



# Peatlands of the Madre de Dios River of Peru: Distribution, Geomorphology, and Habitat Diversity

J. Ethan Householder · John P. Janovec ·  
Mathias W. Tobler · Susan Page · Outi Lähteenoja

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**Abstract** We present results of research concerning the distribution, depth, volume, geomorphology, and habitat diversity of peatlands in the southern Peruvian Amazon. We identified 295 peatlands covering 294 km<sup>2</sup> and ranging in size from 10 to 3,500 ha. Individual peatlands were mostly restricted to the meander belt of the Madre de Dios River. Mean peat depth was 2.54±1.84 m ( $n=429$ ), however we encountered depths to 9 m and 10% of the measurements exceeded 5 m. We developed a calibration factor to calculate peat volume across the study area, estimating total peat volume within 295 peatlands at 657±119 Mm<sup>3</sup>. An interpolated depth map of subsurface morphology of a single peatland showed that fluvial features were well-conserved beneath several meters of peat and three distinct subsurface

geomorphological units defined by peat depth could be identified: the Primary Basin, Secondary Basin, and Intrabasin flats. Subsurface geomorphology resulted in increased within-habitat heterogeneity and explained 35% of the variation of pixel values extracted from Landsat<sup>TM</sup> imagery. Representing a hydrological link from elevated uplands to the lower floodplains, peatlands in Madre de Dios are especially threatened on local scales by habitat alteration in the uplands and gold mining in the floodplains.

**Keywords** Amazon · Madre de Dios · Peat · Peru · South America · Wetlands · Tropical peatlands

## Introduction

Tropical peatlands are receiving growing attention due to their increasingly recognized role in the global carbon cycle (Wieder et al. 2007), greenhouse gas exchange (Roulet 2000; Jauhiainen et al. 2005), hydrological interactions (Chason and Siegel 1986; Hoekman 2007), paleoecology (Anderson 1975; Barberi et al. 2000; Page et al. 2004), and maintenance of biological diversity (Sebastian 2002). Page et al. (2011) recently estimated total tropical peatland coverage at about 440,000 km<sup>2</sup>, representing 11% of global peatland area. Despite the comparatively limited area they occupy, tropical peatlands amount to almost a fifth of the total global peat carbon pool and a quarter of global peat volume, thus their importance in the global carbon cycle seems disproportionate to their limited surface area. For example, during the 1997 El Niño event burning peats in Indonesia sent the equivalent of 13–40% of global carbon emissions from fossil fuels into the atmosphere (Page et al. 2002). Unfortunately, despite their potential for large negative and positive feedbacks to the climate system through

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J. E. Householder (✉) · J. P. Janovec  
Botanical Research Institute of Texas,  
1700 University Drive,  
Fort Worth, TX 76107, USA  
e-mail: jehouseholder@gmail.com

J. E. Householder  
Graduate Program in Ecology,  
Instituto Nacional de Pesquisas da Amazônia – INPA,  
CP 478, 69011-970, Manaus, Amazonas, Brazil

M. W. Tobler  
San Diego Zoo Institute for Conservation Research,  
15600 San Pasqual Valley Road,  
Escondido, CA 92027-7000, USA

S. Page  
Department of Geography, University of Leicester,  
Leicester, UK

O. Lähteenoja  
Department of Biology, University of Turku,  
Turku, Finland

sequestration and emission of greenhouse gases, tropical peatlands are not explicitly included in either global climate models or in predictions of future climate change (Schulman et al. 1999; Wieder et al. 2007; Li et al. 2007).

Lowland tropical peats are commonly associated with anoxic environments that retard high tropical soil respiration rates and allow the build up of thick peat (Bailey 1951). Southeastern Asia currently contains the majority (77%) of tropical peat but it is not clear to what extent this figure is a legacy of an unbalanced geographic concentration of peatland studies (Page et al. 2011). For example the Amazon represents the most extensive, least explored, continuous humid tropical forest on the planet. Draining one fifth of global freshwater runoff and presenting minimal topographical relief, the Amazonian lowlands might be expected to contain extensive swamp areas where peats might form (Junk 1983; Schulman et al. 1999). In contrast to southeastern Asia where below-ground carbon in the form of peat is recognized to represent well over half of the regional carbon pool (Page et al. 2011), discussions of carbon sources and sinks in Amazonia are almost entirely limited to vegetation and minerogenic soils (Schulman et al. 1999; Cummings et al. 2002; Houghton 2005).

There are a number of scattered reports about Amazonian peatlands (Junk 1983; Suszczyński 1984; Shier 1985; Andriess 1988; Dubroeuq and Volkoff 1998; Osher and Buol 1998; Batjes and Dijkshoorn 1999; Schulman et al. 1999; Barberi et al. 2000; Ledru 2001; Ruokolainen et al. 2001; Guzmán Castillo 2007; Hamilton et al. 2007; Chimner and Karberg 2008). However, they are often embedded within larger ecological studies and their anecdotal nature is of no use in terms of quantifying peat formation patterns and distribution in the Amazon basin. In a few recent studies in the northern Peruvian Amazon, Lähteenoja et al. (2009) and Lähteenoja and Page (2011) reported extensive peat deposits which reached depths to 7.5 m and showed high rates of carbon accumulation. Such deep peats decidedly lay to rest the idea that the prevailing conditions in Amazonia are unfavorable to peat formation. Moreover, 150,000 km<sup>2</sup> of peatland have been recently estimated to occur in the Amazon, over ten times previous estimates (Schulman et al. 1999; Ruokolainen et al. 2001). In terms of total area, this puts Amazonian peatlands in close standing with those of Indonesia, suggesting that their role in global processes may be of similar magnitude. Unfortunately, extensive field verification of remotely sensed data at such broad scales is unfeasible, thus ground observations, measurements, and detailed geomorphological descriptions of peatlands are still needed in the Amazon.

This study provides a detailed account of peatlands along a single Amazonian tributary in southeastern Peru. We draw on several years of extensive ground observations and measurements to address the following questions: (1) How are

peatlands distributed across the landscape? (2) What is the total area and volume of peat along the Madre de Dios River valley? (3) Do peatlands share a common geomorphology and if so, how does geomorphology affect habitat diversity? We hope to facilitate further studies of these important wetland ecosystems and to promote their protection, especially as they and the ecosystem services they provide are increasingly threatened by human activities such as large-scale agriculture, cattle ranching, deforestation and gold mining.

## Methods

### Study Site

This study was carried out in the Peruvian portion of the Madre de Dios River watershed below 400 msl. The Madre de Dios River is the major drainage tributary of the Beni-Mamore foreland basin of the southwestern headwaters region of the Amazon basin. Deeply entrenched within thick, alluvial deposits corresponding to the late Neogene (Campbell 2001; Campbell et al. 2006), the river shows high rates of lateral channel migration within its meander belt and high levels of suspended sediments. Major geomorphological features of the landscape include upland terrace or *terra firme* (non-flooded rainforest) habitat on ancient, dissected Neogene sediments and lowlying floodplain habitat on recent Andean-derived alluvium (Goulding et al. 2003). Within the meander belt fluvial features such as oxbow lakes, swales, levees, and depressions are numerous (Hamilton et al. 2007). Impermeable clay beds of the Ipururu formation (Middle Miocene age) comprise the basement layer, often visible at low water levels and occasionally forming mild river rapids due to differential erosion (Campbell et al. 2006). The climate is humid tropical with annual rainfall varying between 2,000 and 3,500 mm with a strong dry season between August and October. The vegetation is mostly evergreen with large, scattered stands of bamboo as well as large *Mauritia flexuosa* palm swamps (Foster et al. 1994; Goulding et al. 2003).

### Remote-sensing

To obtain data on the distribution of peatlands as well as the volume of accumulated peat we combined remote sensing with field observations. Image analysis was performed on an area covered by two Landsat<sup>TM</sup> 7 ETM+ scenes (path/row 2/69 [23 August 2001] and 3/69 [23 May 2000], orthorectified and projected to UTM Zone 19S) obtained from the Global Landcover Facility (<http://glcf.umiacs.umd.edu/>). To extract all the peatlands from the images we used a maximum-likelihood classification in Envi 3.6 (ITT Visual Information Solutions) using all but the thermal bands. As preliminary field work showed that peatlands can readily be identified as

blue-purple areas in Landsat satellite images when using a 5,4,3 band combination, ground control points were selected directly from the images. To improve classification results we also selected ground control points for other landcover types such as open water, bare minerogenic soil, terra firme, and floodplain forest, as well as clouds and shadows. Results were checked visually against the false-color image and ground-truthed during field expeditions. After classification we merged data from the two images and extracted the peatlands as a vector layer. We removed patches that were smaller than 10 ha since those were often small stands of *Mauritia flexuosa* along creeks or caused by misclassification of a few pixels.

### Fieldwork

Field verification took place in conjunction with related floristic and ecological studies, enabling us to verify the classification with over 800 georeferenced points distributed between 35 peatlands where organic substrates were positively confirmed. In 10 peatlands a single 10 m steel rebar was used to measure peat depth every 100 m along linear, 1–4 km transects, in most cases completely traversing the peatland. The rebar was pushed completely into the peat until reaching a clay foundation below. Clay residues remained visible on the rebar even after removal through several meters of peat and were used to identify the depth at which clay and organic horizons transitioned. The interface between the clay foundation and organic peat was often abrupt and easily recognized. Repeated measurements at the same point varied  $\pm 5\%$  of the total peat depth being measured. Geographical coordinates as well as notes about and photos of the dominant vegetation were recorded at all sampling points. Depth measurements of one medium-sized (250 ha) peatland near the Los Amigos Biological Station or Centro de Interpretación y Capacitación de Río Amigos (subsequently referred to as the “CICRA peatland”) were extensively mapped out in north–south transects spaced 200 m apart. Topographical variation in one peatland was measured across its width (from the terrace escarpment to the floodplains) using a 50 m tube filled with water. We began at the highest point, using two wooden stakes with reference marks 50 cm from the base on either end of the 50 m water level. At one end, water level was maintained at the reference mark of one stake. At the other end, topographical variation within the 50 m section was calculated as the difference between the height of the water level and the reference level of the second stake. The water level was then moved to the next 50 m section and the process repeated until the entire peatland was traversed.

### Analysis

A natural neighbors interpolation method was used to produce a surface display of the CICRA peatland bathymetry.

We used a natural neighbors interpolation because interpolated values are calculated locally and it works equally well with regularly and irregularly distributed data (Watson 1992). Using the interpolated map as a guide we identified three subsurface geomorphological units within the CICRA peatland. To aid in delineating geomorphological units we produced a contour map based on the natural neighbors interpolation. The 3.5 m contour line (with 0 m beginning at the peat surface) was used as a cutoff to separate different units. To test whether subsurface geomorphology contributed to habitat heterogeneity we extracted pixel values (Band 1–6) from a Landsat™ satellite image (path/row 3/69 [23 May 2000]) at 70 systematically chosen pixels within each geomorphological unit of more or less equal size. We used Principle Components Analysis and Analysis of Similarities (Oksanen et al. 2010) to quantify variation in pixel values from each geomorphological unit. The Analysis of Similarities is based on the difference of mean ranks of dissimilarity values between groups and within groups. Statistical significance was assessed by 999 permutations of group labels to obtain an empirical distribution using the R-language function *anosim* in the *vegan* library.

Peat volume in the CICRA peatland was estimated using the natural neighbors interpolated bathymetry map and the surface volume tool in the ESRI ArcMap 9.2 3D Analyst extension, assuming a horizontal reference plane. We tested the effects of different interpolations on the calculation of volume using a variety of interpolation techniques, including inverse distance weighting, kriging, and splines. The natural neighbors interpolation produced the most conservative result for peat volume in the CICRA peatland, so we based further calculations on this estimate. To extrapolate total peat volume for the entire study region a simple multiplication of mean peat depth (estimated from 10 peatlands) by regional peatland area would be inaccurate due to the amount of subsurface complexity. Transects in many peatlands were directed through the central portion where peats may be deeper on average than in marginal areas. To account for this bias, we calculated a calibration factor using measurements from the CICRA peatland relating true volume (based on the interpolated depth map) to that predicted by multiplying CICRA peatland area by subsamples of CICRA mean peat depth. Fifteen subsamples of mean peat depth were estimated from 15 random transects with 20 to 30 sampling points each. We used transects with 20–30 points because other peatlands were sampled along similar-sized transects.

## Results

### Distribution

Through the remote sensing analysis we identified 295 peatlands covering approximately 294 km<sup>2</sup> along the river

meander belt within the study area (Fig. 1). Peatland area ranged from 10 to 3,500 ha with a mean size of 100 ha. Five peatlands exceeded 1,000 ha and 13 peatlands exceeded 500 ha. Seventy percent of the peatland area was restricted to the north side of the Madre de Dios River

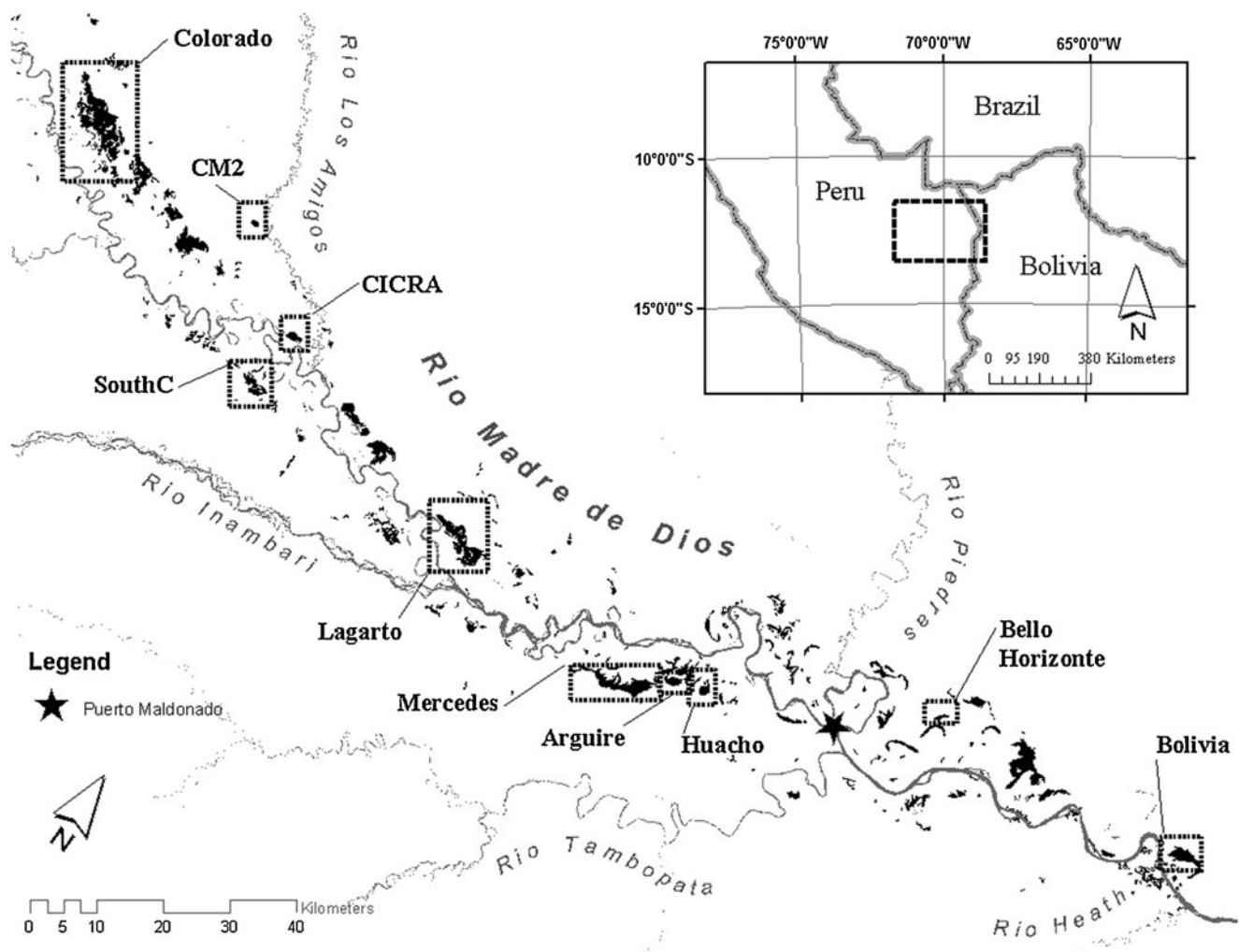
#### Peat Depth and Volume

We measured peat depth at 429 points distributed across 10 peatlands (Table 1). Mean peat depth (mean±stand. dev.) was  $2.54\pm 1.84$  m ( $n=429$ ). The maximum depth measured was 9 m and 10% of the measurements were over 5 m deep. Mean depth in the systematically mapped CICRA peatland was  $3.16\pm 1.97$  m ( $n=194$ ) and the volume of peat stored was  $5.85$  Mm<sup>3</sup> or  $2.34$  Mm<sup>3</sup>/km<sup>2</sup> of peatland area. In the CICRA peatland, estimates of peat volume derived from multiplying subsamples of mean peat depth from random

transects by surface area tended to overestimate volume derived from the interpolated bathymetry map by  $12\pm 16\%$ . Using this calibration factor, assuming that our estimate of mean peat depth of 2.54 m from 429 measurements distributed across the landscape is accurate for the entire study area, we estimate that total volume of peat stored in Madre de Dios peatlands is  $657\pm 119$  Mm<sup>3</sup>.

#### Geomorphology

In all the peatlands we visited, deep peats exceeding 3.5 m were always measured at sites near the distal margins of the floodplain and formed distinct basins 200–300 m wide (Fig. 2a). Shallow and intermediate peats extended 2–3 km beyond the basins and gradually transitioned to mineral soils supporting floodplain forest vegetation. Using the interpolated depth map of the CICRA peatland we were able to



**Fig. 1** Distribution of peatlands (black) along the floodplain of Rio Madre de Dios, Peru. Only the ten peatlands where peat depths were measured are designated with dashed boxes. The names of peatlands

correspond to Table 1. Twenty-five other peatlands within the study region were visited to verify the classification, including over 800 groundtruthing points, but for clarity are not designated here



**Table 1** Measurement of peat depth at 429 points distributed among 10 peatlands in Madre de Dios, Peru. Depth measurements were made every 100 m along straight line transects, generally passing through the central portion of each peatland. Peatland names correspond to Fig. 1

Peatland name	Size (ha)	Centroid location	Number of measurements	Min depth (cm)	Max depth (cm)	Mean depth (cm)
Arguire	229	12° 38' 08" S 69° 22' 21" W	11	212	414	304.0
Bello Horizonte	112	12° 28' 38" S 69° 02' 59" W	15	10	180	108.0
Boli	755	12° 26' 38" S 68° 41' 15" W	22	45	409	185.0
CICRA <sup>a</sup>	235	12° 33' 51" S 70° 05' 36" W	194	10	900	316.0
CM2	15	12° 27' 54" S 70° 15' 26" W	15	36	156	85.9
Colorado	3,592	12° 27' 50" S 70° 30' 45" W	38	48	307	165.9
Huacho	542	12° 38' 57" S 69° 24' 52" W	20	46	695	275.3
Lagarto	1,657	12° 38' 58" S 69° 46' 44" W	60	38	900	234.8
Mercedes	1,681	12° 41' 26" S 69° 27' 19" W	41	15	820	245.9
SouthC	529	12° 39' 09" S 70° 07' 27" W	13	10	208	117.4

<sup>a</sup> CICRA peatland was completely mapped out in north–south transects

classify three subsurface geomorphological subunits, the Primary Basin, Secondary Basin, and Intrabasin Flats (Fig. 2b). The Primary and Secondary Basins formed horseshoe-shaped basins where the deepest peats (>3.5 m) occurred. These basins supported a dense swamp forest dominated by *Mauritia flexuosa*. Their size and shape indicate a fluvial origin similar to oxbow lake formation. The third geomorphological unit identified in the CICRA peatland, the Intrabasin Flats, was a broadly circular area composed of slightly fluctuating shallow peats (<3.5 m) supporting open mire and bog vegetation dominated by Cyperaceae and scattered *Mauritia flexuosa*. These three geomorphological units accounted for 35% of the variation in pixel values extracted from the Landsat™ satellite image. Band 4 loadings showed high correlation with the first axis and separated the Primary and Secondary basins. The Secondary Basin formed a relatively well-defined cluster at large values of the axis. Band 5 was well correlated with the secondary axis and separated the two basins from the Intrabasin Flats. Within groups, the Secondary Basin showed the lowest mean Euclidean distance between pairwise comparisons (5.15), followed by the Intrabasin Flats (5.61) and the Primary Basin (6.97). An Analysis of Similarity test suggested that differences between geomorphological subunits were not random ( $p < 0.001$ ) and repeated tests of all pairwise comparisons between groups of pixels in different subunits were significantly different ( $p < 0.001$ ) (Table 2).

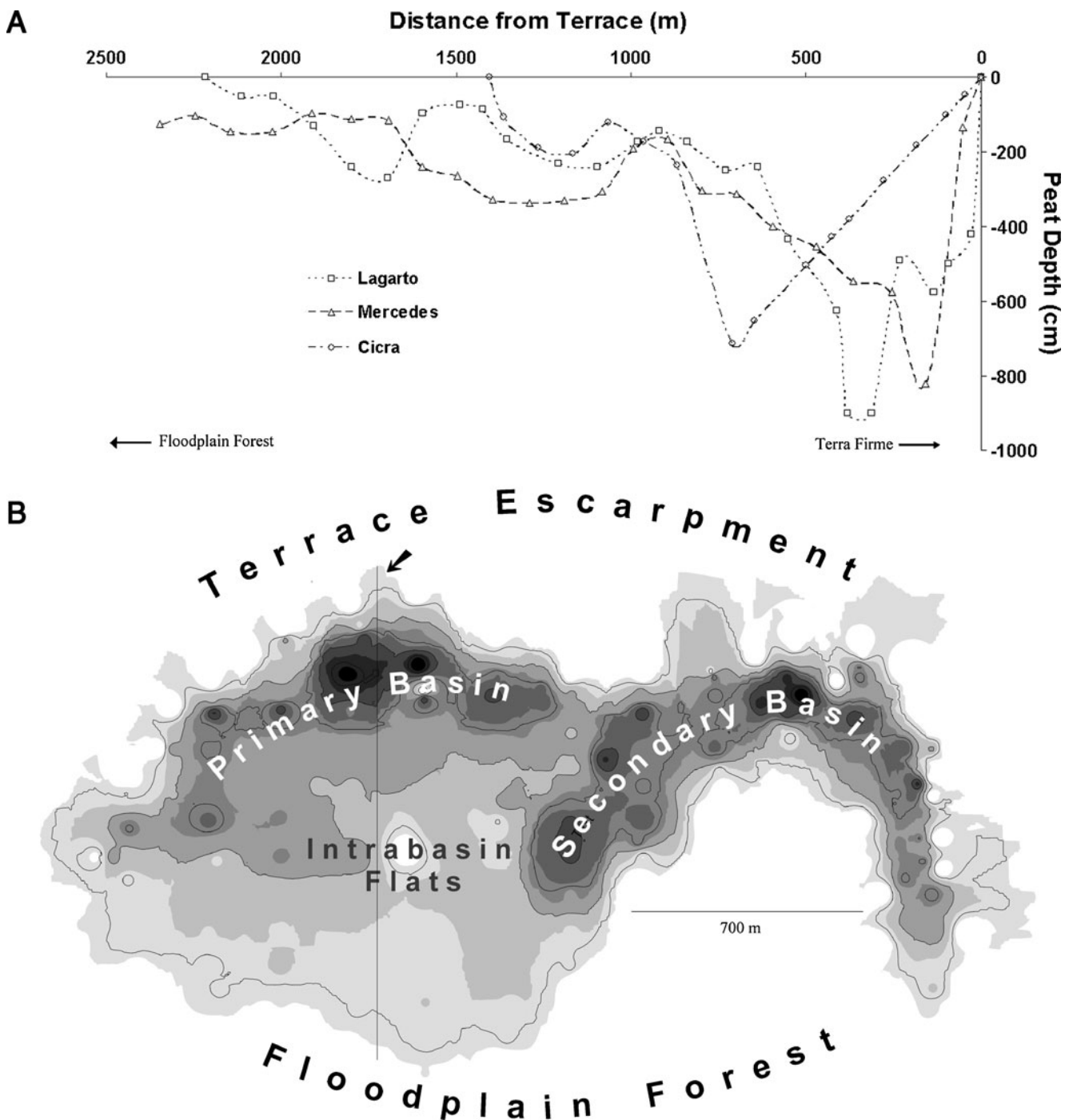
The single peatland we leveled (Mercedes) had a width of 1,000 m. The mean downward slope from the terrace escarpment to floodplain forest was 0.27 cm/m but this was not homogenous along the transect. Initial slopes were 0.66 cm/m in the first 200 m near the terrace escarpment where peat depths were greater, becoming essentially flat at 0.062 cm/m for the remaining 800 m where peats were

shallow. All peats were below the level of seep emergence and we were not able to confirm domed peats.

## Discussion

### Distribution and Hydrogeomorphic Setting

We report extensive peat deposits, including the deepest peats yet recorded for the Amazon, and support the conclusions of several investigators (Schulman et al. 1999; Lahteenoja et al. 2009; Ruokolainen et al. 2001) who have argued that Amazonian peats are important in terms of coverage and carbon stocks. Similar to what Lahteenoja et al. (2009) observed in northeastern Peru, peatlands in our study region were restricted to the floodplain of the main river channel and incorporated into topographical features created by fluvial processes. Peatlands in Madre de Dios were generally located on the distal margins (farthest from the river) of the meander belt with one side abutting steep-faced terrace escarpments (Madre de Dios formation). Numerous small, perennial seeps emerged from the base of the terrace escarpment at the interface of the thick unconsolidated sediment of the Madre de Dios formation and a blue/grey clay foundation that we interpret as the Ipururu formation (Campbell et al. 2006). Groundwater emergence at these points is the result of a hydraulic gradient driven by infiltration of rainfall in the more elevated uplands and an impervious basement layer that causes groundwater to flow laterally (Fig. 3). Incoming seep waters feeding peatlands were clear and sediment free and these water sources likely control peatland distribution on the landscape. We found that water flow through peatlands was almost imperceptible except after precipitation events. Outgoing water was funneled through several outlets in each peatland, forming blackwater streams (pH 4.2–5.6). In many cases animal salt



**Fig. 2 a&b.** Two and three dimensional representations of subsurface morphology of different peatlands in Madre de Dios, Peru. Above (a), peat profiles in three selected peatlands showing common geomorphology. Below (b), subsurface contour map of the of the CICRA peatland

based on a natural neighbors interpolation of systematic depth measurements. The *arrow* indicates the transect designated in one of the profiles above

licks were associated with the water inlets and outlets of peatlands.

Worth noting is that the canopy dominant in Madre de Dios peatlands, as well in the majority of those reported by Lähteenoja et al. (2009), is the arborescent palm *Mauritia*

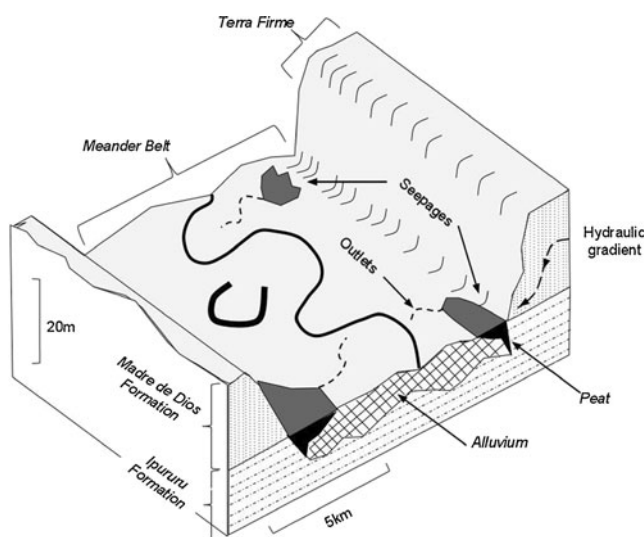
*flexuosa* (Arecaceae). The palm has a neotropical distribution occurring from Panama in the north to Minas Geras in southern Brazil and the base of the Andes Mountains in the west to near the Brazilian Atlantic forests, often forming monodominant stands with densities exceeding

**Table 2** Mean euclidean distances (left of slash) and Analysis of Similarity Statistics (right of slash) between three geomorphologically derived groups taken from the PCA ordination

	Primary basin	Secondary basin	Interfluvial flats
Primary basin	0	7.68/0.24 <sup>a</sup>	8.61/0.42 <sup>a</sup>
Secondary basin		0	8.39/0.61 <sup>a</sup>
Interbasin flats			0

<sup>a</sup>  $P < 0.001$

300 ind/ha where substrates are more or less permanently saturated (Gonzalez Rivadeneyra 1971; Goulding and Smith 2007). These formations are called *buritizais* in Brazil, *aguajales* in Peru, *morichales* in Venezuela, *moritales* in Ecuador, and *cananguchales* in Colombia (Kahn 1991a, b). *Mauritia flexuosa* can contribute significantly to high rates of carbon accumulation in these peatlands due to its extensive underground root system (Granville 1974; Kahn 1977), high productivity of leaf litter, and monodominance in waterlogged substrates (Lähteenoja et al. 2009). Thus, we suspect that the palm is one of the dominant producers of peat in the Amazon and substantial peat deposits formed largely by this single species may be more common in the Amazon than previously supposed.



**Fig. 3** Schematic summarizing the geomorphological context of Madre de Dios peatlands through a transverse cut. Peatlands generally occur at the interface of the Madre de Dios and Ipururu formations along a hydrological gradient from uplands to the low floodplain. The Ipururu basement is largely impermeable, forcing water to move laterally and forming numerous small seepages that feed peatlands with sediment free water. Outlets are an important source of sediment free water in a region characterized by white water rivers with heavy sediment loads

## Peat Depth and Volume

We were able to provide an estimate of peat volume along a significant stretch of an important Amazonian tributary, a key step towards quantifying the importance of Amazonian peatlands in global biogeochemical processes. Using the total peat volume ( $657 \text{ Mm}^3$ ) of the Madre de Dios peatlands in combination with the average C content (47.3%) and dry bulk density ( $86,678 \text{ gm}^{-3}$ ) of the northern Peruvian peatlands (data from Lähteenoja et al. 2009, 2012), the total peat C stock of the Madre de Dios peatlands would be 0.027 Gt. This is about 0.4% of the peat C stock estimated to be located in the Pastaza-Maranón basin in northern Peru (6.2 Gt, Lähteenoja et al. 2012) and 0.03% of the best estimate of the global tropical peat C stock (88.599 Gt, Page et al. 2011). In summary, even if the total C stock of the Madre de Dios peatlands alone may not add significantly to the global total tropical peat C stock, the area is of special regional importance for harboring the deepest documented peat cores of the Amazon. Their radiocarbon dating and palynological analysis could reveal interesting information of the past changes of Amazonian vegetation and climate.

Lähteenoja et al. (2012) showed that peatlands in the northern Peruvian Amazon have maximum depths of 7.5 m, corresponding to ages of 8,870 cal years BP. Lateral migration of the main river channel seemed to set an upper limit on peat accumulation as established peatlands were consumed and rejuvenated by fluvial disturbance. Given the dynamic setting and length of time needed to build up deep organic deposits, what circumstances contribute to the formation of peats of up to 9 m in Madre de Dios? We offer three hypotheses, as follows. (1) A hydrological gradient from the uplands combined with an impermeable basement layer elevates the local water table well above the peak river flood pulse and maintains substrates waterlogged throughout the year, thus slowing oxidation of soil carbon. In our area even the deepest peat deposits were well below their major water source and perennially saturated with water. In contrast, the deepest organic deposits in northern Peru occurred on domed peats, supposedly above the local water table and maximum flood pulse of the river. Under the less water-logged conditions of northern Peruvian domed peats, oxidation may counterbalance carbon accumulation and rates of peat buildup are likely reduced. (2) The geographical location of peatlands near their water source (perennial seeps) minimizes infilling from sedimentation of mineral particulates. Madre de Dios peatlands do not show thermal stratification in areas of open water bodies (Goulding et al. 2003) and ionic composition of water is similar to that of groundwater (Hamilton et al. 2007), suggesting that these peatlands have continuous water inputs from groundwater and do not have regular connections with sediment-laden fluvial sources, even during high floods. Furthermore, the

subsurface fluvial features of peatlands in Madre de Dios are remarkably well-conserved, suggesting that the normally rapid depositional and erosional processes that normally plug meander scars are slow relative to peat accumulation in the immediate vicinity of peatlands. (3) Fluvial perturbation of the Madre de Dios River is reduced due to nonrandom lateral movement of the main channel. The tilting of basement layers from northeast to southwest results in unidirectional lateral migration of the Madre de Dios River towards the southwest, evident in a series of fossil floodplain margins (Räsänen et al. 1987). This agrees with our findings that 70% of peatland area is restricted to the northern margin of the river where fluvial perturbation may be reduced at time scales significantly large to allow for the slow accumulation of deep peat. These hypotheses are not mutually exclusive and likely work in concert to produce the deep peat deposits observed in Madre de Dios.

### Geomorphology and Habitat Diversity

Madre de Dios peatlands share a common geomorphology as products of active fluvial processes and are incorporated into superimposed meander scars that create basins with intervening flat areas. This subsurface complexity contributes to habitat heterogeneity, so that the Primary Basin, Secondary Basin, and Intrabasin Flats in the CICRA peatland were readily distinguished by remotely sensed data. On the ground the distinction between the flats and the basins are reflected in large structural differences in the vegetation. From the basins to the flats a dense forest dominated by *M. flexuosa* brusquely grades to open Cyperaceae bogs and mires with dispersed palms. Mean canopy coverage along this sequence is reduced from over 85% to less than 10% (Householder, unpublished data). We suggest that this large structural change and compositional turnover is due to an abrupt hydrological gradient occurring at the interface of these two subsurface structures. In contrast, the distinction between Primary and Secondary Basins in the CICRA peatland may be due to successional processes. The Law of Superposition suggests that the Primary Basin was formed by fluvial activity first and the Secondary Basin was the result of an independent scarring event at later date. Further evidence that the Secondary Basin formed subsequently comes from the presence of a large (3-ha) pond in its southeastern extremity that has yet to fill in with organic matter. In the Secondary Basin the relatively restricted distribution of pixel values along the primary and secondary axes of the PCA suggested a more homogenous forest cover in this relatively younger basin. *Mauritia flexuosa* is a colonizing species capable of forming initially dense, homogenous stands during primary succession. Establishment of colonizing trees (other than *M. flexuosa*) in an area at a young successional stage would be initially limited by deep shade in the understory as well as unstable peat surfaces. This could result in a relatively

uniform canopy and spectral signature. In contrast, large trees with trunk diameters greater than 60 cm and tall, broad canopies such as *Ficus spp.* (Moraceae) and *Sloanea sp.* (Elaeocarpaceae) become co-dominant in a more diverse overstory in the Primary Basin, likely contributing to variation in the spectral signal. Thus, we suggest that variation between the two basins is due to slow successional processes in independent meander scars of different ages, although this could be heavily modified by differences in hydrological parameters. In either case, subsurface complexity contributes to within-habitat heterogeneity and increased beta diversity, factors that should be considered in future studies concerning biological diversity and ecosystem processes. For example, ongoing vegetation sampling has revealed an unexpectedly complex flora including over 800 plant species (Atrium 2011). Although a detailed description could only be offered for the CICRA site, all peatlands visited showed similar patterns with subsurface geomorphological features and vegetation structure on the surface that could be reliably predicted from inspection of satellite imagery.

### Conservation Implications

The geographic distribution of Western Amazonian peatlands along major floodplains renders them particularly vulnerable. In Madre de Dios, Peru, illegal gold mining in the floodplains has exploded in the last 10 years as gold prices steadily rise and increased mechanization intensifies the destructive potential of small-scale mining operations. On the ground we found that 40% of visited peatlands were currently being mined or showed signs of recent mining activity. Dredging can directly destroy peatlands or indirectly degrade them through increased sedimentation from tailings, alteration of hydrologic regime, or localized lowering of the water table. Additionally, the humic-rich waters of organic-rich substrates facilitate mercury methylation (Forsberg et al. 1995; Silva-Forsberg et al. 1999; Jardim et al. 2010), raising urgent conservation questions regarding bioaccumulation of mercury in animals (and humans) with trophic connections to *M. flexuosa* wetlands. At the same time increased deforestation in the uplands threatens to alter the hydrological gradient that sustains peatlands. Indeed, peatlands form a fragile hydrological link between the elevated uplands and the river. Alterations in the water balance due to habitat alteration in the uplands influencing water inflows or destructive human activities in the floodplains that can modify outflows (for example if miners breach key topographical features that impede flow) are serious local threats.

Large-scale climate change across the Amazon basin may represent the single most pernicious threat to the long-term survival of Amazonian peatland communities as we know them. Predicted alterations in Amazonian precipitation patterns (Harris et al. 2008) may have region-wide repercussions



on these and other non-fluvial wetlands. Within the coming decades we may witness drastic changes and perhaps widespread loss of these and similar non-fluvial wetland ecosystems across the Amazon basin. Therefore, there is an urgent need to build a baseline of data about the distribution and biological diversity of these Amazonian wetland ecosystems so that we are better equipped to manage and mitigate as threats grow. Conservation efforts focused on these wetlands dominated by *Mauritia flexuosa* have not kept pace with the growing threats and are often ignored by conservation planners, probably because these wetlands are simply “off the map”. Lack of protective legislation is partly a reflection of the scarcity of information that is available to lawmakers. Ideally some or all of the peat wetlands included in this study should be recognized by the Ramsar convention active in Peru. Management of this vital resource will only be effective once the interconnections between overall ecosystem integrity and the provision of goods and services to human beings are clearly recognized.

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