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An expert system model for mapping tropical wetlands and peatlands reveals South America as the largest contributor

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Abstract

Wetlands are important providers of ecosystem services and key regulators of climate change. They positively contribute to global warming through their greenhouse gas emissions, and negatively through the accumulation of organic material in histosols, particularly in peatlands. Our understanding of wetlands' services is currently constrained by limited knowledge on their distribution, extent, volume, interannual flood variability and disturbance levels. We present an expert system approach to estimate wetland and peatland areas, depths and volumes, which relies on three biophysical indices related to wetland and peat formation: (1) long-term water supply exceeding atmospheric water demand; (2) annually or seasonally water-logged soils; and (3) a geomorphological position where water is supplied and retained. Tropical and subtropical wetlands estimates reach 4.7 million km^2 (Mkm^2). In line with current understanding, the American continent is the major contributor (45%), and Brazil, with its Amazonian interfluvial region, contains the largest tropical wetland area (800,720 km^2). Our model suggests, however, unprecedented extents and volumes of peatland in the tropics (1.7 Mkm^2 and 7,268 (6,076–7,368) km^3), which more than threefold current estimates. Unlike current understanding, our estimates suggest that South America and not Asia contributes the most to tropical peatland area and volume (ca. 44% for both) partly related to some yet unaccounted extended deep deposits but mainly to extended but shallow peat in the Amazon Basin. Brazil leads the peatland area and volume contribution. Asia hosts 38% of both tropical peat area and volume with Indonesia as the main regional contributor and still the holder of the deepest and most extended peat areas in the tropics. Africa hosts more peat than previously reported but climatic and topographic contexts leave it as the least peat-forming continent. Our results suggest large biases in our current understanding of the distribution, area and volumes of tropical peat and their continental contributions.

KEYWORDS
climate change, land use, peatlands, tropics, wetlands

1 | INTRODUCTION

Wetlands are global hotspots of biological diversity (Gibbs, 2000; Junk et al., 2006), ecosystem productivity (Rocha & Goulden, 2009) and economic activity (aquaculture, tourism, timber; Junk et al., 2014). They are key regulators of biogeochemical cycles, including water flows and associated nutrients (C, N, P), pollutants and sediments, coastal erosion and land stabilization (Blumenfeld, Lu, Christophersen, & Coates, 2009; Junk et al., 2013; Keddy et al., 2009). Wetlands also play fundamental roles in climate change regulation and mitigation with unmanaged wetlands being the largest and most uncertain natural sources of methane (CH_4) in the global CH_4 budget (Matthews & Fung, 1987; Petrescu et al., 2010, 2015) and the presumed drivers of the interannual variations in CH_4 atmospheric growth rates (Denman et al., 2007; Melton et al., 2013; Montzka, Dlugokencky, & Butler, 2011; Petrescu et al., 2015). Under favourable hydrological conditions undisturbed wetlands are reported to act as moderate CH_4 and N_2O sources (Frolking et al., 2011) or to counterbalance their CH_4 emissions (Petrescu et al., 2015), while also acting as long-term soil carbon reservoirs dating back to the Holocene (Lähteenoja & Roucoux, 2010; Yu, Loisel, Brosseau, & Beilman, 2010). For their multiple ecosystem services, the need for wetland conservation is widely recognized (i.e. the Ramsar convention, Ramsar 2013) but has long been challenged by national development policies and short-term economic priorities (An et al., 2007; Junk et al., 2013; Keddy et al., 2009; Paulson Report, 2015). Thus, drainage, fire and conversion to agriculture and agroforestry are presently turning wetlands and peatlands into net emission sources of GHG (Frolking et al., 2011; Page et al., 2002; Petrescu et al., 2015; Turetsky et al., 2015; Van der Werf et al., 2010), and doing so at an accelerating pace (Davidson, 2014; Junk et al., 2013).

There are considerable uncertainty about fundamental wetland variables such as their global distribution, spatial extent and temporal dynamics (Melton et al., 2013; Montzka et al., 2011; Petrescu et al., 2015; Wania et al., 2013; Zhang, Zimermann, Kaplan, & Poulter, 2016). Efforts to assess global wetland extents, and associated CH_4 emissions include the Wetland and Wetland CH_4 Inter-comparison of Models Project (WETCHIMP; Melton et al., 2013; Wania et al., 2013). Their results concluded that the estimates of wetland area varied ca. fourfold in modelled area simulations (7.1–26.9 Mkm^2) and three-fold (4.3–12.9 Mkm^2) in observational mapping (Melton et al., 2013). The current variability in the estimates of wetland area still precludes the appropriate parameterization of wetland models to assess GHG emissions (Melton et al., 2013; Zhang et al., 2016). Part of the variability in areas and volumes relate to definition issues, and to the temporality of the inundation patterns which complicate comparisons among estimates (Junk et al., 2011, 2014; Page, Rieley, & Banks, 2011). The lack of robust validation processes also affects the available data, particularly in the tropics. This is problematic as tropical peatlands are an important focus of international climate change concerns due to the magnitude of their GHG emissions under climatic and human pressures (Gaveau et al., 2014; Hooijer et al., 2010; Montzka et al., 2011; Petrescu et al., 2015; Turetsky et al., 2015; Van der Werf et al., 2008). The need for developing robust, comparable, and detailed tropical wetland and peatland maps could not be more urgent.

Methodologically, global wetland area assessments are complex (Gallant, 2015) and have relied on either hydrological models or remote sensing, or combinations thereof, but have been restricted to coarse scales (i.e. Global Natural Wetlands by Matthews and Fung (1987); the Global Freshwater Wetlands by Stillwell-Soller, Klinger, Pollard, and Thompson (1995); or the Global Hydrographic Data (GgHydro) by Cogley (2003), or the Global Lakes and Wetlands Database, GLWD, by Lehner and Döll (2004)). Moderate to fine scales have lately been produced by combining multisource remote sensing, hydrological models, and ground sampling, but they focus on specific regions only (e.g. Bwangoy, Hansen, Roy, De Grandi, & Justice, 2010; Draper et al., 2014; Dargie et al., 2017). The results from these studies indicate that the historical records underestimate wetland and peatland areas in the tropics. Considerations when mapping global wetlands and peatlands can be subdivided into:

1. *Preassessment choices:* including variations in the definitions of wetlands and peatlands, and different spatial and temporal scales used for estimating wetland and peatland areas. (Estupinan-Suarez et al., 2015; Junk et al., 2014; Matthews & Fung, 1987; Page et al., 2011; Zhang et al., 2016)
2. *Assessment constraints:* Methodological choices, which range from the interpretation of analogic maps and topographic data to hydrological modelling and to remote sensing both passive (optical, microwave) and active (radar, LIDAR). Each method is constrained by data availability, which is often cumbersome in tropical regions. (Ballhorn et al., 2009; Draper et al., 2014; Estupinan-Suarez et al., 2015; Melton et al., 2013; Wania et al., 2013)
3. *Postassessment limitations:* lack of ground-truthing data sets to validate the location, area and carbon stocks of the identified wetlands and organic soil areas. Frey and Smith (2007).

Partly considering the issues above, in this study we present a novel method for mapping wetlands and peatlands in the tropics and subtropics including estimations of their soil depths, at a spatial resolution of 232 m. Our method draws on the premise that combining different data sources and methods is the best approach to map wetlands and peatlands (Bwangoy, Hansen, Roy, De Grandi, & Justice, 2010; Lang, Bourgeau-Chavez, Tiner, & Klemas, 2015; Zhang et al., 2016). Our pantropical wetland/peatland map uses a hybrid expert system method that combines hydrological modelling, time-series analysis of soil moisture phenology from optical satellite images and hydro-geomorphology from topographic data, to capture key properties of wetland/peatland development.

Our goals are as follows: (1) to characterize the spatial distribution of wetlands and peatlands in the tropics and subtropics; and (2) to estimate the depths and volumes of peatlands. Peat is here defined as any soil having at least 30 cm of decomposed or semidecomposed organic material with at least 50% of organic matter. We compare our wetland results with five well-known global data sets on wetland estimates and our peatland maps with ground peatland points.

2 | MATERIALS AND METHODS

The study covers the tropics and subtropics (38°N to 56°S; 161°E to 117°W; pantropics), includes 146 countries but excludes small islands, New Zealand and Taiwan (see country list in the Supporting Information). Our wetland categorization builds on the Ramsar (2013) definitions of wetlands (for a review of wetland classifications, see Finlayson & van der Valk, 1995). Of the five major wetland types defined by Ramsar (2013), this study concerns estuarine, lacustrine, riverine and palustrine wetlands; marine wetlands are not included. The size limitation used by Ramsar (i.e. 8 ha for defining lakes) is disregarded in this study. In agreement with the Ramsar definitions, but in contrast to the traditional definition of swamps in the United States, swamps are not necessarily forested. While the Ramsar definition is oriented towards ecological habitats, this study is primarily oriented towards soil organic content based on soil moisture conditions. We distinguish between seven main wetland categories: open water, mangrove, swamp, fen, riverine/lacustrine, floodplain (and other intermittent water bodies) and marsh (Table 1). We use the term "swamp" for wetlands with dominating saturated soil conditions. Marshes represent "drier" wetland categories. We recognize floodouts (permanently flooded alluvial deposits) as peat-forming swamps. Four of our seven wetland categories accumulate in situ produced peat (mangrove, swamp, fen and riverine/lacustrine). Open water bodies, intermittent water bodies and floodplains do not accumulate organic matter, whereas some subcategories of marshes can accumulate organic matter (although not forming peat).

Drawing on the methods presented in Gumbricht (2015), we develop a knowledge-based (see Kelly et al. (2013) for knowledge-based and expert systems), top-down approach using expert rules that offer comparable data among countries in a transparent and consistent manner. The expert rules rely on three key properties of wetland development: (1) interannual water input exceeds the atmospheric water demand; (2) annually/seasonally wet or inundated soils (phenology); and (3) a geomorphology that supports water accumulation and wetland development (see summary in Table 2).

2.1 | Interannual water balance—Wetland Topographic Convergence Indices (wTCI)

These indices are modified versions of the well-known Topographic Convergence/Wetness Index (TCI) which originally uses upslope contributing areas and local slope to determine an index of soil moisture for each point (Beven & Kirkby, 1979). For tropical regions, Gumbricht (2015) adopted several modifications (see Supporting Information for details). We applied Gumbricht (2015)'s distributed

TABLE 1 Wetland categories considered in this research

Category	Geomorphology	Moisture conditions	Vegetation and soil conditions
Open water	Lakes and permanent rivers	Open water surface	–
Mangrove	In close proximity to coast or estuaries.	Permanently wet, but with tidal variations in water levels.	Dominated by different mangrove species; peat formation, but with limited depth.
Swamps (incl. bogs)	Usually bound to valleys and plains; planar surfaces.	Wet all year around, but not necessarily inundated.	Usually tree covered. Peat domes with peat depths up to 45 m; otherwise with more limited peat depths.
Fens	In valleys or lower slope positions.	Mainly fed by ground water, and thus a stable water supply.	Often nutrient-rich and with dense vegetation; peat forming.
Riverine and lacustrine	Aligned with the adjacent water body.	Permanently wet.	Varying vegetation, not seldom with zonation reflecting proximity to water source; peat forming.
Floodplains (floodouts)	Floodouts: On alluvial deposits.	Fed by permanent rivers, large variations in water levels but never drying out.	Forested or nonforested; grasses, rushes and sedges; peat forming. Peat forming.
	Floodplains: On alluvial deposits or in valleys	Annual flooding and drying regime with distinct dry season.	Forested or nonforested. No peat formation.
Marshes	General marshes: in valleys and plains, coastal marshes, salt marshes, savannah and prairie marshes, etc.	No distinct intra-annual wetness cycle, permanently moist but not necessarily water-saturated soils.	Usually not forested; grasses, rushes and sedges, but also herbs and bushes; no peat formation, but organic matter accumulation can occur, mixed with minerogenic sediments.
	Wetlands in arid climate: formed in channel valleys and over alluvial deposits.	With a pronounced seasonality in soil moisture regime usually determined by lateral flow components.	Can be regarded as an intermediate category between floodplains/floodouts and marshes, restricted to arid climate. Organic matter accumulation can occur, mixed with minerogenic sediments.
	Wet meadows: transition zones between wetlands and surrounding drylands, sometimes on open slopes.	Varying water source dependent on hydrological position and landscape geomorphology.	Usually dominated by grasslands, woody vegetation if the soil moisture regime allows. No or little organic matter accumulation.

TABLE 2 Summary of the methods used to produce indices applied in the expert rule classification of tropical wetlands and peatlands. The rules are given as generalized semantic statements and are not exhaustive. The restrictions for hydrological terrain relief are given in Table S1. In the table, riverine also includes lacustrine, floodplains also include floodouts, and refET is short for reference evapotranspiration. Mangroves and forested peat domes must have at least 25% tree cover (derived from MODIS product MOD44B). Forested peat domes is a subcategory of swamps

Index	Input data	Method	Generalized expert rule application
Interannual water balance	Precipitation and refET; DEM (SRTM) for flow routing	Distributed hydrological model including flood module; modified versions of the Topographic Convergence/Wetness Index	All wetlands except mangrove: constrained to cells where total annual inflow exceeds refET Forested peat domes: dominated by precipitation that must exceed refET Riverine and floodplain: sourced by flood water Fens: bound to groundwater discharge areas Swamps: bound to wetter sites
Intra-annual soil wetness phenology	MODIS satellite data (MCD43A4)	Estimation of soil wetness using the Transformed Wetness Index; time-series smoothing and phenological characterization	Open water: permanently inundated Mangrove: permanently wet, but allowing for tidal variation Forested peat domes: wet periods dominating, but allowing drier periods Riverine: annual inundation with otherwise wet conditions Floodplain: annual soil wetness variation, including inundation Swamps: permanent wet soils, but not necessarily inundated Marshes: wet periods dominating, but allowing drier periods (subclasses constrained differently)
Hydro-geomorphological characterization	DEM (SRTM) supplemented with surface flow estimates from the distributed hydrological model	Multiscale determination of landform elements; estimation of hydrological terrain relief, slope and curvatures; proximity analysis	Mangrove: within 5 km from sea or estuary at maximum 45 m above sea level, neither channel nor peak Forested peat domes: neither channel nor peak/ridge Riverine: juxtaposition adjacent to water source in plain or valley Floodplains: restricted to plain or U-shaped valley Fens: restricted to lower slopes or valleys Swamps: only restricted by terrain relief (see Table S1) Marshes: restricted to plains, U-shaped valleys or lower slopes

hydrological model to simulate surface run-off, groundwater flow and flooding volumes. The model calculates vertical water balance in each time step (month) and routes surplus water over a DEM while allowing evapotranspiration adjusted by topographic conditions up to the reference evapotranspiration. Flow is separated into ground water and surface flow. A separate routine is used for estimating flood volumes. The model was calibrated against a compiled data set of global statistical run-off data. The estimated flow components are used for deriving both a general wetland TCI (which we call wTCI, Figure 1a), as well as specific versions of wTCI used for distinguishing different wetland categories. Only areas for which the hydrological model estimate annual humid conditions (total water inflow exceeding reference evapotranspiration) are open for wetland development. The specific wTCI versions eliminate different flow components which help distinguish wetland categories based on water sources (Table 2).

2.2 | Soil wetness phenology—Transformed Wetness Index (TWI)

Transformed Wetness Index is an algorithm developed to estimate surface soil moisture content from optical satellite imagery (Gumbricht, 2015, 2016). At its core, TWI is a nonlinear normalized difference index defined by soil brightness and open water optimized for capturing variations in soil moisture, and calibrated against data available from the International Soil Moisture Network (ISMN; Ochsner et al., 2013). We used TWI for estimating intra-annual variations (phenology) of soil surface wetness based on annual time series of MODIS optical images (see Gumbricht, 2016 for details). Apart from the mean soil moisture content (Figure 1b), the soil moisture phenology was used to determine periods of inundation and water saturation, as well as lengths of periods with soil water content above/below given thresholds. The TWI phenology was subsequently used for identifying different wetland categories, ranging from permanent water bodies that require complete annual inundation, to marshes that require seasonal wet soil conditions but no annual inundation (Table 1).

2.3 | Hydro-geomorphological maps and indices

Geomorphological data can assist in both mapping wetlands and interpreting wetland attributes, including wetland class and depth. One problem with geomorphological data is that landforms are usually defined for local or regional conditions, including lithological and vegetation classes (e.g., Ballantine et al. 2005). To avoid this' we mapped

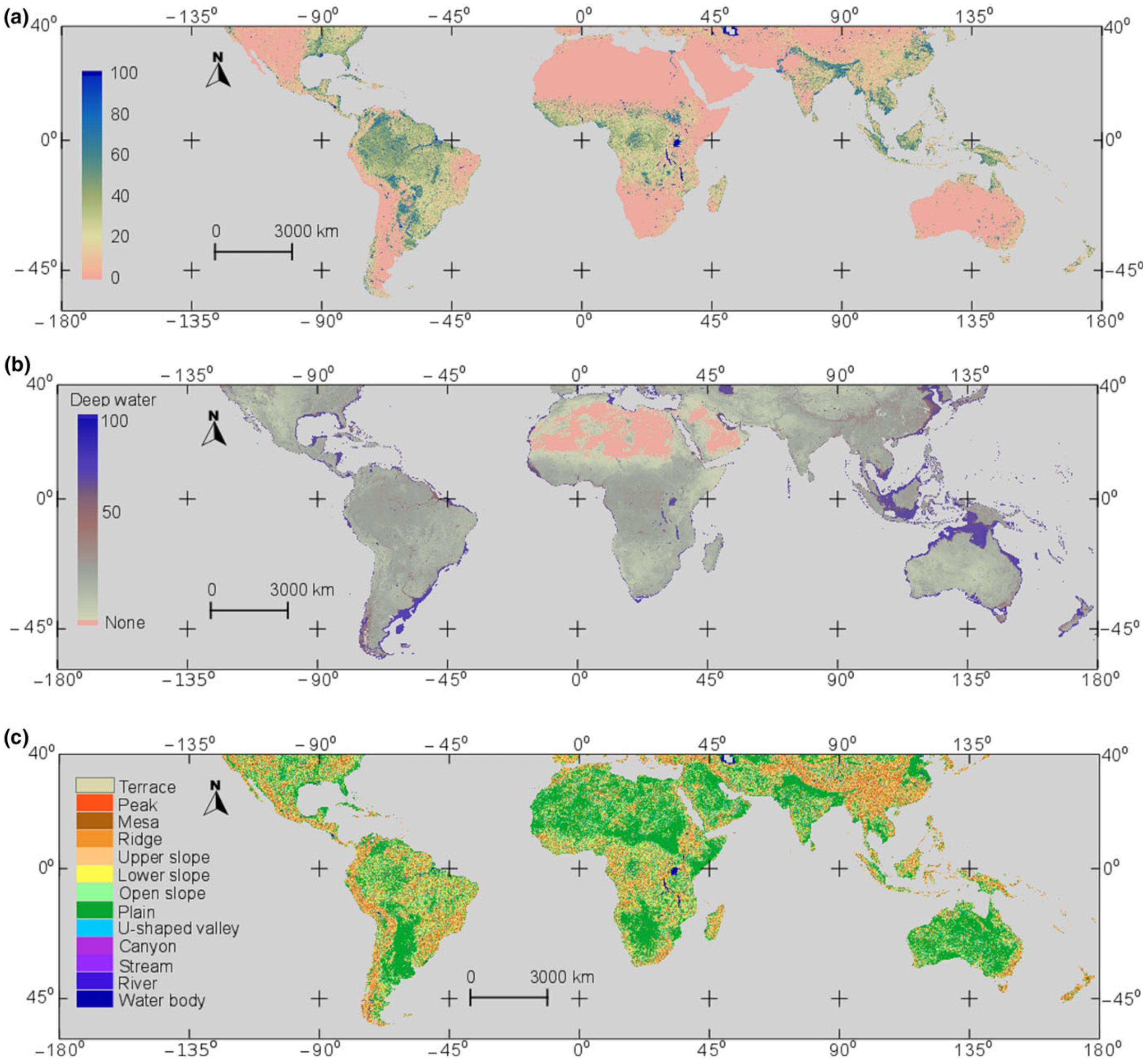

FIGURE 1 (a) Wetland Topographic Convergence Index (wTCI) defined from local vertical water balance, upstream flow accumulation and estimated flood volumes, combined with local topography. wTCI is arbitrarily scaled between 1 and 100 with higher values denoting a wetter surface. Only areas where water input exceeds potential evapotranspiration have values assigned, and the rest are set to zero. (b) Average Transformed Wetness Index (TWI) for year 2011, expressed as the ratio of water volume over total volume, converted to per cent. Assuming a soil porosity of 50%, a TWI of 50 represents a fully water-saturated soil, values above 50 suggest inundation and values of 100 suggest deep open water. (c) Global tropical and subtropical landform map with thirteen geomorphological categories derived from topographic data

general landscape geomorphological elements (i.e. plains, valleys, slopes, ridges) using topographic data as suggested by Weiss (2001). We produced a geomorphological map (Figure 1c) using multiscaled Topographic Position Indices (TPIs; *ibid*) and a more hydro-geomorphological version using multiscale profile curvatures (Wood, 1996). Both maps include the classes suggested by Weiss (2001) supplemented with hydrological features produced by Gumbricht's (2015) hydrological model. Additionally, we produced three maps on hydrological terrain relief, defined as the drop in elevation compared to the nearest drainage point (river, stream, sea; Table S1):

1. Peat dome terrain relieves were wetlands constrained to humid climates that were drained by permanent rivers (identified from the hydrological model). These rivers were used as the reference lowest point, to assign the maximum depth of the organic layer in the peat domes (i.e. drop in elevation between the highest peat dome point and the riverbed elevation)
2. Plain and open slope terrain relieves were wetlands drained by river channels. These channels were used both for identifying potential flood plains and for assigning the maximum depth of riverine/lacustrine wetlands, floodplains, floodouts, swamps and marshes.

3. Valley-bound terrain relieves were wetlands drained by smaller streams. It included fens and marshes' wetland categories. These streams were used as the reference lowest point, to assign the maximum depth for these wetland categories.

2.4 | Data sets

2.4.1 | Model data sets

We used MODIS (MCD43A4) images taken at 16-day intervals for mapping the duration of wet and inundated soil conditions for 2011. Data from adjacent dates in 2010 and 2012 were used to bridge data gaps at the beginning and end of 2011. For the equatorial region (≤10° latitude), the full time series of 2010 and 2012 was used to fill in cloud-related gaps, whereas for other regions we focused on 2011. We used monthly mean precipitation for 1950–2000 from the WorldClim global data set (Hijmans, Cameron, Parra, Jones, & Jarvis, 2005) and monthly evapotranspiration from New, Lister, Hulme, and Makin (2002). For topography, we used a hydrologically corrected version of the Shuttle Radar Topography Mission (SRTM) at 250 m produced by CIAT (International Center for Tropical Agriculture), with an estimated relative error of 1.6–3.3 m (Brown, Sarabandi, & Pierce, 2005). Please see the "caveats, errors and improvements" section, for known errors and caveats in these data sets.

2.4.2 | Wetland comparative data sets

We selected five spatial data sets offering global wetland area estimates, to compare our results.

1. The Global Land Cover GLC250-2010, an aggregation of the GlobeLand30 (National Geomatics Center of China, 2014). The original map is a global land cover map at 30-m resolution based on Landsat TM, ETM and the HJ-1 Chinese satellite for Environmental Disaster Alleviation, for ±1 year around year 2010. Data used here were aggregated to 250 m.
2. The Global Lakes and Wetlands Database GLWD-3 by Lehner and Döll (2004), a global 30-s resolution raster map that was produced by combining existing maps with other data sources on water bodies and wetlands.
3. Matthews and Fung (1987), the first global database of wetlands at 1° resolution is a digitization of traditional maps based on field and aerial surveys.
4. The Global Freshwater Wetlands by Stillwell-Soller et al. (1995), a 1° resolution wetland data set assembled from two data sets: Aselmann and Crutzen's (1989) wetland cover data complemented with Alaskan wetland maps (fens and bogs).
5. The Global Hydrographic Data (GgHydro) by Cogley (2003), a 1° resolution global data set containing hydrological and terrain properties including wetlands.

None of these maps represent, however, ground truthing. They are, instead, area estimates derived from remote sensing and external data sources.

2.4.3 | Peatland profile data set

We compiled a data set of geo-positioned tropical peat profiles with information on peat depth and organic matter content, adhering to our definition of peat ($n = 275$). Points were taken from the literature (N. Herold, unpublished data), and from shared field work data (E. Householder, unpublished data; Fig. S1).

2.5 | Produced maps

2.5.1 | Wetland and peatland maps

The general expert rules assigned for distinguishing the wetland categories adopted in the study are summarized in Table 2. Swamps and marshes each include distinct subcategories, expressed through separate rules in the expert systems. Floodouts are included in the swamp category but methodologically distinguished using a combination of swamp and floodplain rules. The peatland map is derived by separating out the peat-forming wetlands (Table 2). Peat is here defined as any soil having at least 30 cm of decomposed or semidecomposed organic material with at least 50% of organic matter. This corresponds to 29% of carbon content using 1.72 as the transformation factor. Peatlands refer to landscapes with peat deposits without specific thresholds for minimum continuous peat area, nor for minimum depths (further than the 30 cm threshold selected for the definition of peat).

2.5.2 | Soil depth maps

To estimate organic layer depth, we assumed that the terrain relief maps represent the metric distance from the ground surface of wetlands to their mineral bedding. For each wetland category, two depth restrictions were defined: an initial dichotomic restriction on depth occurrence depending on peat formation or not, and a second depth assigning the maximum depth of organic matter using reported values in literature (Table S1). In effect, this means that:

1. We assume that coastal peat domes have their basal level at sea level and that inland peat domes have their basal level coinciding with the levels of adjacent rivers. This is an oversimplification, but data on the depth and mineral bedding of peat domes in South-East Asia support this assumption (A. Hoijer, unpublished data).
2. Extended alluvial deposits with floodouts, including many of the largest pantropical wetlands (i.e. Pantanal in South America, the Sudd, the Niger Inland Delta and the Okavango in Africa, the Indo-Ganges plateau), have surfaces almost perfectly aligned with the geoid. These wetlands can then be assumed to have a near planar (geoid parallel) mineral bedding, with a high degree of certainty (Gumbricht et al., 2002).
3. Valley-bound wetlands and wetlands on open slopes can have highly varying topographic bedding conditions. Anticipating that these wetlands initially developed at level with the feeding/draining channel or stream, we assume that the mineral bedding is

near the level of the adjacent channel or open water, with depth following the general slope profile curvature.

Depths are prompted by biases in the SRTM DEM data (see the "caveat, errors and improvement" section).

2.6 | Validation processes

2.6.1 | Comparison of wetlands and peatlands

We cross-validated our wetland area estimates against the five global wetland area data sets, at the country level (positional errors discourage direct overlay for cross-validation). For peatlands, we compared our peatland area, depth and volume, with Page et al. (2011) at the country level (58 common countries; Table S2). We recognize that several recently researched and quantified large peatland complexes are missing in Page et al. (2011)'s data set. We thus also compare our results with more recent studies on rainforest peatlands in the Amazon and Congo basins, and for nonrainforest histosols in French Guiana.

2.6.2 | Ground validation of peatlands

We overlaid the compiled ground data set of peatland profiles to our map and also created a one-pixel buffer (232 m) for each point, allowing for minor positional inaccuracies. Also, as a visual validation, we contrasted our peatland map against six major peat deposits reported by Lawson et al. (2015; Fig. S2).

2.7 | Caveats, errors and improvements

Our approach suffers from errors in the source data of key variables used in our model: elevation, soil moisture (phenology) and climate. The SRTM digital elevation data (DEM) are erroneous over dense canopies (artificially heighten ground elevation), and over small water bodies (artificially lowered ground elevation). The general tendency of these errors is an overestimation of the soil depth of forested swamps. Comparing our depth estimates with ground profiles, we consequently found a bias in our data that mainly affected our deepest pixels, which showed twofold depth values compared with the profiles' data (see Fig. S3). To account for this bias, we re-estimated countries' peat volumes by halving the established maximum depth thresholds used to parameterize the different wetland types (Table S1). We offer minimum–maximum volumes accordingly. More recent global DEMs including estimates on uncertainties could be used for reducing this threshold effects.

Another source of error lies in the adoption of optical data for time-series analysis and estimation of soil moisture phenology. Optical sensors cannot capture ground conditions under cloud cover, and thus tend to miss floods and inundated soil conditions during wet seasons with persistent cloud cover. Our results thus tend to underestimate floodplains, classifying them as marshes, or escaping detection altogether. Contrarily, we overestimate the extent of wetlands and peatlands as a result of a bias in the Transformed Wetness Index (TWI) that exaggerates the soil moisture content in regions where the canopy casts shadows. TWI includes an indirect removal of the vegetation signal, but dark soils artificially increase soil moisture estimates. This effect is particularly pronounced in temperate needleleaf forests (Gumbricht, 2016). This problem could be overcome by either adjusting TWI for canopy cover, or calibrating the TWI using microwave data. On the other hand, dense stands of wetland grasses and sedges (i.e. reeds and papyrus) cause TWI to underestimate the actual soil moisture conditions. This results in an underestimation of wetland and peatland areas in parts of the Okavango Delta, as well as in the many papyrus- and reed-dominated wetlands along streams and smaller rivers (e.g. Uganda). Other floodout wetlands, that form peat, are thus also omitted or underestimated (i.e. the Sudd in Southern Sudan and the Niger Inland Delta in Mali).

The largest model problem stems from errors in the climate data. Thus, precipitation records over large parts of the tropics, including the Amazon and Congo basins, are inaccurate. Our hydrological model was calibrated against a global set of run-off stations, and any global bias in the climate data should have been overcome. However, we could achieve more accurate run-off predictions using regional calibration settings, by identifying better climate records for different regions or both. Moreover, our study is based on a combination of long-term statistical climate data, but a shorter period of satellite observations for soil wetness analyses. Our soil moisture (phenology) results thus reflect the situation in and around 2011 (2010–2012 for latitudes below 10°). These years do not represent climatic "normality" with 2010/2012 being among the driest/wettest years on record for the tropical region and with 2011 developing strong La Niña that led to excess precipitation and flooding in parts of the tropics (Espinoza et al., 2013; Marengo et al., 2013; Torti, 2012). Excess rainfall in the Amazon during 2011 may have affected TWI and have led to overestimated soil moisture contents, which the model is more prone to assign to peat-forming wetlands. As the access and accumulation of both climate data and satellite observation increase, the model could be adopted for multiyear studies, or even for predicting changes in wetland and peatland area in future scenarios of climate change (see Supporting Information for further suggestions on model improvement).

We lack sufficient data to quantify the errors or to estimate any ranges of statistical accuracies from the accumulated errors and the error propagation. The results presented thus represent a single global model parameterization, with two different depth estimates used for volumetric calculations.

3 | RESULTS

3.1 | Wetlands

Our method estimates the pantropical wetlands cover 4.7 Mkm^2 (5.3 Mkm^2 including open water; Figure 2), which is in the high range of other wetland extents for the same study area (Table 3).

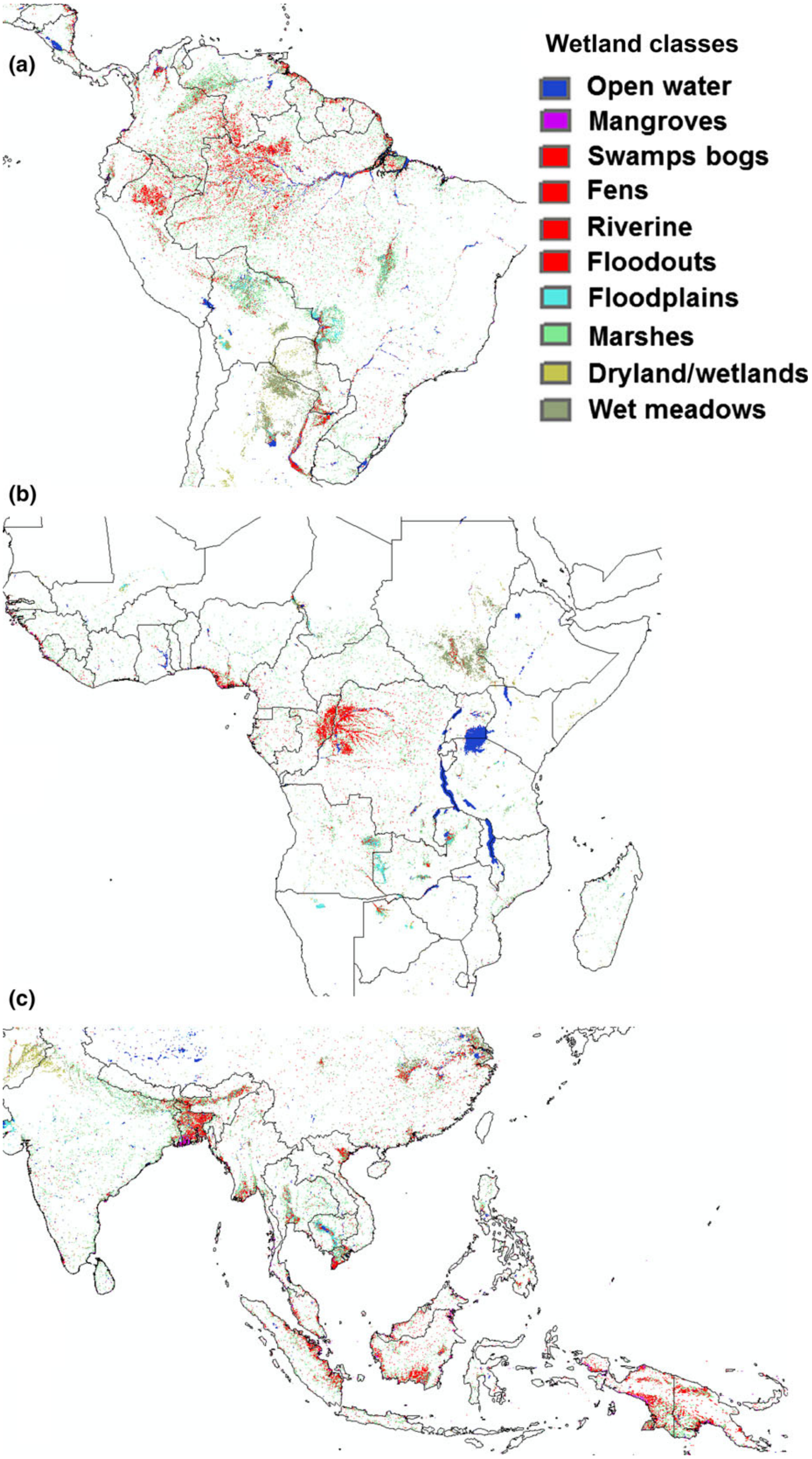

FIGURE 2 Distribution of our wetland classes in the tropics and subtropics (232 m). Colours represent different wetland types. In red are wetlands that form peat

Marshes were our most abundant wetland class (59%) followed by swamps (29% including floodouts) and floodplains (5%). Mangroves are estimated to make up 4% of the total wetland area with ca. 180,000 km^2. Our estimates of wetland area are close to the GLWD data set (4.8 Mkm^2; Lehner & Döll, 2004), and much larger than the GLC250-2010 (1.8 km^2; Table 3). All wetland data sets agreed on four top contributors (i.e. countries that add up to 80% of the total tropical wetland area): Brazil, Indonesia, Argentina and the tropical/subtropical United States (Figure 3). Five of six data sets also agreed on the importance of China, Australia and DRC. Four of six agreed on the importance of Peru, Bolivia, Venezuela and Paraguay. From a continental perspective, all data sets, except Cogley's GgHydro, agreed that America was the largest contributor to wetland areas followed by Asia, except Matthews and Fung (1987) that had Africa as the second largest contributor (Fig. S4).

3.2 | Peatlands

Our model estimates unprecedented areas of pantropical peatlands: 1.7 Mkm^2, an associated peat volume of 7,268 (6,076–7,368) km^3 and a mean depth of 3.6–4.3 m (Table 4, Figure 4). Some of these peatlands are yet underreported, and many of them are outside Asia (Figure 5). Ground validation showed good agreement with 65% of the soil profiles overlaying peat pixels in our maps. Indonesia, where more complete data exist, showed an agreement of 74%. Compared with recent reports on peatland areas, our spatial estimates closely match the peatland areas in the Pastaza–Marañón (Peruvian Amazon, Lähteenoja et al., 2012; Draper et al., 2014; 40,838 vs. 35,600 km^2 our estimates vs. Draper et al., 2014) and the Cuvette Centrale (Congo Basin, Dargie et al., 2017; 125,440 vs. 145,500 km^2; Table 5). Our depth and volume estimates are, however, substantially higher for both sites (Table 5). For the coastal region of the French Guiana our estimated area (2,016 km^2, excluding mangrove) is close to early estimates of peatland extend reported for the region (i.e. 1,620–1,720 km^2), but higher than the latest reports (Cubizolle et al., 2013).

TABLE 3 Area estimates of tropical wetlands for our study area and global extent, for our data set and six other data sets. Global estimates are extracted from Melton et al. (2013)

Wetland classes	Area for the tropics and subtropics km^2
Open water	604,670
Mangroves	179,795 (4%)
Swamps	1,003,719 (21%)
Floodout swamp	366,314 (8%)
Fens	142,860 (3%)
Riverine	3,842 (0.1%)
Floodplain	247,448 (5%)
Marshes	1,665,660 (35%)
Marshes—Dryland/wetland	275,273 (6%)
Marshes—Wet meadows	846,004 (18%)
Total Wetlands[a]	4,730,921

Other wetland data sets	Area for the tropics and subtropics Mkm^2	Global area[a] Mkm^2
This study	4.7	
GLWD-3 Lehner and Döll (2004)	4.8	9.2
Stillwell-Soller et al. (1995)	3.4	4.8
GgHydro Cogley (2003)	2.8	4.3
Matthews and Fung (1987)	2.2	5.3
GLC250-2010 National Geomatics Center of China (2014)	1.8	2.6
Aselmann and Crutzen (1989)		5.7

[a] Total wetland areas do not include open water.

For the same study area previously reported by Page et al. (2011), our estimates are ca. threefold tropical peat areas (1.5 vs. 0.44 Mkm^2) and volumes (6,991 vs. 1,758 km^3; Table 4). Among the top contributors to pantropical peat area and volume (understood as countries adding up to 80% of the tropical peatland area) are, in this order: Brazil (18%, 20%), Indonesia (13% and 18%), DRC (7%, 10%), China (5%, 3%), Colombia (4%, 5%), Peru (4%, 6%), United States (4%, 2%), Bangladesh (3%, 3%), India (3%, 2%) or Venezuela (3%, 4%), among others (Figs S5–S8).

In terms of peatland area, continental areas show twofold increases in Asia and three- to fourfold increases in South America (Table 4), while the recent reports by Dargie et al.(2017) put our estimates at approximately 1.25 times the current estimates for Africa. South America (with a tropical area contribution of 46%) and not Asia (36%) holds the largest area of tropical peatland according to our estimates (Table 4). Brazil (312,250 km^2) and not Indonesia (225,420 km^2) leads the contribution to tropical peatland area (Table 6). A comparison of top contributors highlights differences between our data and existing estimates: (1) unaccounted countries (i.e. Argentina and the United States are top contributors in our study but unaccounted in Page's); (2) previously not recognized top contributors (i.e. India, Bangladesh or Viet Nam); (3) countries in our study with substantially higher estimates (i.e. Colombia, China and Venezuela) compared with existing records; and (4) countries for which we estimate large peat deposits that were previously unrecognized (i.e. Zambia, Sudan, Uganda, Guyana and Panama; Figs S5 and S6). Peatland volumes: our results indicate a general increase in tropical peat volume on all the continents (Table 4). According to our estimates, South America (42%) holds the largest peat volume followed by Asia (39%; Table 4), with Brazil (1,489 km^3) holding more volume than Indonesia (1,388 km^3; Table 6). Top contributors with underreported contribution include Brazil, Peru, Venezuela, Colombia, Argentina, Colombia, China, India and Bangladesh (Figs S6 and S7). Peatland depths: Depth plays a role in the volume increases outside Asia. Thus, while our Asian area estimates more than double Page et al.'s, they barely double their volume (Table 4). Along this line, our estimates for Indonesia and Malaysia (area, volume, depths) are very close to those previously reported (Table 6). Asian differences then relate to some unaccounted deep deposits such as those in Indonesian Papua, but mainly to extended but less deep deposits in the river deltas of Bangladesh, Viet Nam, Cambodia, Myanmar, Thailand or Brunei (Fig. S8). Five of the fifteen countries with the deepest peat deposits in our data are in South America (Ecuador, Suriname, Peru, Brazil, Venezuela), and five in Africa (Congo, DRC, Nigeria, Ivory Coast, Equatorial Guinea; Fig. S8).

If we select standard values for bulk density (0.09 g/cm^3) and for carbon content (56%), as in Page et al. (2011), we would report 350 GtC, more than three times current estimates, including recent discoveries.

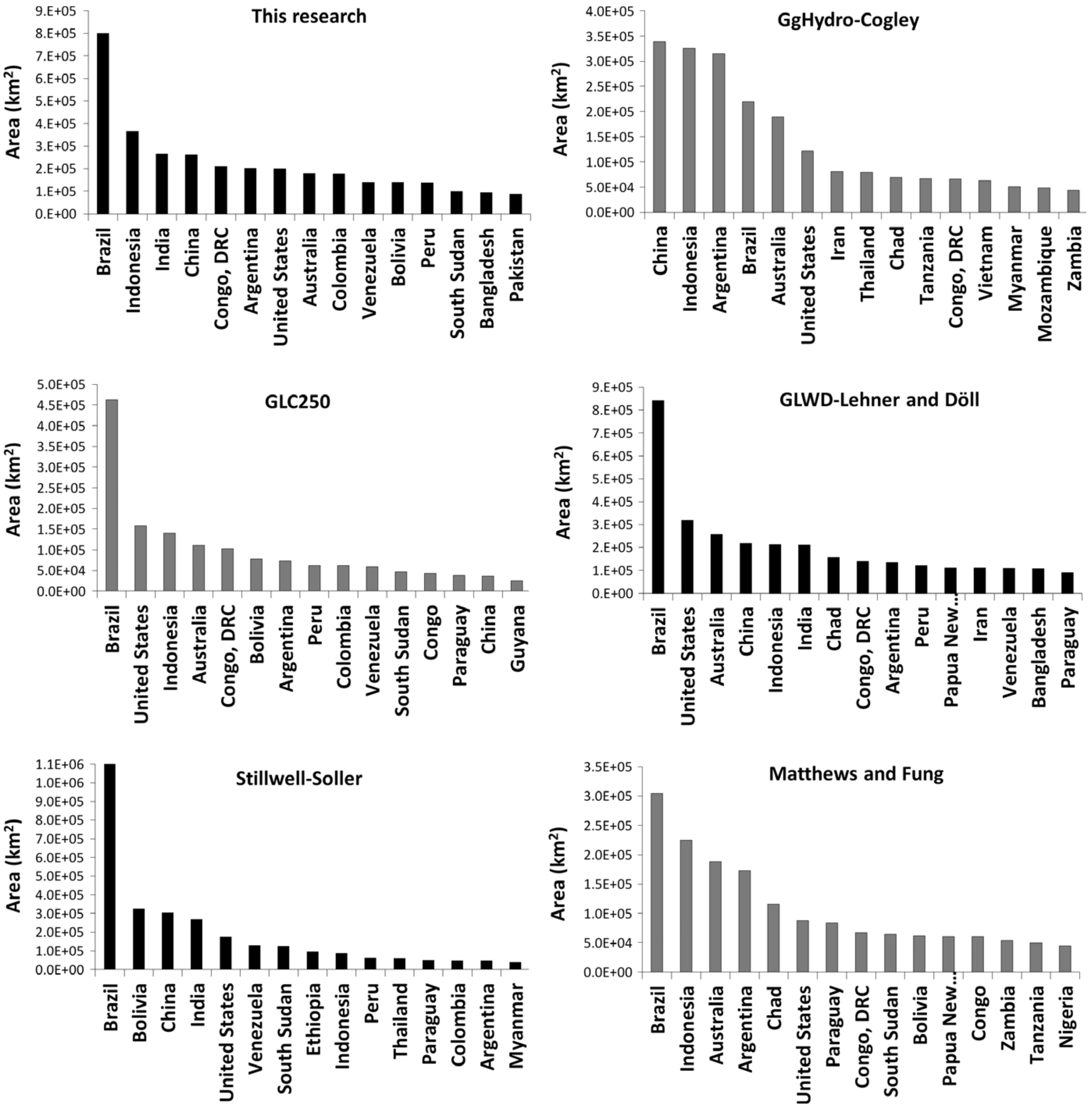

FIGURE 3 Country contribution to tropical wetland area by order of area importance, from this study and from five other wetland data sets: The GLC250-2010 (National Geomatics Center of China, 2014); the Global Lakes and Wetlands Database by Lehner and Döll (2004); Matthews and Fung (1987); the regional Freshwater Wetlands by Stillwell-Soller et al. (1995); the GgHydro by Cogley (2003). Comparisons to independent data sets were performed on spatial subsets consistent with this study. Please note that y-axes have different scales

4 | DISCUSSION

A fundamental problem when mapping wetlands and peatlands is the lack of standardized criteria by which wetlands and peatlands are defined and identified, and the lack of classification systems that take into account specific hydrological conditions and respective plant communities (Junk et al., 2011, 2014). Our approach considers some of these constraints by developing a hybrid wetland mapping method that combines topographic data and hydrological modelling with time-series data on soil moisture retrieved from optical satellite imagery. This approach allows to map pantropical wetland and peatland extents at an unprecedented scale of 232 m using a single method and a single parameterization. The method is deterministic in its core and is based on expert rules which can be easily adjusted by experts, for regional conditions. The method is, however, affected by errors in the source data and model, for which we have

TABLE 4 Peatland areas, volumes and carbon contents as reported by Page et al. (2011) and by this study. M = 10^6, million. Note that the recently researched peatland complexes in primarily Africa and America are not included in the data from Page et al. (2011), see text

	Total area Mkm²	Volume km³	Depth (m)	Continental peatland area (km²) and contribution (%)			Continental peatland volume (km³) and contribution (%)			Depth (m)		
				Asia[c]	America[d]	Africa	Asia	America	Africa	Asia	America	Africa
Page et al. (2011)	0.44 (0.39–0.66)	1,758 (1,585–1,822)	2.3	254,115 (241,451–347,051) (57%)	130,860 (116,096–175,146) (30%)	55,860 (29,464–135,043) (13%)	1,368 (1,322–1,396) (78%)	252 (228–266) (14%)	138 (70–161) (8%)	3.2	1.4	2.5
This study[a]	1.5	6,991 (5,765–7,079)	3.7–4.5	618,979 (36%)	629,189 (46%)	257,038 (18%)	2,699 (2,209–2,729) (39%)	2,916 (2,414–2,959) (42%)	1,376 (1,142–1,391) (20%)	3.6–4.4	3.9–4.7	4.4–5.2
This study[b]	1.7	7,268	3.6–4.3	647,764 (38%)	750,000 (44%)	291,407 (17%)	2,730 (2,376–2,763) (38%)	3,117 (2,350–3,160) (43%)	1,411 (1,213–1,429) (19%)	3.5–4.3	3.5–4.2	4.1–4.9

[a] To allow comparisons, values reported on this row correspond to the same countries as reported by Page et al. (2011) (i.e. 58 common countries). See Table S2 for the country list.

[b] Values reported on this row correspond to the study area of this research, which is larger than Page et al. (2011)'s and covers the tropics and the subtropics (i.e. 146 countries). Contributions from the Middle East are not shown (area: 10,829 (0.6%); volume: 9 (0.1%); depth: 1 m).

[c] Asia includes South-East Asia (Brunei, Indonesia, Malaysia, Myanmar, Papua New Guinea, Philippines, Thailand, Viet Nam), other Asian countries (Bangladesh, China, India, Sri Lanka) and the Pacific (Australia—Queensland, Fiji), as in Page et al. (2011).

[d] America includes Central and South America.

suggested different solutions (see the "caveats, errors, improvements" section).

While the extent and volume of wetlands and peatlands remain unknown due to unavailable ground data against which to validate existing estimates, our modelled estimates showed good agreement with our collected field points. Our hybrid approach suggests, however, comparatively larger wetland and peatland extents and volumes than currently reported in other data sets. This is partly because our approach avoids omissions including undetected inundation patterns under dense canopy covers (Estupinan-Suarez, Florez-Ayala, Quinones, Pacheco, & Santos, 2015; Hess et al., 2015). These last authors report 25% of wetland area omissions in the Amazon when using optical remote sensing alone over areas with dense tree cover. Our approach also reduces commission errors compared with remote sensing or hydrological modelling alone, by including topographic data, which Bwangoy, Hansen, Roy, De Grandi, and Justice (2010) reported improved wetland mapping. Moreover, we do not exclude wetlands/peatlands under human use and paddy rice that fulfils the wetland thresholds would be included. Our approach also identifies seasonally inundated wetlands besides permanently inundated areas, and we detect soil wetness and topographic conditions that favour waterlogging in the absence of flooding (due to rain-fed or groundwater-fed sources). As expected, our finer spatial scale (232 m) captures smaller wetland features that add up to significantly larger areas than previously reported, as it was the case for the Amazon (Hess, Melack, & Simonetti, 1990; Junk et al., 2013) and for the Congo Basin (Bwangoy, Hansen, Roy, De Grandi, & Justice, 2010).

Our results underestimate, however, wetland and peatland areas in some regions, and our model misclassifies some particular wetland categories (floodplains, riverine). Most notably, our model and parameterization do not capture mountainous wetlands and peatlands, including the Paramos and Puna in the Andes (Benavides, 2014; Román-Cuesta et al., 2011; Ruthsatz, 2012; Salvador, Monerris, & Rochefort, 2014), Campos de Altitude in Brazil (Behling, 2007) and Tepuis (Zinck & García, 2011). We also miss drained and degraded peat domes as their surfaces have dried out (see the case of the Sumatran peats in the discussion). Floodplains and riverine wetlands suffer from classification biases, the first due to persistent cloud cover that might miss flooding episodes and tends to recategorize floodplains as marshes and the second due to a scale problem with smaller and narrower wetlands escaping detection (Kaptue-Tchuente, Roujean, & De Jong, 2011). Solving these problems would require a stratified model parameterization for mountainous regions, microwave observations to assess soil moisture under clouds, for floodplains, and the adoption of higher-resolution DEM and satellite data for narrow channels (riverine wetlands).

4.1 | Wetlands

Our wetland area estimate (4.7 Mkm²) is the closest to the GLWD-3 data (4.8 Mkm²; Lehner & Döll, 2004), which Hess et al. (2015) also identified as the closest data set to their Amazonian radar-based wetland research. Multisource approaches, such as GLWD, should

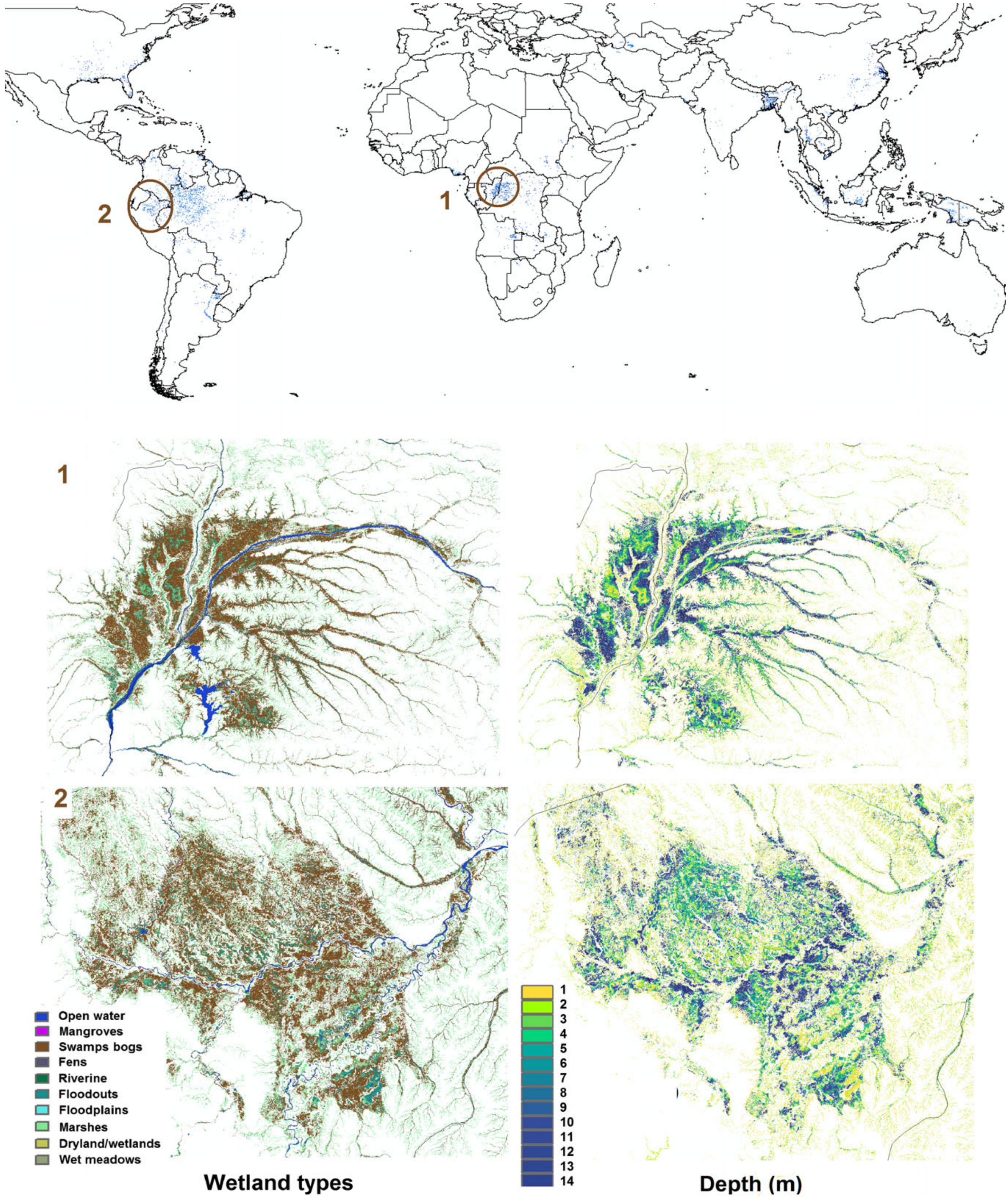

FIGURE 4 Distribution of tropical and subtropical peatlands with black circles locating colossal peat deposits in (1) the Cuvette Centrale, in the border between Congo and Congo-DRC; and (2) the Pastaza–Marañón in Peru. The lower panels show the detailed wetland composition and depths (m) of these peat deposits as produced by our maps. Swamps, riverine and floodout swamps are the wetlands that form peat in these complexes

therefore be preferred for wetland mapping as they better capture wetland attributes and can yield estimates closer to those of fine-resolution mapping (Hess et al., 2015). Our estimates are also in line with Melton et al. (2013) who suggest that available global wetland maps underestimate the wetland extent in the humid tropics, as supported by unmodelled but remotely sensed and atmospherically

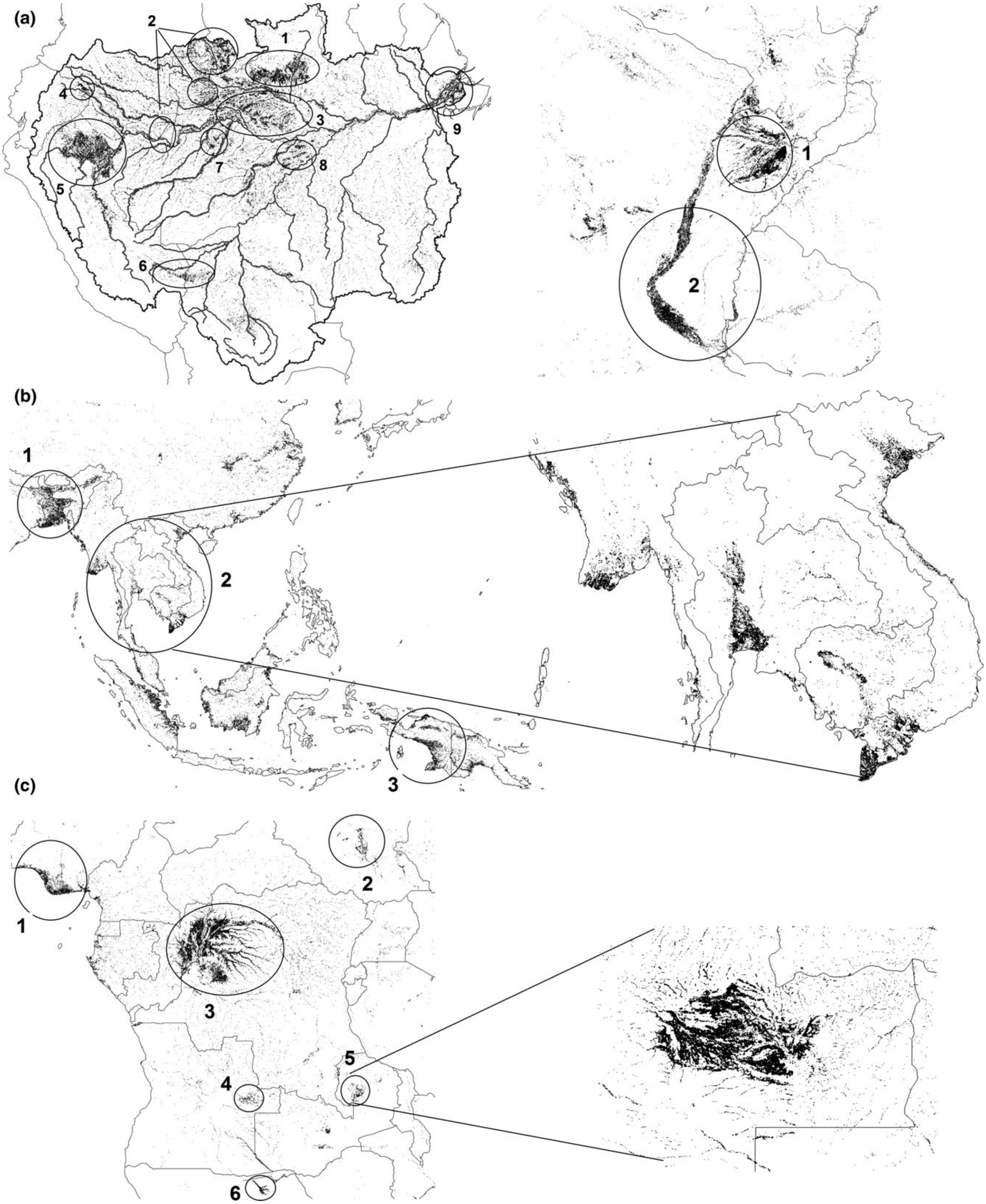

FIGURE 5 Nonexhaustive view of underreported peat deposits identified in this study in South America (a), Asia (b) and Africa (c). Some key peat areas in South America include the Amazon Basin (nine different sites), and (1) the Ibera Wetlands; (2) La Plata River and tributaries (Paraguay and Paraná), both in Argentina. Asia contains more peat than reported in river deltas, particularly in (1) Bangladesh; and (2) the Mekong and Red rivers in Viet Nam, Irrawaddy in Myanmar/Burma, Chao Phraya in Thailand and the wetlands of the lower Mekong River in Cambodia; and (3) Indonesian Papua. African underreported peatlands include (1) the Niger River Delta; (2) the Sudd in South Sudan; (3) the Cuvette Centrale (recently ground-validated by Dargie et al. (2017)); (4) the Cameia wetlands in Angola; (5) the Bangweulu and other wetlands in Zambia; and (6) the Okavango Delta in Botswana

TABLE 5 Comparison of the results presented in this study with more recent studies including ground data collection and/or refined spatial mapping efforts

	Area (km^2) (other study)	Area (km^2) (this study)	Volume (km^3) (other study)	Volume (km^3) (this study)	Depth (m) (other study)	Depth (m) (this study)
Pastaza–Marañón (Draper et al., 2014)	35,600	40,838	707	257	2.0	6.3
French Guiana (nonrainforest region) (Cubizolle et al., 2013)	975	2,016 (excl. mangrove)	Not given	8.4	Not given	3.8
Congo Basin (Dargie et al., 2017)	145,500	125,440	600	915	4.2	6.9

TABLE 6 Area (km^2), volume (km^3) and depths (m) in Page et al. (2011) data and in this study, for the three top country contributors in each continent based on the results of this research. Depths in Page et al. represent mean best estimates while ours represent the mean depths from all the peat-forming wetlands (mangroves, swamps, fens, riverine wetlands and floodout swamps). Latest published peat areas in Peru and DRC-Congo are not included in these estimates (see Table 5 for these values)

		Area (km^2) Page et al. (2011)	Area (km^2) this study	Volume (km^3) Page et al. (2011)	Volume (km^3) this study	Depth (m) Page et al. (2011)	Depth (m) this study
Asia	Indonesia	206,950 (206,950–270,630)	225,420	1,138 (1,138–1,157)	1,388 (1,089–1,396)	5.5	4.9–6.2
	Malaysia	25,889 (22,490–29,649)	29,649	181 (157–182)	180 (142–181)	7.0	4.8–6.1
	Papua New Guinea	10,986 (5,000–28,942)	45,018	27 (13–33)	220 (177–222)	2.5	3.9–4.9
South America	Brazil	25,000 (15,000–55,000)	312,250	50 (3–59)	1,489 (1,218–1,512)	2.0	3.9–4.8
	Colombia	5,043 (3,390–10,000)	74,950	3 (2–4)	327 (277–332)	0.5	3.7–4.4
	Peru	50,000 (50,000–50,000)	74,644	88 (88–88)	449 (385–453)	1.75	5.2–6.0
Africa	Congo-DRC	2,800 (400–10,000)	115,690	11 (2–13)	747 (633–754)	4	5.5–6.5
	Congo	6,219 (2,900–16,177)	43,769	47 (22–50)	345 (286–346)	7.5	6.5–7.9
	Nigeria	1,840 (120–7,000)	21,685	9 (1–11)	113 (97–114)	5	4.5–5.2

detected wide-spread CH_4 emissions (Frankenberg et al., 2008; Montzka et al., 2011). Regionally, our model identifies Brazil as the major contributor to South American wetlands (800,720 km^2 without open water, and ca. 56% of the Amazon Basin area), and the major contributor to tropical wetland area (17%), followed by a distant Indonesia (7.7%), India (5.6%), China (5.5%), DRC (4.4%) and several American countries (Argentina (4.3%), United States (4.2%), Colombia (3.8%), Venezuela (3.0%), Bolivia (2.9%) and Peru (2.9%)). All the data sets, except the GgHydro, agreed on the major role of Brazilian wetlands. Our wetland area estimate for Brazil is in line with GLWD, GFW and Matthews and Fung (1987), but conservative compared with Junk, Fernandez Piedade, Parolin, Wittmann, and Alho. (2010), Junk et al. (2011, 2013) who offer educated guesses of ca. 1.4 Mkm^2 (20% of the Brazilian territory), and up to 2 Mkm^2 when small order streams are included. Hess et al. (2015) suggest lower wetland area estimates for the Amazon Basin: 840,000 km^2 (52% in Brazil), using radar-derived approaches. This last estimate does not include, however, nonflooded waterlogged soils as they are not detectable with L-band SAR radar methods.

Continentally, all databases agree that tropical and subtropical America (including the United States) is the main contributor to pantropical wetlands, mainly driven by South America. This relates to the presence of vast river systems such as the Amazon, Orinoco and Paraná/Paraguay rivers that hold the highest discharge flows in the world and whose flat interfluvial areas are periodically flooded forming extended wetlands (see Junk et al., 2011). Complex wetland types have been defined for the Amazon Basin, many of them belonging to the floodplain category with a pulsing water level (up to 10 m difference) and pronounced dry and wet periods (Junk et al., 2011, 2013). The concept and definition of floodplain open up to an interesting discussion that affects the estimates of tropical peat. Thus, floodplains, under our definition, are wetlands fed by river rising and associated flooding but with soils that dry out during the dry season. Floodplains do not form peat (Table 2). The categorization of Amazonian wetlands as floodplains would therefore exclude peat formation in the Amazon. However, our model sees at 232 m of spatial resolution that many Amazonian soils are too wet to be floodplains. Many are either wet all year around although not necessarily flooded (i.e. rainfall-fed such as swamp bogs, or groundwater-fed such as fens), or are river-fed with large variations in water levels but never drying out (i.e. floodout swamps; Table 2). Thus, our model categorizes the Brazilian Amazonian wetlands into swamps (26%), fens (6%), riverine (oxbow lakes; 0.1%), floodout swamps (6%), floodplains (5%) and marshes (46%), with the first four classes forming peat (38%). Our model sees only 5% of floodplains, against Junk, Fernandez Piedade, Parolin, Wittmann, and Alho. (2010)'s educated guess of 35% of floodplains in central Amazonia. On the other extreme of soil humidity are the marshes (46%), which our model captures as areas with seasonally drying soils (Table 2). However, marshes are a loose category in our model that occurs when dryness is beyond floodplain thresholds and, as explained before, the 46% area of marshes likely includes misclassified Amazonian floodplains. Nor marshes nor floodplains form peat (Table 2) and our high peat areas mainly related to the swamp categories. In general, our peat area estimates may reflect a data bias due to the use of year 2011 for the soil wetness index, which was an anomalously wet year. Further, multitemporal data are needed to confirm whether soil humidity in the Brazilian Amazon and elsewhere is in average as high as detected, or year 2011 is biasing the results towards more humidity and therefore larger areas of wetlands and peatlands.

Several rivers such as the Nile, Zaire, Niger, Zambesi and Okavango with fringing floodplains and internal deltas dominate the scenario of African wetlands (Junk et al., 2013). Most of them have a pronounced wet and dry period and are also subject to a flood pulse (Junk et al., 2013). However, as it happened in the Amazon Basin, hydrological and soil moisture conditions make our model reclassify some of these floodplains as wetter peat-forming wetlands (i.e. swamps). For the case of Congo-DRC, this reclassification probed correct, with our model estimating 46% of hydrological peat-forming swamps in the area of DRC's Cuvette Centrale (ca. 100,000 km^2) versus the 145,500 km^2 of swamps reported by Dargie et al. (2017) for the entire Cuvette Centrale region (Figure 4 and Fig. S2). These values are also in line with Vancutsem, Pekel, and Evrard (2009) who reported 108,713 km^2 of wetlands for DRC (94% forested). Our model identifies DRC (24% of the African wetland area, 210,133 km^2 and 4.4% of pantropical wetland area), South Sudan (11%), Congo (7%), Zambia (7%), Angola (6%), Nigeria (5%) and Tanzania (2.6%) among the major wetland contributors in Africa. In Asia, monsoonal climate favours the occurrence of intermittent wetlands and together with varied local climatic conditions leads to a large diversity of wetland types and extents (Junk et al., 2013). Large SE Asian rivers such as the Mekong, Ganges, Brahmaputra, Irrawaddy, Indus are accompanied by extended fringing floodplains and form large deltas. Indonesia (22% of Asian wetlands and 7.7% of pantropical wetlands), India (15%), tropical China (15%), tropical Australia (10%), Bangladesh (5%), Pakistan (5%) and Papua New Guinea (4%) are among our largest wetland contributors in Asia.

4.2 | Peatlands

Our estimate of pantropical peatland areas and volumes are threefold the statistical data compiled by Page et al. (2011) at country level. These authors did not include, however, some of the large peatland complexes recently researched outside Asia, which our data showed good agreement with: Cuvette Centrale Congolaise (Bwangoy, Hansen, Roy, De Grandi, & Justice, 2010; Campbell, 2005; Dargie et al., 2017; Evrard, 1968) and the Pastaza–Marañon (Draper et al., 2014; Lähteenoja et al., 2012). As it was the case of wetlands, the lack of a standardized definition of peatland also hampers the comparison of peat estimates (Biancalani & Avagyan, 2014). In our case, our peat definition is an expert assumption and more fieldwork is needed to validate whether our maps correctly locate peat and whether this peat responds to the way we define it (≥50% organic content and ≥30 cm deep). Some peat overestimation may then be expected because our model does not account for disturbances such as fire or river dynamics (i.e. erosion), nor does it consider soil lithology other than through soil wetness responses, and some areas with hydrological good conditions may not store peat (Lähteenoja et al., 2012). However, our data showed good validation results (65%) and good visual agreement with Lawson et al. (2015)'s six largest tropical peat reservoirs (Fig. S1). Therefore, and while further ground validation is needed, we sustain that our large peat estimates are realistic and far much more peat exists in the tropics than previously estimated.

Our peatland data highlight current misconceptions in peat area estimates, distributions and continental contributions, which currently hold South-East Asia as the major tropical contributor (Page et al., 2011). As mentioned by other researchers, African and South American peats remain poorly studied due to logistic (i.e. accessibility) and methodological constraints (i.e. cloud persistence for remote sensing, or lack of climate data for hydrological modeling; Schulman & Ruokolainen, 1999; Ruokolainen, Schulman, & Tuomisto, 2001; Lähteenoja, Ruokolainen, Schulman, & Oinonen, 2009; Householder, Janovec, Tobler, Page, & Lähteenoja, 2012; Draper et al., 2014; Lawson et al., 2015; Dargie et al., 2017). In our model, South American peat areas overpass the Asian contribution, with Brazil hosting larger areas (18% of pantropical peat area) and volumes (20% of pantropical peat volume) than Indonesia (13% and 18%), which only but mirrors its role as the largest wetland country in the tropics. This new ranking is likely an underestimation due to the omission of extended montane peats along the Latin American mountain ranges. South-East Asian peatlands will likely remain as the most extensive and deepest tropical peats (Lähteenoja, Flores, & Nelson, 2013; Page et al., 2011) as Latin American peat depths are thinner and vast continuous extents of peat are rarer (Lähteenoja et al., 2013). Thus, with some exceptions, the Brazilian peat would relate instead to smaller and shallower peat deposits that add up to large extensions and volumes.

African peatlands are the least known (Cris, Buckmaster, Bain, & Bonn, 2014; Joosten, Tapio-Bistrom, & Tol, 2012). However, due to climatic and topographic contexts, our results suggest that this continent hosts the lowest peat areas (257,038 km^2) and volumes (1,376 km^3) and suffers from less underestimation than the American continent. The equatorial Congo Basin constitutes the second largest river basin on Earth with 3,747,320 km2 of catchment area (Runge, 2008). Its central section counts on vast stretches of swamp forest (Bwangoy et al., 2010) with reported peat accumulations of up to 7 m. This area is known as the 'Cuvette Centrale Congolaise' (Campbell, 2005; Dargie et al. 2017; Evrard, 1968). Besides the large wetland and peatland areas of the Cuvette Centrale (Campbell, 2005; Dargie et al., 2017; Evrard, 1968; Runge, 2008), extensive peats occur associated with inland deltas such as the Okavango Delta and the Sudd in Botswana and South Sudan, respectively (McCarthy, 1993). Coastal peat deposits, such as those on the Indian Ocean seaboard (i.e. the Mfabeni peat in South Africa) have also reported up

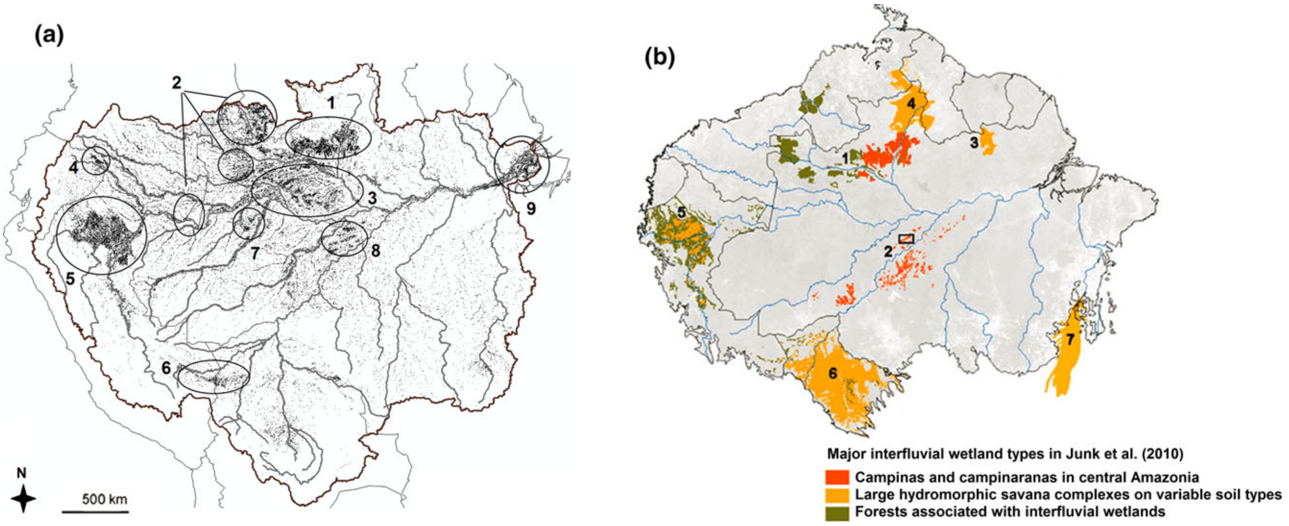

FIGURE 6 Comparison of our Amazonian peat hotspots (a) versus hydromorphic habitats in Figure 5 in Junk et al. (2011) (b). Please note that Amazon Basin boundaries differ

to 12 m of peat (Grundling, Van den Berg, & Price, 2013). For Asia, and compared with the Indonesian peatland map (Wahyunto, Nugroho, & Sulaeman, 2014), our results for swamps (excluding mangroves and floodouts) underestimate the peatlands in Sumatra (46,000 km^2 compared to 56,000 km^2) due to drained peatland that our model does not capture, but overestimate the extents for Papua (51,000 km^2 compared with 39,000 km^2).

Besides these known peat areas, our model suggests several underreported peatland hotspots that would require further research and field validation (Figure 5): the Amazon Basin, Argentina, Niger, Angola, Bangladesh and several river deltas in South-East Asia. The Amazon Basin plays an important role in the observed continental shift on peatland weights. Our model estimates a peatland area and volume of ca. 544,910 km^2 and ca. 2,600 km^3, implying that 38% of the Amazonian wetland area forms peat. Brazil, Peru, Colombia and Venezuela appear as the major contributors. Amazonia harbours a variety of ecosystems that can store organic matter due to waterlogging conditions (i.e. forested and grassy swamps in lowland savannas; swampy palm forests and mixed swamp forests in the rainforest; waterlogged vegetation on *tepuis*; Junk et al., 2011). However, peat formation does not always occur and its presence depends on at least six factors (Lähteenoja et al., 2013): rainfall and hydrology (i.e. amount of rain, increased frequency of droughts), tectonic conditions, topography, minerogenic subsoil types, river dynamics and frequency of fires.

Educated guesses of peatland area in the Amazon range between 150,000 km^2 (Schulman & Ruokolainen, 1999; Ruokolainen et al., 2001; mainly swamps), 200,000 km^2 of (semi)permanently flooded woody vegetation (Hess et al., 2015) and 488,374 km^2 of major interfluvial wetlands affected by uncertain but periodically floodable or waterlogged conditions (Junk et al., 2011), which could potentially accumulate peat. Our peat estimates are higher than these educated guesses due to peat presence in new Amazonian areas (Figure 6a). Junk et al. (2011) identified seven major Amazonian regions that could potentially form peat (Figure 6b, figure 5 in Junk et al. (2011); see Supporting Information for further details). Field efforts have confirmed peat presence in region 1, in the middle Rio Negro Basin (Lähteenoja et al., 2013) and in the upper Rio Negro Basin (Bardy, Derenne, Allard, Benedetti, & Fritsch 2011; Do Nascimiento et al., 2004; Dubroeucq & Volkoff, 1998; Horbe, Horbe, & Suguio, 2004; Montes et al., 2011). Extended peat deposits have been described in region 5, in the north-western Amazonian Pastaza–Marañón river basins (Lähteenoja et al., 2009; Draper et al., 2014; up to 9 m). Smaller deposits exist in region 6 (Figure 6b), in the south-west Amazonian Madre de Dios river Basin (Householder, Janovec, Tobler, Page, & Lähteenoja, 2012; up to 9 m). Our model predicts more Amazonian peat in already identified peat-forming areas such as the Rio Negro Basin (regions 1, 2; Figure 6a); and new peat hotspots in: (1) the area between the Purus and Madeira rivers (region 8); (2) the Island of Marajo (region 9); (3) some Ecuadorian large deposits in the border with Peru, between the upper Napo and the Putumayo rivers (region 4); and (4) locally extended deposits of peat in varzeas in west-central Amazonia (i.e. region 7 and part of region 3; Figure 6a). From these Amazonian hotspots, those on the Rio Negro Basin are contested (F. Wittmann and A. Quesada, personal communication) and would require further fieldwork. Soil drying, the presence of fire and low vegetation productivity due to poor nutrients in blackwater rivers are arguments exposed against our extended peat areas in the Rio Negro Basin (F. Wittmann, personal communication).

Our model estimates larger areas and volumes of wetlands and peatlands compared with hitherto published global estimates. Despite that some regions have overestimated wetland and peatland areas, we believe that our area estimates are rather an underestimation for both wetlands and peatlands, whereas the total peatland volume is more likely an overestimation. The massive scale, isolation and unavailability of most Latin American and African peatlands have so far protected them from large-scale human degradation, keeping them out of the interest of the international community, in opposition to the heavily disturbed Asian peatlands. New climatic stresses, such as increased droughts and fire frequencies could, however, reverse their forgotten status (Junk et al., 2013; Malhi et al., 2008). If proven correct, our peatland estimates would evidence the current misconception of the contribution of tropical peatlands to the global carbon budget, with tropical peat volumes more than doubling current estimates. This carries large implications for the role of pantropical wetlands and peatlands in the global GHG budgets, with large risks of increased emissions both from land conversions and as a result of feedback loops in the climate system.

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REFERENCES

An, S., Li, H., Guan, B., Zhou, C., Wang, Z., Deng, Z., . . . Li, H. (2007). China's natural wetlands: Past problems, current status, and future challenges. *Ambio*, *36*, 335–343.

Aselmann, I., & Crutzen, P. (1989). Global distribution of natural freshwater wetlands and rice paddies, their net primary productivity, seasonality and possible methane emissions. *Journal of Atmospheric Chemistry*, *8*, 307–358.

Ballantine, J., Okin, G., Prentiss, D., & Roberts, D. (2005). Mapping North African landforms using continental scale unmixing of MODIS imagery. *Remote Sensing of the Environment*, *97*, 470–483.

Ballhorn, U., Siegert, F., Mason, M., & Limin, S. (2009). Derivation of burn scar depths and estimation of carbon emissions with LIDAR in Indonesian peatlands. *Proceedings of the National Academy of Sciences of the United States of America*, *106*, 21213–21218.

Bardy, M., Derenne, S., Allard, T., Benedetti, M. F., & Fritsch, E. (2011). Podzolisation and exportation of organic matter in black waters of the Rio Negro (upper Amazon basin, Brazil). *Biogeochemistry*, *106*, 71–88.

Behling, H. (2007). Late Quaternary vegetation, fire and climate dynamics of Serra do Araçatuba in the Atlantic coastal mountains of Parana State, southern Brazil. *Vegetation History and Archaeobotany*, *17*, 77–85.

Benavides, J. (2014). The effect of drainage on organic matter accumulation and plant communities o high-altitude peatlands in the Colombian tropical Andes. *Mires and Peat*, *15*, 1–15.

Beven, K., & Kirkby, M. (1979). A physically based, variable contributing area model of basin hydrology. *Hydrological Sciences Bulletin*, *24*, 43–69.

Biancalani, R., & Avagyan, A. (2014). Towards climate-responsible peatlands management. Mitigation of climate change in agriculture. Series 9. Food and Agriculture Organization of the United Nations, Italy, Rome.

Blumenfeld, S., Lu, C., Christophersen, T., & Coates, D. (2009). Water, Wetlands and Forests. A Review of Ecological, Economic and Policy Linkages. Secretariat of the Convention on Biological Diversity and Secretariat of the Ramsar Convention on Wetlands. CBD Technical Series No. 47. Montreal, Canada.

Brown, C., Sarabandi, K., & Pierce, L. (2005). Validation of the shuttle radar topography mission height data. *IEEE Transactions on Geoscience and Remote Sensing*, *43*, 1707–1715.

Bwangoy, J. R., Hansen, M., Roy, D., De Grandi, G., & Justice, J. (2010). Wetland mapping in the Congo Basin using optical and radar remotely sensed data and derived topographical indices. *Remote Sensing of the Environment*, *114*, 73–86.

Campbell, D. (2005). The Congo River Basin. In L. H. Fraser, & P. A. Keddy (Eds.), *The world's largest wetlands: Ecology and conservation* (pp. 149–165). Cambridge, UK: Cambridge University Press.

Cogley, J. (2003). GGHYDRO - Global Hydrographic Data, Release 2.3.1, Trent Technical Note 2003-1, Department of Geography, Trent University, Peterborough, Ontario, Canada.

Cris, R., Buckmaster, S., Bain, C., & Reed, M. (Eds) (2014). Global Peatland Restoration demonstrating SUCCESS. IUCN UK National Committee Peatland Programme, Edinburgh.

Cubizolle, H., Mouandza, M., & Muller, F. (2013). Mires and histosols in French Guiana (South America) new data relating to location and area. *Mires and Peat*, *12*, 1–10.

Dargie, G., Lewis, S., Lawson, I., Mitchard, E., Page, S., Bocko, Y., & Ifo, S. (2017). Age, extent and carbon storage of the central Congo Basin peatland complex. *Nature*, *542*, 86–90.

Davidson, N. (2014). How much wetland has the world lost? Long-term and recent trends in global wetland area. *Marine and Freshwater Research*, *65*, 934–941.

Denman, K. L., Brasseur, G., Chidthaisong, A., Ciais, P., Cox, P. M., Dickinson, R. E., . . . Zhang, X. (2007). Couplings between changes in the climate system and biogeochemistry. In S. Solomon, et al. (Eds.), *Climate change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change* (pp. 1–90). Cambridge, UK: Cambridge University Press.

Do Nascimento, N. R., Bueno, G. T., Fritsch, E., Herbillon, A. J., Allard, T., Melfi, A. J., . . . Li, Y. (2004). Podzolization as a deferralitization process: A study of an Acrisol-Podzol sequence derived from Palaeozoic sandstones in the northern upper Amazon Basin. *European Journal of Soil Science*, *55*, 523–538.

Draper, F. C., Roucoux, K. H., Lawson, I. T., Mitchard, E. T. A., Honorio Coronado, E. H., Lahteenoja, O., . . . Baker, T. R. (2014). The distribution and amount of carbon in the largest peatland complex in Amazonia. *Environmental Research Letters*, *9*, 124017–124029.

Dubroeucq, D., & Volkoff, B. (1998). From Oxisols to Spodosols and Histosols: Evolution of the soil mantles in the Rio Negro Basin (Amazonia). *Catena*, *32*, 245–280.

Espinoza, J. C., Ronchail, J., Frappart, F., Lavado, W., Santini, W., & Guyot, J. L. (2013). The major floods in the Amazonas River and tributaries (western Amazon Basin) during the 1970-2012 period: A focus on the 2012 flood. *Journal of Hydrometeorology*, *14*, 1000–1008.

Estupinan-Suarez, L. M., Florez-Ayala, C., Quinones, M. J., Pacheco, A. M., & Santos, A. C. (2015). Detection and characterization of Colombian wetlands: Integrating geospatial data with remote sensing derived data. Using ALOS PALSAR and MODIS imagery. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XL-7/W3*, 375–383.

Evrard, C. (1968). Recherches écologiques sur le peuplement forestier des sols hydromorphes de la cuvette centrale congolaise. Série scientifique 110. Institut National pur l'Etude Agronomique au Congo. Bruxelles. Belgique.

Finlayson, C., & van der Valk, A. (1995). Wetland Classification and Inventory: A Summary. *Vegetation*, *118*, 185–192.

Frankenberg, C., Bergamaschi, P., Butz, A., Houweling, S., Meirink, J. F., Notholt, J., . . . Aben, I. (2008). Tropical methane emissions: A revised view from SCIAMACHY onboard ENVISAT. *Geophysical Research Letters*, *35*, L15811–L15816.

Frey, K., & Smith, L. (2007). How well do we know northern land cover? Comparison of four global vegetation and wetland products with a new ground-truth database for West Siberia. *Global Biogeochemical Cycles*, *21*, GB1016.

Frolking, S., Talbot, J., Jones, M., Treat, C., Kauffman, J., Tuittiila, E. S., & Roulet, N. (2011). Peatlands in the Earth's 21st century climate system. *Environmental Research*, *19*, 371–396.

Gallant, A. (2015). The Challenges of remote monitoring of wetlands. *Remote Sensing*, *7*, 10938–10950.

Gaveau, D. L., Salim, M. A., Hergoualc'h, K., Locatelli, B., Sloan, S., Wooster, M., … Sheil, D. (2014). Major atmospheric emissions from peat fires in Southeast Asia during non-drought years: Evidence from the 2013 Sumatran fires. *Scientific Reports*, *4*, 6112–6119.

Gibbs, J. (2000). Wetland loss and biodiversity conservation. *Conservation Biology*, *14*, 314–317.

Grundling, A., Van den Berg, E., & Price, J. (2013). Assessing the distribution of wetlands over wet and dry periods and land-use change on the Maputaland Coastal Plain, north-eastern KwaZulu-Natal, South Africa. *South African Journal of Geomatics*, *2*, N2.

Gumbricht, T. (2015). Hybrid mapping of pantropical wetlands from optical satellite images, hydrology and geomorphology. In R. W. Tiner, M. W. Lang, & V. V. Klemas (Eds.), *Remote sensing of wetlands: Applications and advances* (pp. 433–452). Boca Raton, FL: CRP Press, Taylor and Francis Group.

Gumbricht, T. (2016). Soil moisture dynamics estimated from MODIS time series images. In Y. Ban (Ed.), *Multitemporal remote sensing. Remote sensing and digital image processing* (pp. 233–255). Cham, Switzerland: Springer International Publishing. doi:10.1007/978-3-319-47037-5_12

Gumbricht, T., McCarthy, T. S., McCarthy, J., Roy, D., Frost, P. E., & Wessels, K. (2002). Remote sensing to detect sub-surface peat firs and peat fire scars in the Okavango Delta, Botswana. *South African Journal of Science*, *98*, 351–358.

Hess, L. L., Melack, J. M., Affonso, A. G., Barbosa, C., Gastil-Buhl, M., & Novo, E. M. (2015). Wetlands of the lowland Amazon Basin: Extent, vegetative cover, and dual-season inundated area as mapped with JERS-1 synthetic aperture radar. *Wetlands*, *35*, 745–756.

Hess, L., Melack, J., & Simonetti, D. (1990). Radar detection of flooding beneath the forest canopy: A review. *International Journal of Remote Sensing*, *11*, 1313–1325.

Hijmans, R., Cameron, S., Parra, J., Jones, P., & Jarvis, A. (2005). Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology*, *25*, 1965–1978.

Hooijer, A., Page, S., Canadell, J. G., Silvius, M., Kwadijk, J., Wösten, H., & Jauhiainen, J. (2010). Current and future CO_2 emissions from drained peatlands in Southeast Asia. *Biogeosciences*, *7*, 1505–1514.

Horbe, A. M., Horbe, M. A., & Suguio, K. (2004). Tropical Spodosols in northeastern Amazonas State, Brazil. *Geoderma*, *119*, 55–68.

Householder, E., Janovec, J., Tobler, M., Page, S., & Lähteenoja, O. (2012). Peatlands of Madre de Dios River of Peru: Distribution, geomorphology and habitat diversity. *Wetlands*, *32*, 359–368.

Joosten, H., Tapio-Bistrom, M. L., & Tol, S. (2012). Peatlands-guidance for climate change mitigation through conservation, rehabilitation and sustainable use. Mitigation of climate change in agriculture. Series 5. Food and Agriculture Organization and Wetlands International. FAO, Rome, Italy.

Junk, W., An, S., Finlayson, C., Gopal, B., Kvet, J., Mitchell, S., … Robart, R. (2013). Current state of knowledge regarding the world's wetlands and their future under global climate change: A synthesis. *Aquatic Sciences*, *75*, 151–167.

Junk, W., Brown, M., Campbell, C., Finlayson, M., Gopal, B., Ramberg, L., & Warner, B. (2006). The comparative biodiversity of seven globally important wetlands: A synthesis. *Aquatic Sciences*, *68*, 400–414.

Junk, W., Fernandez Piedade, M. T., Schöngart, J., Cohn-Haft, M., Adeney, J. M., & Wittmann, F. (2011). A classification of major naturally occurring Amazonian lowland wetlands. *Wetlands*, *31*, 623–640.

Junk, W., FernandezPiedade, M. T., Lourival, R., Wittmann, F., Kandus, P., Lacerda, L., … Agostinho, A. (2014). Brazilian wetlands: Their definition, delineation, and classification for research, sustainable management, and protection. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *24*, 5–22.

Junk, W., Fernandez Piedade, M. T., Parolin, P., Wittmann, F., & Schöngart, J. (2010). Ecophysiology, biodiversity and sustainable management of central Amazonian floodplain forests: A synthesis. In W. Jung, M. Piedade, F. Wittmann, J. Schoengart, P. Parolin (Eds.), *Amazonian floodplain forests*. Volume 210 of the series ecological studies (pp. 511–540). Dordrecht: Springer.

Kaptue-Tchuente, A., Roujean, J. L., & De Jong, S. (2011). Comparison and relative quality assessment of the GLC2000, GLOBCOVER, MODIS and ECOCLIMAP land cover data sets at the African continental scale. *International Journal of Applied Earth Observation and Geoinformation*, *13*, 207–219.

Keddy, P., Fraser, L., Solomeshch, A., Junk, W., Campbell, D., Arroyo, M., & Alho, C. (2009). Wet and wonderful: The world's largest wetlands are conservation priorities. *BioScience*, *59*, 39–51.

Kelly, R., Jakeman, A., Barreteau, O., Borsuk, M., ElSawah, S., Hamilton, S., … Voinov, A. (2013). Selecting among five common modelling approaches for integrated environmental assessment and management. *Environmental Modelling and Software*, *47*, 159–181.

Lähteenoja, O., Flores, B., & Nelson, B. (2013). Tropical peat accumulation in Central Amazonia. *Wetlands*, *33*, 495–503.

Lähteenoja, O., Reategui, Y. R., Räsänen, M., Torres, D. D. C., Oinonen, M., & Page, S. (2012). The large Amazonian peatland carbon sink in the subsiding Pastaza-Marañón foreland basin, Peru. *Global Change Biology*, *18*, 164–178.

Lähteenoja, O., & Roucoux, K. (2010). Inception, history and development of peatlands in the Amazon Basin. *Pages News*, *18*, 27–29.

Lähteenoja, O., Ruokolainen, K., Schulman, L., & Oinonen, M. (2009). Amazonian peatlands: An ignored C sinks and potential source. *Global Change Biology*, *15*, 2311–2320.

Lang, M., Bourgeau-Chavez, L., Tiner, R., & Klemas, V. (2015). Advances in remotely sensed data and techniques for wetland mapping and monitoring. In R. Tiner, M. Lang, & V. Klemas (Eds.), *Remote sensing of wetlands: Applications and advances* (pp. 79–117). Boca Raton, FL: CRC Press.

Lawson, I. T., Kelly, T., Aplin, P., Boom, A., Dargie, G., Draper, F., … Wheeler, J. (2015). Improving estimates of tropical peatland area, carbon storage, and greenhouse gas fluxes. *Wetlands Ecology and Management*, *23*, 327–346.

Lehner, B., & Döll, P. (2004). Development and validation of a global database of lakes reservoirs and wetlands. *Journal of Hydrology*, *296*, 1–22.

Malhi, Y., Roberts, T., Betts, R., Killeen, T., Li, W., & Nobre, C. (2008). Climate change, deforestation and the fate of the Amazon. *Science*, *319*, 169–172.

Marengo, J. A., Borma, L., Rodriguez, D., Pinho, P., Soares, W., & Alves, L. (2013). Recent extremes of drought and flooding in Amazonia: Vulnerabilities and human adaptation. *American Journal of Climate Change*, *2*, 87–96.

McCarthy, T. S. (1993). The great inland deltas of Africa. *Journal of African Earth Sciences*, *17*, 275–291.

Matthews, E., & Fung, I. (1987). Methane emissions from natural wetlands: Global distribution, area, and environmental characteristics of sources. *Global Biogeochemical Cycles*, *1*, 61–86.

Melton, J., Wania, R., Hodson, E., Poulter, B., Ringeval, B., Spahni, R., … Kaplan, J. (2013). Present state of global wetland extent and wetland methane modelling: Conclusions from a model inter-comparison project. (WETCHIMP). *Biogeosciences*, *10*, 753–782.

Montes, C., Lucas, Y., Pereira, O. J., Achard, R., Grimaldi, M., & Melfi, A. (2011). Deep plant-derived carbon storage in Amazonian Podsols. *Biogeosciences*, *8*, 113–120.

Montzka, S. A., Dlugokencky, E. J., & Butler, J. H. (2011). Non-CO_2 greenhouse gases and climate change. *Nature*, *476*, 43–51.

National Geomatics Center of China (2014). *30 m Global Land Cover Dataset. GlobeLand30*. Retrieved from http://www.globallandcover.com/home/Enbackground.aspx

New, M., Lister, D., Hulme, M., & Makin, I. (2002). A high-resolution data set of surface climate over global land areas. *Climate Research*, *21*, 1–25.

Ochsner, T. E., Cosh, M. H., Cuenca, R. H., Dorigo, W. A., Draper, C. S., Hagimoto, Y., . . . Zreda, M. (2013). State of the art in large- scale soil moisture monitoring. *Soil Science Society of America Journal*, *77*(6), 1888.

Page, S., Rieley, J., & Banks, C. (2011). Global and regional importance of the tropical peatland carbon pool. *Global Change Biology*, *17*, 798–818.

Page, S., Siegert, F., Rieley, J. O., Boehm, H. D., Jaya, A., & Limin, S. (2002). The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature*, *420*, 61–65.

Paulson Report (2015). *Coastal wetland conservation blueprint project in China. Main findings and recommendations*. Retrieved from http://www.paulsoninstitute.org/wp-content/uploads/2015/10/Conclusions-and-Recommendations-Coastal-Blueprint-Project-2015October.pdf

Petrescu, A. M., Lohila, A., Tuovinen, J. P., Baldocchi, D., Desai, A., Roulet, N., . . . Cescatti, A. (2015). The uncertain climate footprint of wetlands under human pressure. *Proceedings of the National Academy of Sciences of the United States of America*, *112*, 4594–4599.

Petrescu, A. M., van Beek, L., van Huissteden, J., Prigent, C., Sachs, T., Corradi, C., . . . Dolman, A. (2010). Modelling regional to global CH4 emissions from boreal and arctic wetlands. *Global Biogeochemical Cycles*, *24*, GB4009.

Ramsar (2013). *The Ramsar convention manual: a guide to the convention on wetlands*, 6th ed. Retrieved from http://www.ramsar.org/sites/default/files/documents/library/manual6-2013-e.pdf

Rocha, A., & Goulden, M. (2009). Why is marsh productivity so high? New insights from eddy covariance and biomass measurements in a Typha marsh. *Agricultural and Forest Meteorology*, *49*, 159–168.

Román-Cuesta, R. M., Salinas, N., Asbjornsen, H., Oliveras, I., Huaman, V., Gutiérrez, Y., . . . Malhi, Y. (2011). Implications of fires on carbon budgets in Andean cloud montane forest: The importance of peat soils and tree resprouting. *Forest Ecology and Management*, *261*, 1987–1997.

Runge, J. (2008). The Congo River, Central Africa. In A. Gupta (Ed), *Large rivers: Geomorphology and management* (pp. 293–311). Chichester: John Wiley & Sons Ltd.

Ruokolainen, K., Schulman, L., & Tuomisto, H. (2001). On Amazonian peatlands. *International Mire Conservation Group Newsletter*, *4*, 8–10.

Ruthsatz, B. (2012). Vegetación y ecología de los bofedales altoandinos de Bolivia. *Phytocoenologia*, *42*, 133–179.

Salvador, F., Monerris, J., & Rochefort, L. (2014). Peatlands of the Peruvian Puna ecoregion: Types, characteristics and disturbance. *Mires and Peat*, *15*, 1–17.

Schulman, L., & Ruokolainen, K. (1999). Parameters for global ecosystem models. *Nature*, *399*, 535–536.

Stillwell-Soller, L., Klinger, L., Pollard, D., & Thompson, S. (1995). The global distribution of freshwater wetlands. NCAR Technical note: TN-416 + STR. Boulder, CO: National Center for Atmospheric Research.

Torti, J. (2012). Floods in Southeast Asia: A health priority. *Journal of Global Health*, *2*, 020304. doi:10.7189/jogh.02.020304

Turetsky, M., Benscoter, B., Page, S., Rein, G., van der Werf, G., & Watts, A. (2015). Global vulnerability of peatlands to fire and carbon loss. *Nature Geosciences*, *8*, 11–14.

Van der Werf, G., Dempewolf, J., Trigg, S., Randerson, J., Kasibhatla, P., Giglio, L., . . . DeFries, R. (2008). Climate regulation of fire emissions and deforestation in equatorial Asia. *Proceedings of the National Academy of Sciences of the United States of America*, *105*, 20350–20355.

der Werf, G., Randerson, J., Giglio, L., Collatz, G., Mu, M., Kasibhatla, P., . . . van Leeuwen, T. (2010). Global fire emissions and the contribution of deforestation, savannah, forest, agricultural, and peat fires (1997–2009). *Atmospheric Chemistry and Physics*, *10*, 11707–11735.

Vancutsem, C., Pekel, J., & Evrard, C. (2009). Mapping and characterizing the vegetation types of the Democratic Republic of Congo using spot vegetation time series. *International Journal of Applied Earth Observation and Geoinformation*, *11*, 62–76.

Wahyunto, W., Nugroho, K., & Sulaeman, Y.(2014) Indonesian peatland map: method, certainty, and uses. In *Proceedings of National Seminar: PengelolaanBerkelanjutanLahanGambutTerdegradasiuntukMitigasiEmisi GRK danPeningkatanNilaiEkonomi. Jakarta, Indonesia*. Retrieve from https://www.researchgate.net/profile/Yiyi_Sulaeman/publication/293821145_INDONESIAN_PEATLAND_MAP_METHOD_CERTAINTY_AND_USES/links/56bc185b08ae2481ab6ae990.pdf

Wania, R., Melton, J., Hodson, E., Poulter, B., Ringeval, B., Spahni, R., . . . Kaplan, J. (2013). Present state of global wetland extent and wetland methane modelling: Methodology of a model intercomparison project (WETCHIMP). *Geoscientific Model Development Discussions*, *5*, 4071–4136.

Weiss, A. (2001). *Topographic positions and landforms analysis*. ESRI International User Conference, San Diego, CA. Retrieved from http://www.jennessent.com/downloads/tpi-poster-tnc_18x22.pdf

Wood, J. (1996). *The geomorphological characterisation of digital elevation models*. PhD thesis. University of Leicester, Leicester, UK.

Yu, Z., Loisel, J., Brosseau, D., & Beilman, D. (2010). Global peatland dynamics since the Last Glacial Maximum. *Geophysical Research Letters*, *37*, L13402.

Zhang, Z., Zimermann, N., Kaplan, J., & Poulter, B. (2016). Modeling spatiotemporal dynamics of global wetlands: Comprehensive evaluation of a new sub-grid TOPMODEL parameterization and uncertainties. *Biogeosciences*, *13*, 1387–1408.

Zinck, J. A., & García, P. (2011). Tepui peatlands: Setting and features. In J. A. Zinck, & O. Huber (Eds.), *Peatlands of the western Guayana highlands, Venezuela*. Ecological Studies 217. Berlin Heidelberg: Springer-Verlag.

SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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