic-rich sediments in freshwater wetlands, which generally have low concentrations of alternate electron acceptors, results in anoxic conditions favoring methane production. Emission to the atmosphere of methane from submerged sediments occurs via diffusion across the air–water interface, ebullition, and through the stems of plants. The amount of methane released to the atmosphere can be reduced considerably through methane oxidation by methanotrophic bacteria.

The Amazon basin covers a large portion of the humid neotropics and contains riverine floodplains and other wetlands that are estimated to exceed 1 million square kilometers in area (Junk 1993, 1997). The flooded forests, lakes and floating macrophytes of Amazonian wetlands are believed to be globally significant sources of tropospheric methane (Bartlett et al., 1988). Evasion of CO₂ from these wetlands to the atmosphere, extrapolated over the whole basin, is at least 10 times the fluvial export of organic carbon to the ocean and is of comparable magnitude to some estimates of carbon sequestration by upland forests (Richey et al., 2002).

Remote sensing makes possible the quantitative analysis of inundation and vegetative cover in wetlands in the Amazon basin. Optical remote sensing has been used to distinguish and map vegetation types in the Amazon, when favorable conditions allow acquisition of images (Melack et al., 1994; Mertes et al., 1995; Novo et al., 1997). Observations with high-resolution optical sensors are frequently impeded by cloud cover or smoke over much of the Amazon basin, precluding the monthly or better temporal resolution required to document seasonally varying flood extent. Alternatively, passive microwave sensors and active microwave systems (radar), which are much less influenced by clouds and smoke and can penetrate vegetation at some wavelengths, have been employed to detect the presence of surface water and, in the case of radar, to observe the vegetative structure (Sippel et al., 1994; Hess et al., 1995; Costa et al., 1998; Melack & Hess, 1998). Repetitive passive microwave observations by satellites reveal the seasonal changes in flood extent that characterize most tropical wetlands (Hamilton et al., 2002).
Habitats in the central Amazon floodplain

Within the floodplains of the central Amazon basin, which is the focus of our analyses, the major wetland habitats are represented by a mosaic of lakes and channels (open waters), flooded forests, woodlands and shrublands, and herbaceous plant communities. Thousands of waterbodies varying widely in size and shape occur in the fringing floodplains; these waters lie in depressions that are inundated most or all of the year (Sippel et al., 1992). Water and solutes are supplied to floodplain waterbodies from direct precipitation, seepage, local runoff and adjacent rivers in varying proportions (Forsberg et al., 1988; Lesack & Melack, 1995). Inventories of the floristic composition of floodplain forests indicate that many species are widespread, that a successional sequence occurs from recently colonized areas to mature forests, and that the length of inundation influences the vegetation composition (Worbes et al., 1992; Piedade et al., 2001). Primary production of forests tends to increase with stand age (Worbes, 1997). Herbaceous plants form extensive areas of floating emergent macrophytes during inundated periods. Three grasses, *Paspalum repens*, *P. fasciculatum* and *Echinochloa polystachya*, often comprise most of the biomass; less abundant, nongrass genera include *Eichhornia*, *Salvinia* and *Oryza*. These communities, and especially *Echinochloa*, are very productive and undergo an annual cycle of growth and decay linked to the changing water levels (Piedade et al., 1991; Junk & Piedade, 1993).

Methods

Remote sensing data

Synthetic aperture radar (SAR) can detect flooding beneath a forest canopy because smooth water surfaces produce strong specular reflections, which are in turn reflected back toward the sensor by branches and trunks. The returns received from flooded forest stands are brighter than those from unflooded stands, particularly using horizontally polarized L-band radar (Hess et al., 1995; Wang et al., 1995). A similar mechanism enables flooded marsh to be distinguished from unflooded marsh or other herbaceous vegetation such as pasture.

The mosaicking of SAR images of the Amazon acquired by the Japanese Earth Resources Satellite-1 (JERS-1) during low- and high-water stages (Rosenqvist et al., 2000; Siqueira et al., 2000; Chapman et al., 2002) has made possible, for the first time, basin-wide delineation of wetland area and vegetative structure. Hess et al. (2003) have developed a wetlands mask and a classification of vegetative–hydrologic state using the JERS-1 mosaics for a 1.77 million square kilometers quadrat (Fig. 1), extending 18° in longitude by 8° in latitude and covering about one-third of the lowland Amazon basin (defined as the area less than 500 m in elevation).

The first step in wetlands mapping using the radar mosaics was creation of a wetlands mask, a binary classification denoting wetland and nonwetland areas (Hess et al., 2003). Wetlands were defined as: (1) areas that were inundated during either or both JERS-1 mosaic acquisition periods and (2) areas not flooded on either date, but which were adjacent to or surrounded by flooded areas and displayed landforms consistent with wetland geomorphology. Creation of a wetlands mask permitted calculation of total area subject to inundation and eliminated from the classification process nonwetland areas that might produce backscattering similar to that of wetlands. Homogeneous
regions were identified using automated image segmentation and polygon clustering, and the resulting polygons were edited manually. Wetland extent was delineated with an overall accuracy of 95%.

Following wetlands delineation, areas within the wetlands mask were classified into cover states for both seasons (Hess et al., 2003). Cover states consist of land cover classes determined by vegetation physiognomy (nonvegetated, herbaceous, shrub, woodland and forest) and by inundation state (flooded or nonflooded). Shrubs are defined as woody plants with multiple stems, which lack definite crowns and are less than 5 m tall; the woodland cover state is defined to have less than 60% canopy cover. This vegetative-hydrologic classification scheme meets the criteria for a 'functional parameterization' of wetlands (Sabagian & Melack, 1998), with classes suitable for biogeochemical modeling of wetland functions. For the cover state mapping, a rule-based classifier was applied to the two-season backscattering coefficients of individual pixels. Decision rules were derived by analysis of backscattering responses for training polygons and of values reported in the literature for these communities (Hess et al., 1995; Costa et al., 2002). Accuracy of the classified mosaics, which have a pixel size of 100 m, was assessed using geocoded, high-resolution digital videography (Hess et al., 2002). Four aerial videographic surveys were conducted during high- and low-water periods to acquire data sets suitable for training of classification algorithms and assessment of classification accuracy. On both low- and high-water mosaics, user's accuracy for open water was greater than 93%. User's accuracies were 87% (high water) and 63% (low water) for flooded forest, and 71% (high water) and 73% (low water) for aquatic macrophytes (Hess et al., 2003).

Because river stage is closely related to extent of inundation in the large riverine floodplains of the Amazon (Hamilton et al., 2002), long-term stage records provide a basis for relating the inundated extent imaged on the JERS-1 mosaics to both long-term average conditions and to conditions during the Scanning Multichannel Microwave Radiometer (SMMR) observation period. Based on 1903–1999 river stage records for Manaus, which typically show a seasonal change of ca. 10 m, the May–June 1996 JERS-1 mosaic imaged a typical annual maximum stage (36 cm higher than the long-term mean annual maximum) and the October 1995 low-water mosaic imaged a lower than normal minimum stage (300 cm lower than the long-term mean annual minimum). River stages at other mainstem Solimões/Amazon River sites were similar to average high-water conditions on the high-water mosaic, and 130–380 cm lower than the average annual minimum on the low-water mosaic. High-water stage was not optimally timed for areas south of about 6°S and the dual-season mosaics captured less than 80% of the range between high- and low-water stages for tributary floodplains around the margins of the central Amazon study quadrat (Hess et al., 2003). For mainstem and lower tributary sites in the central and eastern parts of the study quadrat, the range captured was larger than average, because of the unusually low water levels on the 1995 mosaic.

Satellite-borne passive microwave sensors can record patterns of seasonal inundation in large floodplains and wetlands (Sippel et al., 1998). Passive microwave observations reveal the presence of surface water beneath cloud cover and vegetation. For the study of land surface features, the effects of atmospheric variability can be significantly reduced by calculating the difference between vertically and horizontally polarized brightness temperatures at 37 GHz. Sippel et al. (1998) determined seasonal and interannual variations in inundation for the mainstem Solimões/Amazon floodplain in Brazil based on an analysis of the 37 GHz polarization difference observed by the SMMR on the Nimbus-7 satellite. Flooded area was estimated at monthly intervals from January 1979 through August 1987 using mixing models that account for major landscape types with distinctive microwave emissions. Hydrogeomorphic subregions were delineated and open-water area independently determined from side-looking airborne radar or Landsat images as part of the procedure. The algorithms were developed and calibrated by drawing on multiple sources of information on geomorphology, vegetation and inundation, and the results were validated by comparison with river stage records in areas of floodplain where inundation is known to be controlled by a large river. Based on Sippel et al.'s (1998) passive microwave analyses for a 9-year period, the total area along the mainstem Solimões/Amazon River (70–54°W) that was subject to flooding, although not all at the same time, was 94 700 km². Our estimate for floodable area based on the JERS-1 mosaic for the same area agrees closely at 95 400 km².

Field measurements

Methane emission rates from the central Amazon floodplain have been measured using chambers in a variety of habitats and during various stages in the seasonal flood cycle (Bartlett et al., 1988, 1990; Crill et al., 1988; Devol et al., 1988, 1990, 1994; Wassmann et al., 1992; Wassmann & Thein, 1994; Engle & Melack, 2000). Emission rates have also been measured for the mainstem Solimões/Amazon River channel (Richey et al., 1988) and in the Jau River floodplain within the Negro River basin (Rosenqvist et al., 2002). Extrapolation of these measurements to the overall
region requires consideration of how well they represent
the mean annual emission from those habitats, as well as
how to link the measurements to the various wetland
environments beyond the well-studied central Amazon
floodplain. As Wassmann & Martius (1997) note, the
published results range widely among habitats, and the
relative magnitude of the fluxes, when habitats are
compared, is not fully consistent. Potential reasons for
these differences and variability include undersampling
of the full extent of diel, episodic (e.g. Engle & Melack,
2000), seasonal and interannual variations; the small
area captured by the floating chambers, especially in
light of the importance of ebullition which is very
patchy in time and space and accounts for 20–80% of the
emission; and local to regional differences in the
hydrological and ecological conditions. Further uncer-
tainties in assessment of regional methane emission
include the lack of measurements of the floodplain soils
during transitions between drying and wetting (cf.
Smith et al., 2000 for the Orinoco floodplain).

Devol et al. (1990) reported results from nearly
monthly measurements of methane emission made in
eight lakes near Manaus separated into open water,
flooded forest and herbaceous macrophyte habitats.
Although from a limited area, these results are the only
sampling of seasonal variations at the same sites
through a full year. In addition, Devol et al. (1990)
compared methane flux measurements from high- and
low-water cruises along a 1500 km reach of the
mainstem Solimões/Amazon floodplain with monthly
data from the lakes near Manaus. They found no
statistical differences between the data from the cruises
and lake surveys for either flooded forests or open
water but found that in waters containing aquatic
macrophytes high-water emission rates were signifi-
cantly higher than those at low water. Devol et al.’s
(1990) results that combine the floodplain survey with
the seasonal lake data are well suited to our require-
ments for calculations of regional fluxes because they
are extensive in space and span a full year at several
locations. Further, Bartlett & Harriss (1993) examined
all the available measurements of methane emission for
the Amazon basin, and the average emission rates they
selected for aquatic macrophytes, flooded forests and
open water were similar to the means reported by
Devol et al. (1990). To determine habitat-specific fluxes
for our calculations of regional emissions for the
mainstem Solimões/Amazon floodplain and the central
basin as well as for the error analysis (see below), we
required access to the individual measurements sum-
marized in Devol et al. (1990), and these were made
available (A. Devol, personal communication). Some of
our means (Table 1) differ slightly from those reported
in Devol et al. (1990).

Richey et al. (1988) combined measurements of
dissolved methane concentrations in the mainstem
Solimões/Amazon with estimates of air–water
gas-exchange rates (Devol et al., 1987) to determine a
diffusive evasion rate of 3.3 mg CH₄ m⁻² day⁻¹ for the
mainstem river channel. We applied this value to our
calculations in which river channel is a separate
category of open water.

We express the emission rates used in our regiona-
lizations as kg C km⁻² day⁻¹ or Mg C km⁻² day⁻¹,
where Mg is 10⁶ g. We do so for ease in extrapolation
to large areas and for ready comparisons with other
terms in the carbon cycle. Regional totals are usually
expressed as Tg C, where Tg is 10¹² g; occasionally
Gg C, where Gg is 10³ g.

Regional analyses

Combining our remote sensing-derived calculations of
the temporal variations in inundated area and vegeta-
tive cover with methane emissions measurements is an
upscaling exercise generically similar to that discussed
by Van Bodegom et al. (2002) and to that performed by
Bartlett et al. (1989). Our approach utilized a nested
design in which we regionalized the data to increas-
ingly larger areas. To quantify the uncertainties we
employed a Monte Carlo error analysis that incorpo-
rated uncertainties associated with each term in our
calculations. We also estimated interannual variations
in inundation to allow comparison with uncertainty.

Our calculations for the Amazon basin were per-
formed on regions delineated by hydrological and
geomorphological criteria and based on the availability
of information on inundation, vegetative cover and

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<tr>
<th>Aquatic habitat</th>
<th>n</th>
<th>Mean</th>
<th>SD</th>
</tr>
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<tbody>
<tr>
<td>Aquatic macrophyte (high)</td>
<td>66</td>
<td>243</td>
<td>54</td>
</tr>
<tr>
<td>Aquatic macrophyte (low)</td>
<td>55</td>
<td>92</td>
<td>25</td>
</tr>
<tr>
<td>Flooded forest</td>
<td>58</td>
<td>91</td>
<td>40</td>
</tr>
<tr>
<td>Open water</td>
<td>165</td>
<td>38</td>
<td>6</td>
</tr>
</tbody>
</table>

High and low refer to values during high and low water levels
as designated in Devol et al. (1990).
methane emissions. We calculated methane emission separately for the following areas (Fig. 1): (1) the mainstem Solimões/Amazon floodplain from 54 to 70°W (reaches 1–11 of Sippel et al., 1998), and two subdivisions of this reach (reaches 1–8 and 9–11; Sippel et al., 1998); (2) all wetlands within the 1.77 million square kilometers quadrat analyzed by Richey et al. (2002) and Hess et al. (2003) and (3) the whole Amazon basin below the 500 m contour. In addition, methane emissions were estimated for two seasonally flooded savannas within the Amazon basin (Roraima in the Branco River basin, Brazil, and the Llanos de Mojos in the Madeira River basin, Bolivia), as well as three extensive wetlands outside of the basin (Bananal Island, the Pantanal and the Llanos del Orinoco). Published estimates of methane emission rates for Amazonian reservoirs and blackwater tributaries of the Negro River are also summarized and evaluated.

Classification within the wetland mask of the JERS-1 quadrat distinguished open water, flooded and un-flooded forest, flooded woodland, flooded and un-flooded shrubland, flooded herbaceous vegetation, nonflooded herbaceous vegetation or bare ground, and a small mixed category (Hess et al., 2003). For the purpose of calculating methane emission, we used only flooded classes and combined classes to be compatible with the habitats for which there are methane emission measurements. The flooded woodland habitat commonly has floating macrophytes covering much of the water’s surface, and is therefore added to the floating macrophyte area for calculation of methane emission. In contrast, the flooded shrub habitat, with its dense canopy cover, does not have floating macrophytes and was added to the flooded forest habitat. The small mixed class was added to the floating macrophyte category because it commonly occurs along channel edges where herbaceous plants tend to grow. For the mainstem Solimões/Amazon River, river channel areas were obtained from Sippel et al. (1998) and accounted for separately from the rest of the open water category.

Regional fluxes \( F \) (in units of Tg C yr\(^{-1} \)) for a whole region were calculated using the general expression:

\[
F = \sum_{j=1}^{4} \sum_{i=1}^{12} t_i A_{ij} f_{ij},
\]

where \( t \) is the number of days per month, \( f \) is methane emission (expressed as kg C km\(^{-2} \) day\(^{-1} \) for each habitat), \( A \) is the flooded area of each habitat at each month for the region, \( i \) is each month incremented from 1 to 12, and \( j \) is each habitat (i.e. floating macrophytes (1), flooded forest (2), open water (3) or mainstem river channel (4)).

More specifically, our calculations for the fringing floodplain of the Solimões/Amazon River in Brazil from 70 to 54°W were done as follows: (1) The region represented by fringing floodplains was delineated based on geomorphology as indicated by side-looking airborne radar images from the RADAMBRASIL project (Sippel et al., 1992), SMMR analyses of inundated area (Sippel et al., 1998) and JERS-1 analyses of inundation, vegetation, and geomorphology (Hess et al., in press). (2) Monthly mean and maximum and minimum inundation areas for the time period January 1979 through August 1987 were obtained from the SMMR analyses of Sippel et al. (1998). (3) Vegetative cover classes at high- and low-water levels for aquatic habitats in each reach were obtained from the JERS-1 analyses (Hess et al., 2003). (4) Changes in vegetative cover were interpolated between the high and low estimates by recombining the two sets of fractional coverage weighted linearly by proximity to the time of acquisition of the high- and low-water data. Multi-temporal measurements at selected sites were used to validate this approach. (5) Methane emissions for each habitat, as described above, were then multiplied by the monthly estimates of the inundated area occupied by each habitat. (6) Areal emission rates were summed over the annual period for each reach.

Our calculations for all the wetlands within the 1.77 million square kilometers quadrat, which was also analyzed by Richey et al. (2002) and Hess et al. (2003), were done as follows: (1) Twenty-five basins tributary to the mainstem floodplain lying within the quadrat were delineated (E. Mayorga, J. E. Richey, personal communication). (2) The areas within the wetland mask and of associated aquatic habitats at high- and low-water were extracted from the JERS-1 mosaic based on Hess et al. (2003). (3) Multiyear stage data from each tributary basin were used to compute mean monthly stage (Richey et al., 2002). A normalized hydrograph for the nearest neighboring basin with similar climatology was used for the five basins without gauging records. To interpolate the inundated areas from the high- and low-water JERS-1 values to a full year, the mean monthly stage data were employed under the assumption of the temporal coherence between stage height and areal extent of inundation. Sippel et al. (1998) and Hamilton et al. (2002) demonstrate that this assumption is reasonable for floodplains bordering large rivers, including the Amazon River, based on their comparison of stage with inundation derived from the SMMR data. (4) Changes in vegetative cover were interpolated between the high and low estimates by recombining the two sets of fractional coverage linearly weighted by proximity to the time of acquisition of the high- and low-water data. As mentioned above within the
description of the production of the wetland mask and elaborated in Hess et al. (2003), the validity of this assumption is weaker on the upper tributary reaches included in the quadrat and is weakest in the southwestern region when compared with the mainstem Solimões/Amazon River because of the different seasonality in those areas. (5) Methane emissions measured for each habitat were multiplied by the monthly estimates of area occupied by each aquatic habitat. (6) Areal emission rates were summed for each basin and for the whole quadrat; the annual emission for the mainstem Solimões/Amazon floodplain was added to the total for its tributaries.

We performed an error analysis for the terms in Eqn (1) for methane flux (f) and flooded habitats (A) using Monte Carlo methods. Uncertainties expressed as the standard deviation (SD) of means in the emission rates for open water, flooded forests and floating macrophytes (Table 1) were estimated by bootstrapped sampling of the set of individual measurements reported in Devol et al. (1990). We did not use the standard errors reported by Devol et al. (1990) because the emission data are not normally distributed.

Uncertainties in the areas of wetland habitats were estimated with class probabilities derived from error matrices based on randomly located test pixels (Hess et al., 2003) and sampling frequencies derived from mapped class proportions in the fringing floodplains of the Solimões/Amazon mainstem and in the 1.77 km² central quadrat (Table 2). The uncertainties, which reflect both the degree of confusion between classes and the relative areas of the classes for each date and region, range from 2% to 13%. A normal distribution with a SD of 25% of the mean was used for the SMMR estimates of inundated area per month based on the sensitivity analysis in Sippel et al. (1998). A normal distribution with a SD of 10% of the mean was used for open water in the Solimões/Amazon River channel based on Sippel et al. (1998).

Results

Mainstem Solimões/Amazon River in Brazil

Monthly variations in areal extent of the aquatic habitats used in the calculations of methane emission for the mainstem Solimões/Amazon floodplain and for the western and eastern reaches of the mainstem are illustrated in Fig. 2. For the whole mainstem reach, flooded forest varied from 6700 to 34,400 km², aquatic herbaceous macrophytes from 6900 to 14,000 km², and floodplain open water (river channels excluded) from 1500 to 11,000 km². The western reach has a considerably greater proportion of flooded forest than the eastern reach.

Mean annual methane emission rates (Tg C yr⁻¹) are about the same for aquatic macrophyte-dominated habitats (0.63) and flooded forests (0.61) and are lowest for open water (0.09) and river channels (0.008) (Table 3). The total annual rate of methane emission for the mainstem floodplain has a mean of 1.3 Tg C yr⁻¹, and a SD of 0.3 Tg C yr⁻¹.

Most of the uncertainty in the regional annual fluxes is associated with uncertainty in the measurements of methane emission (Fig. 3). For example, if the SD of the mean for the annual rate of emission for the mainstem floodplain is computed without including the error associated with measurements of emission rates, the SD is 33% of the full SD (Table 3). As discussed above, measurements of emissions, especially those made in floating macrophytes or under conditions conducive to ebullition, are highly variable. In contrast, the regional calculations of areal extent of flooded habitats from the remote sensing data are more robust than might be

| Table 2 | Monte Carlo-based uncertainties (standard deviation as % of mean) of areal estimates of high-water habitats (A) and low-water habitats (B) |
|------------------|-----------------|-----------------|-----------------|-----------------|
|                 | Open water      | All non-flooded | Aquatic macrophyte | Flooded forest |
| (A) High water  |                 |                 |                   |                 |
| Central basin   | 3.9             | 6.1             | 7.2               | 2.9             |
| Mainstem W      | 4.0             | 6.0             | 7.3               | 2.9             |
| Mainstem E      | 1.9             | 9.9             | 5.4               | 4.6             |
| Mainstem W + E  | 2.9             | 8.2             | 7.4               | 2.8             |
| (B) Low water   |                 |                 |                   |                 |
| Central basin   | 4.9             | 2.5             | 8.2               | 7.9             |
| Mainstem W      | 5.4             | 2.2             | 9.6               | 8.0             |
| Mainstem E      | 2.3             | 3.0             | 7.4               | 13.1            |
| Mainstem W + E  | 3.8             | 2.4             | 9.1               | 8.9             |

Solimões/Amazon River reaches and central basin quadrat are indicated on Fig. 1.
initially assumed based on the producer’s and user’s accuracies (Hess et al., 2003). User’s accuracies (which are input to the Monte Carlo simulation) indicate how likely it is that a pixel mapped into a given class actually belongs to that class. In contrast, the error analysis is concerned with aggregate estimates. Therefore, for example, errors introduced by forest pixels being misclassified as macrophytes tend to be balanced by macrophyte pixels misclassified as forest. Uncertainty was also reduced by lumping together habitat types.

To illustrate aggregate sources of uncertainty and interannual variation in the regional methane emission estimates, we combined our uncertainty estimates for the terms in Eqn (1) with interannual variations in inundation as reported by Sippel et al. (1998). The full

Table 3 Annual methane emission (Tg C yr⁻¹) from each floodplain aquatic habitat and from the river channel of the Solimões/Amazon mainstem

<table>
<thead>
<tr>
<th>Aquatic habitat</th>
<th>Methane emission (Tg C yr⁻¹)</th>
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<tbody>
<tr>
<td>Aquatic macrophyte</td>
<td>0.63</td>
</tr>
<tr>
<td>Flooded forest</td>
<td>0.61</td>
</tr>
<tr>
<td>Open water</td>
<td>0.087</td>
</tr>
<tr>
<td>River channel</td>
<td>0.0078</td>
</tr>
<tr>
<td>Total</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Means and standard deviation (SD) of the means (derived from Monte Carlo error analysis) are presented.
range of annual methane emission for the combined western and eastern mainstem varied from 0.67 Tg C yr\(^{-1}\) for the minimum area flooded to 2.4 Tg C yr\(^{-1}\) for maximum area flooded (Fig. 3).

Central Amazon quadrat

Twenty-five major watersheds tributary to the mainstem Solimões/Amazon River occur partially or fully within the 1.77 million square kilometers quadrat examined by Richey et al. (2002) and Hess et al. (2003). Maximum flooded areas (km\(^2\)) within the quadrat for the large basins include 45,830 (Negro), 30,760 (Purus), 27,170 (Jurua), 20,260 (Japura), 20,580 (Madeira) and 12,860 (Içà). Moderate-to-small basins include the Uatumã (including Balbina Reservoir: 9,800), Coari (6310), Javari (9080), Tefé (3290) and Xingu (4370). The proportion of methane emission associated with the major aquatic habitats varied among the catchments. When summed over 12 months for all catchments and habitats including the mainstem Solimões/Amazon floodplain, methane emission had a mean of 6.8 Tg C yr\(^{-1}\) and a SD of 1.3 Tg C yr\(^{-1}\). Variability associated with interannual differences in inundation would extend this range.

Discussion

Extrapolation to the entire Amazon basin (<500 m above sea level)

To extrapolate our analyses to the whole Amazon basin adds considerable uncertainty because of the lack of direct measurements of emission from seasonally flooded savannas, extensive semipermanently flooded palm swamps in eastern Peru, interfluvial wetlands in the upper Negro basin, freshwater wetlands in the Amazon estuary, and riparian zones of streams and small rivers. Although the SMMR analyses were done for the Bananal in the Tocantins River basin (Hamilton et al., 2002), we do not have complete JERS-1 coverage at high or low water nor have we attempted to generate a wetlands mask for that basin. Therefore, we do not include the Tocantins basin in our Amazon basin-wide estimates.

One approach to extrapolate from a region to the whole basin is that used by Richey et al. (2002), to extrapolate the carbon dioxide evasion estimate from the 1.77 million square kilometers quadrat to additional areas outside the central quadrat. They multiplied the carbon dioxide evasion rate per unit area calculated for the central region by the average annual flooded area for the whole basin. Based on our wetland mask for the Amazon basin below the 500 m contour (J. M. Melack, L. L. Hess, unpublished results), derived using the same methodology as described in Hess et al. (2003), about 17% of the 5.19 million square kilometers in this region is subject to flooding. Floodplains less than about 100 m across are not included in this percentage, and are likely to increase the floodable area to at least 20%, a value similar to that computed for the 1.77 million square kilometers quadrat. The annual mean flooded area for the quadrat was estimated to be 0.25 million square kilometers or about 14% of the total area (Richey et al., 2002). If a similar proportion is applied to the basin area below the 500 m contour, the annual mean flooded area is 0.73 million square kilometers. The methane emission rate per unit area for the mainstem Solimões/Amazon floodplain, calculated using the total annual emission rates in Table 3 and the mean annual flooded area of 42,700 km\(^2\) (determined as monthly means from Sippel et al. (1998) summed over 12 months and divided by 12) is 30.4 Mg C km\(^{-2}\) yr\(^{-1}\). Assuming this rate is representative of basin-wide rates, we estimate the methane emission for the flooded areas of the basin below 500 m elevation to be approximately 22 Tg C yr\(^{-1}\). If converted to the greenhouse warming potential of carbon dioxide based on the factor of 21 (kg CH\(_4\)/kg CO\(_2\)) over a time horizon of 100 years as calculated by Lelieveld et al. (1998), the mean flux is on the order of 0.5 Pg C as CO\(_2\).
which is about a third of the basin-wide estimate in Richey et al. (2002) for CO₂ evasion from Amazonian wetlands and rivers.

Although these calculations suggest that CH₄ and CO₂ emission from wetland environments of the Amazon are of comparable magnitude in terms of radiative forcing in the atmosphere, it is important to note that the bulk of the CO₂ evasion likely represents the return of atmospheric CO₂ that was assimilated by plants relatively recently. Root respiration by floating macrophytes may even be an important process leading to dissolved CO₂ supersaturation (Hamilton et al., 1995), and thus the cycling could occur on a diel time scale. In contrast, the methane emission is not balanced by an equivalent assimilation term.

Terrestrial environments can influence net basin-wide methane fluxes to the atmosphere because methane diffuses into upland soils and can be oxidized by methanotrophic bacteria. Potter et al. (1996) reported an average consumption of methane in soils associated with humid tropical forests of 3.8 ± 0.6 (standard error) kg CH₄ ha⁻¹ yr⁻¹, based on results from 22 studies, and 1.5 kg CH₄ ha⁻¹ yr⁻¹ based on their global model. Pastures created by deforestation can become seasonal or annual net sources of methane, or remain sinks with lower or higher rates than forests (Steudler et al., 1996; Verchot et al., 2000; Fernandes et al., 2002). There are approximately 4 million square kilometers of upland forest and 0.3 million square kilometers of upland pastures in the Amazon basin below 500 m elevation. If the average consumption of 3.8 ± 0.6 (standard error) kg CH₄ ha⁻¹ yr⁻¹ reported by Potter et al. (1996) is applied to the area of upland forests, 1.1 ± 0.2 (standard error) Tg C yr⁻¹ are oxidized in upland soils, a small fraction of the methane emitted from the wetlands. Further, net emission from pastures could return about 0.1 Tg C yr⁻¹ (based on Steudler et al.’s (1996) net emission rate and the above estimate of pasture area), and termites, cattle and biomass burning associated with pastures are likely to return even more methane to the atmosphere (Steudler et al., 1996).

Comparisons with previous estimates for the Solimões/Amazon floodplain

Melack & Forsberg (2001) examined the organic carbon balance for a 2600 km stretch of the floodplain fringing the Solimões/Amazon River from 52.5 to 70.5° W, emphasizing the dominant fluxes and the factors that control them. They used emission rates for aquatic macrophytes, flooded forests and open water with average flooding periods of 182.5, 135 and 365 days and maximum flooded areas of 29,300, 28,200 and 10,370 km², respectively for each habitat. Methane emissions from aquatic macrophytes, flooded forests and open water in lakes were estimated to be 1.25, 0.39 and 0.19 Tg C yr⁻¹, respectively, and total regional methane emission to be about 1.8 Tg C yr⁻¹. If adjusted to the slightly shorter reach used in our analyses, their methane emission estimate would be about 1.7 Tg C yr⁻¹.

Wassmann & Martius (1997) suggested that the main uncertainty for estimates of methane emission from the central Amazon floodplain was insufficient information on the vegetative cover. They estimated the area covered by floating plants to be 40,000 km² (for 9 months), by flooded forest to be 100,000 km² (for 6 months) and by open water in lakes to be 40,000 km² (for 12 months). Using a range of emission rates for each habitat obtained from the published literature, they calculated annual rates to range from 0.29 to 4.74 Tg C yr⁻¹ for floating plants, 0.09 to 3.14 Tg C yr⁻¹ for flooded forests and 0.14 to 0.9 Tg C yr⁻¹ for open water. If maxima or minima are summed, total emission ranges from 0.5 to 8.8 Tg C yr⁻¹. In contrast, Bartlett et al. (1988) used a lake area of 14,700 km² to calculate an annual flux from open water of 0.06 Tg C yr⁻¹.

Devol et al. (1990) combined methane flux measurements from high- and low-water cruises, spanning a 1500 km reach of the mainstem Amazon, with monthly data from lakes near Manaus. They assumed that 30% of a total floodplain area of 140,000 km² is covered by forest that is flooded for 6 months, that open waters average 40% of the area, and that aquatic macrophytes expand from 10% of the floodplain area at low water to 30% during the 6-month high-water period. Combining the emission rates with aquatic habitat areas, they estimated that the central Amazon floodplain emits methane at a rate of 3.8 Tg C yr⁻¹.

Comparison of these earlier estimates to our calculations for the mainstem Solimões/Amazon floodplain (Table 3; Fig. 3) clearly indicates a tendency for over-estimation of CH₄ emission in the earlier studies, resulting from the assumptions that had to be adopted in the absence of direct measurements of extent and variations in inundation area or of vegetative cover. In contrast, our calculations use measurements of variations in inundation and vegetative cover derived from remotely sensed data with rigorous validation. As a result, the uncertainty in the field measurements of methane emission has a much greater impact than that associated with the inundation or vegetative cover in our regional emission estimates for the central Amazon basin.

Related studies of Amazonian reservoirs and tributaries of the Negro River

Methane emission from Amazonian reservoirs has been measured occasionally at several sites in Samuel,
Balbina and Curua-Una reservoirs and more extensively in Tucuruí reservoir (Fearnside, 1997; Rosa et al., 1997; Duchemin et al., 2000; Lima et al., 2000; Lima, 2002). Based on selected methane emission rates available in the published literature, Fearnside (1995) estimated that the emission of methane via diffusion and ebullition from Curua-Una, Tucuruí, Samuel and Balbina reservoirs was approximately 0.2 Tg C yr\(^{-1}\) in 1990. Using a maximal area of 2430 km\(^2\) and a model that assumes 11% of the flux is diffusive and 89% is ebullitive, and incorporating measured daily fluctuations of the water level and reservoir area, Lima (2002) calculated that the annual methane flux from Tucuruí Reservoir is approximately 0.017 Tg C yr\(^{-1}\). These fluxes are small relative to the estimated emissions from floodplains, but will increase as more reservoirs are constructed. Further, Fearnside (2002) estimated that a considerable amount of methane could be released into the atmosphere as the waters from Tucuruí Reservoir pass through the turbines and over the spillway. While based on very few measurements of dissolved methane, the large magnitude of the values indicate that these routes of emission warrant further attention.

A number of blackwater tributaries enter the Negro River along its southern bank from the Uaupés River to the confluence of the Negro and Solimões rivers (Fig. 1). Over 90% of the area subject to inundation is covered by periodically flooded forest located along fringing floodplains and in interfluval wetlands (Hess et al., 2003). The catchment of the Jaú River is an example of such a basin, and Rosenqvist et al. (2002) have developed a spatiotemporal inundation model for the Jaú basin based on a time series of JERS-1 SAR data and measurements of river stage. The inundation data were combined with a model of methane emission, where flux is a function of river stage and flooded area, to provide estimates of daily methane fluxes for the entire Jaú basin. They caution that their extrapolation to the whole basin is based on only one transect of methane flux measurements, albeit with measurements made 18 times between October 1996 and September 1998. Moreover, they acknowledge that their empirical relation between stage and inundated area is not representative of some portions of the basin. The maximum and monthly average flooded areas for the Jaú basin inclusive of the Carabinani tributary and interfluval wetlands were approximately 1400 and 750 km\(^2\), respectively, during the period from October 1995 to October 1996 (Rosenqvist et al., 2002). The total annual methane emission during the period from October 1995 to September 1996 for the Jaú basin was approximately 17 Gg C. The annual emission divided by the monthly average flooded area yields a methane emission rate of 23 Mg C km\(^{-2}\). The comparable value calculated above for the fringing floodplain of Solimões/Amazon main-stem is 30 Mg C km\(^{-2}\) yr\(^{-1}\). Apparently, the averaged areal methane flux from the nutrient-poor blackwater floodplains and wetlands of the Negro basin is slightly less than that for the nutrient-rich whitewater floodplains.

**Savanna wetlands**

There are two extensive regions within the Amazon Basin in which the wetland vegetation is more like savanna than forest: the Llanos de Mojos in Bolivia (upper Madeira River basin) and the savannas of Roraima State in Brazil (Branco River basin, tributary to the Negro River system). Similar environments occur in the tropical lowlands of South America but outside of the Amazon basin, the most extensive of which are Bananal Island on the Araguaia River (Tocantins River basin), the Pantanal on the upper Paraguay River (Paraná River basin) and the Llanos del Orinoco (Orinoco River basin). From the standpoint of methane production and emission, these savanna wetlands share the following features: (1) high primary production by herbaceous plants; (2) shallow depths of inundation (mean depths likely <0.5 m) and (3) high temperatures (as in the central Amazon). Trees occur in varying densities in these floodplains but they are generally sparse except in gallery forests, and herbaceous plant growth covers the ground in most places.

Methane emissions have yet to be measured in these savanna wetlands, and the likely importance of plant stem transport by a variety of rooted emergent species makes emission measurements a daunting prospect. For the time being, their emission rates can be estimated based on measurements from similar environments made elsewhere. Bartlett & Harriss (1993) used a mean emission rate of 233 mg CH\(_4\) m\(^{-2}\) day\(^{-1}\) (=175 kg C km\(^{-2}\) day\(^{-1}\)) for ‘grass mats’ in nonforested tropical floodplains, calculated based on measurements made in floating macrophyte mats of the Amazon and Orinoco floodplains as well as measurements in a marsh in Panama. Their estimate averaged high- and low-water measurements. Considering that most flooded areas in the savanna wetlands dry completely during the low-water season (Hamilton et al., 2002), the high-water measurements are most likely to represent fluxes during the inundation of the savannas. Bartlett & Harriss (1993) also reported a mean for Amazon grass mats during the high-water period of 261 mg CH\(_4\) m\(^{-2}\) day\(^{-1}\) (=196 kg C km\(^{-2}\) day\(^{-1}\)), based on 200 flux measurements from several studies. Methane emission from savanna floodplains of tropical South America is likely to be similar to or greater than this, considering their similar plant production and
temperatures but shallower depth of inundation. Otter & Scholes (2000) showed that shallow inundation (<0.4 m) in South African savanna environments enhances methane emission. On the other hand, Hamilton et al. (1995) reported a mean concentration of dissolved methane of 14 μM for vegetated waters of the Pantanal, which is quite similar to the mean of 12 μM for Amazon floodplain waters reported by Richey et al. (1988), even though the depths where samples were taken in the Pantanal were generally lower (mean ± SD, 1.9 ± 1.6 m). Therefore, we calculated the contributions from these savanna floodplains using the mean methane emission rate for macrophytes at high water in the Amazon (196 kg C km⁻² day⁻¹).

Estimates of methane emission in these savanna floodplains were derived by combining the mean emission rate with observations of inundated area made by passive microwave remote sensing. For each region, we used mean annual inundated area calculated from long-term extensions of the inundation record, based on regressions between observed flooded area and water levels in nearby rivers (Hamilton et al., 2002). Methane emission rates from the major savanna floodplains within and outside of the Amazon Basin are summarized in Table 4.

Despite the considerable uncertainty in areal emission rates, these estimates help to indicate the likely importance of these vast wetlands to the overall emission of methane from lowland tropical wetlands of South America. For example, estimated methane emissions from the Llanos del Orinoco, Llanos de Mojos and Pantanal are similar to those of the fringing floodplain of the Solimões/Amazon River. The estimated annual emission from the Llanos del Orinoco is more than 10 times greater than the annual emission of 0.13 Tg C yr⁻¹ for the 14,500 km² Orinoco River fringing floodplain and upper delta reported by Smith et al. (2000).

The estimates reported here are lower than what would have been attributed to these regions in previous attempts to account for their methane emission, which were reported by latitudinal bands rather than by specific region. Matthews & Fung (1987) and Bartlett & Harriss (1993) assumed that these wetlands were completely flooded for 6 months per year (i.e. mean annual inundation area was 50% of the total area). Aselmann & Crutzen (1989) estimated methane emissions assuming a mean annual inundation of 3.5 months in seasonal floodplains and 5 months in seasonal swamps and marshes of the tropics. The results obtained by passive microwave remote sensing for these savanna floodplains equate to a range of 2.5 months per year for Roraima to 3.9 months per year for the Orinoco, averaging 3.2 months per year for the five savanna floodplains (Hamilton et al., 2002), revealing that previous assumptions about inundation had led to overestimates.

**Relation of methane emission to overall ecosystem production and riverine carbon exports**

Richey et al. (2002) calculated that the diffusive evasion of CO₂ from water to the atmosphere in a 1.77 million square kilometers quadrant in the central Amazon basin was 210 ± 60 Tg C yr⁻¹. For the same region, we estimate that 6.8 ± 1.3 Tg C yr⁻¹ of methane is emitted to the atmosphere. Therefore, methane emission is less than about 4% of the carbon dioxide evasion, and would seem of minor importance to the overall carbon balance of the basin, in spite of its importance in atmospheric radiative forcing as noted above. However, methanogenesis is important to aquatic ecology because it produces high concentrations of methane in floodplain sediments and waters; an unknown but likely significant portion of the methane is oxidized in the floodplain and in recipient river waters, and that could be an important process for consumption of dissolved oxygen (Devol et al., 1994; Hamilton et al., 1997; Engle & Melack, 2000).

Melack & Forsberg’s (2001) estimate of net primary productivity of the central Amazon floodplain from aquatic macrophytes, flooded forests, phytoplankton and periphyton, adjusted to approximate the reach considered here, is about 100 Tg C yr⁻¹. Our estimates of between approximately 1 and 2 Tg C yr⁻¹ of methane emission for the same reach represent between 1% and

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Estimates of mean annual methane emissions from major savanna floodplains within the Amazon River basin (Mojos and Roraima) and elsewhere in tropical South America</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean flooded area (km²)</td>
<td>29,460</td>
</tr>
<tr>
<td>Mean CH₄ emission (Tg C yr⁻¹)</td>
<td>2.10</td>
</tr>
</tbody>
</table>

Inundation areas are long-term means estimated by Hamilton et al. (2002) for the time periods shown in table, and a methane emission rate of 196 kg C km⁻² day⁻¹ is assumed (see text).
2% of the net primary production. In contrast, in an analysis of dissolved gas concentrations, Richey et al. (1988) estimated that almost 20% of the organic carbon derived from primary production and decomposed underwater within the mainstem floodplain or river is released to the atmosphere as methane. Although their rough estimate of primary production is similar to the more recent results used here, their estimate of methane flux of 300 g C m$^{-2}$ yr$^{-1}$ is almost an order of magnitude higher than the flux we have calculated, and was obtained by multiplying measured diffusive fluxes by 5 to account for the ebullitive fluxes that are thought to be the dominant pathway but were not measured in conjunction with the dissolved gas sampling. Furthermore, the dissolved gases reflect only aquatic decomposition, in which methanogenesis would be relatively more important compared with terrestrial decomposition processes that take place above the water and during the dry phase. In contrast to Richey et al. (1988), Whiting & Chanton (1993) report that about 3% of net daily ecosystem production (including vegetation above the water level) is released to the atmosphere as methane, based on an analysis of wetlands of varying productivity in tropical, temperate and boreal regions, and by comparison our estimates of 1–2% seem reasonable.

Export of total organic carbon and of dissolved inorganic carbon by the Amazon River to the Atlantic Ocean are reported to be 36 and 35 Tg C yr$^{-1}$, respectively (Richey et al., 1990). Our estimate of the total methane flux from the Amazon basin below 500 m elevation is of similar magnitude. As was noted by Richey et al. (2002) for carbon dioxide, it appears that the direct release to the atmosphere of carbon species from wetlands and rivers exceeds or rivals fluvial transport.

Further research needs

To improve estimates of methane emission and to forecast changes in emission in the face of changing climate, land use, and river alterations, process-based models that integrate climatic and environmental factors with biological processes need to be developed. Several promising models and approaches exist, but will benefit from some modification for application to the Amazon (Cao et al., 1996; Granberg et al., 1997; Potter, 1997; Walter & Heimann, 2000). For example, Cao et al. (1996) based their calculations of methane emission on carbon supplied by plant primary productivity and organic matter decomposition, regulation of methanogenesis by temperature and soil moisture, and the difference between methane production and oxidation. Even for the well-studied central Amazon floodplain, regional estimates of plant productivity and decomposition are quite limited, and little information on methane oxidation is available. Furthermore, the extensive wetlands in much of the rest of the basin remain little known. Basic information on inundation variability, on the distribution and phenology of the vegetative cover, and on methane emission is needed for the seasonally flooded savannas, extensive swamps in eastern Peru, interfluvial wetlands in the upper Negro basin, freshwater wetlands in the Amazon estuary, and riparian zones of streams and small rivers.

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