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An expert system model for mapping tropical wetlands and peatlands

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Abstract

Our understanding of wetlands' services is currently constrained by limited knowledge on their distribution, extent, volume, inter-annual flood variability, and disturbance levels. We here present an expert system to report on wetland and peat areas, depths and volumes, which relies on three biophysical indices that capture three fundamental properties of wetlands: 1. Long-term water supply exceeding atmospheric water demand; 2. Annually or seasonally water-logged soils; 3. A geomorphological position where water is supplied and retained. Tropical and subtropical wetlands cover 4.7 million km2. In line with current understanding, the American continent is the major contributor (45%) and Brazil, with its Amazonian inter-fluvial region, contains the largest tropical wetland area (800,720 km2). Our model suggests, however, unprecedented extents and volumes of peat in the tropics, mainly outside Asia: 1.7 million km2 and 7,268 (6,076-7,368) km3, which more than three-fold current estimates. Unlike current understanding, South America (particularly Brazil) contributes the most to tropical peat 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. Asia has a second place (38% for both tropical peat area and volume). Indonesia is the main regional contributor and still the holder of the deepest and most extended peat areas in the tropics. Africa hosts much more peat than previously reported but climatic and topographic contexts leave it as the least peat forming continent.

Keywords: wetlands, peatlands, peat deposits tropics, land use, climate change

Introduction, scope and main objectives

Wetlands play fundamental roles in climate change regulation and mitigation, with unmanaged wetlands being the largest natural sources of methane in the global CH_4 budget (Denman et al., 2007; Montzka et al., 2011; Melton et al., 2013; Petrescu *et al.,* 2015). Their participation is however imprecise due to the considerable uncertainty of fundamental wetland variables such as their global distribution, spatial extent, or their temporal dynamics. Efforts to assess global wetland extents include the Wetland and Wetland CH4 Inter-comparison of Models Project (WETCHIMP) (Melton et al., 2013; Wania et al., 2013). Their results concluded that the estimates of wetland area vary ca. four-fold in modelled area simulations (7.1- 26.9 mill km2), and three-fold (4.3-12.9 mill km2) in observational mapping (Melton et al., 2013). Part of this variability relates to the unstandardized definition of wetlands and the temporality of their inundation patterns (Melton et al., 2013; Junk et al., 2014; Zhang et al., 2016). Peatlands are wetlands and, therefore, suffer from the same problems but their assessment of areas and volumes are complicated by unclear definition of what peats and peatlands are (Page et al. 2011; Junk et al., 2011), and by a general lack of data due to their complex monitoring requirements (i.e. soil depths, bulk densities, carbon contents) (Joosten et al. 2012). The lack of robust validation processes (Page et al., 2011) also affect current peat maps, particularly in the tropics. This is problematic since tropical peatlands are an important focus of international concern due to the magnitude of their emissions under intense (van der Werf et al., 2008) or even moderate climatic (Gaveau et al., 2014) and human pressures (Hooijer et al., 2010; Petrescu et al., 2015; Turetsky et al., 2015). The need for developing robust, comparable, and highly detailed tropical wetlands and peatland maps, could not be more urgent. We here present a novel method for mapping wetland/peatlands in the tropics and subtropics including estimations of their soil depths and volumes, at a spatial resolution of 232 meters. Our goals are 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. In this research we define peatlands as areas where soils have a minimum depth of 30 cm and an organic matter content of at least 50 percent (27% of carbon content).

Methodology

We developed a knowledge-based model to estimate the spatial distribution and extent of wetlands, peatlands, soil depths and volumes. Compared to previous mapping efforts, such as remote sensing or analytical assessments through hydrological models, we develop three biophysical indices from observational data: hydrological wetness, satellite-derived soil wetness phenology, and geomorphology, to capture key properties of wetland/peatland development: i) inter-annual water inputs exceed the atmospheric water demand (i.e. potential evapotranspiration), ii) annually or seasonally wet or inundated soils, and iii) the geomorphology supports water accumulation and wetland development. This approach requires data on i) regional and local water balances, ii) soil wetness and soil wetness phenology, and iii) geomorphology. The three biophysical indices are:

1. Wetland Topographic Convergence Indices (wTCI): We applied a hydrological model to simulate surface runoff, groundwater flow and flooding volumes.
2. Transformed Wetness Index (TWI) and soil wetness phenology: We developed an algorithm for capturing intra-annual variations of soil surface wetness (soils wetness phenology) based on an annual time series of MODIS optical images. Soil moisture phenology was also used to determine periods of inundation and water saturation.
3. Hydrogeomorphological maps and indices: We mapped general landscape geomorphological elements (i.e. plains, valleys, slopes, ridges, etc) using topographic data. Three types of drainages and maps were produced that represent three different geomorphological wetlands: 1. Peat domes (sourced by permanent rivers with high flow), 2. Valley bound wetlands (sourced by smaller streams), and 3. wetlands in plains and open slopes (sourced by permanent rivers.

Results

Our model suggests much larger areas and volumes of peatlands in the tropics than previously reported, with estimates that reach 1.7 million km2, and 7,268 (6,076-7,368) km3 (Table 1, Figure 1). Most of these estimates correspond to under-reported peatland areas outside Asia. For the same study area than previous reports (i.e. Page et al., 2011) our estimates of areas suggest two-fold increases in Asia and almost four-fold increases in South America and in Africa (Table 1). South America (with a tropical area contribution of 46%) and not Asia (36%) holds the largest area of tropical peatland. Brazil (312,250 km2) and not Indonesia (225,420 km2) lead the contribution to tropical peatland area. Countries with much larger peat areas than previously reported include Bangladesh, India, Thailand, Viet Nam, Congo DRC, China, Colombia, Brazil and Venezuela. There is a general increase of tropical peat volume in all the continents (Table 1), with South America and Africa having almost ten times more peat volume than previously reported. Asia only sees a two-fold increase. South America (42%) and not Asia (39%) holds the largest peat volume, with Brazil (1,489 km3) holding more volume than Indonesia (1,388 km3). Differences with previous volume reports (i.e Page et al. 2011) highlight the so far under-reported contribution of Brazil, Peru, Venezuela, Colombia and Argentina, as well as DRC, China, India or Bangladesh. Asian differences then relate to some unaccounted deep deposits such as those in Indonesian Papua, but mainly to extended but less deep deposits in Bangladesh, Viet Nam, Cambodia, Myanmar, Thailand or Brunei. The situation out of Asia is a combination of some unaccounted very large and very deep deposits (i.e. Congo-DRC, Peruvian peats), and very extended but shallower peats (i.e northern Amazonia). Our model suggests several under-reported peatland hotspots which would require further research and field validation. A non-exhaustive list includes the Amazon Basin (9 different sites); in Argentina the Ibera Wetlands, and la Plata River and tributaries (Paragay and Paraná). In Asia, almost all the river deltas, particularly in Bangladesh, the Mekong and Red

Rivers in Viet Nam, the Irrawady river in Myanmar/Burma, the Chao Phraya in Thailand, and the wetlands of the lower Mekong River in Cambodia). Indonesian Papua hosts large under-reported peat deposits. In African the model highlights the Niger River Delta, the Sudd in South Sudan, and the Cameia wetlands in Angola. Zambia hosts a diversity of locally important peat deposits, among them those in the Bangweulu wetlands. We also see more peat on the Okavango River and on the Cuvette Centrale. In terms of carbon stocks, if we selected standard values for bulk density (0.09 g.cm-3) and for carbon content (56%), we would report 352 GtC of peat soil carbon, more than three times current estimates (88 GtC) (Pag et al. 2011).

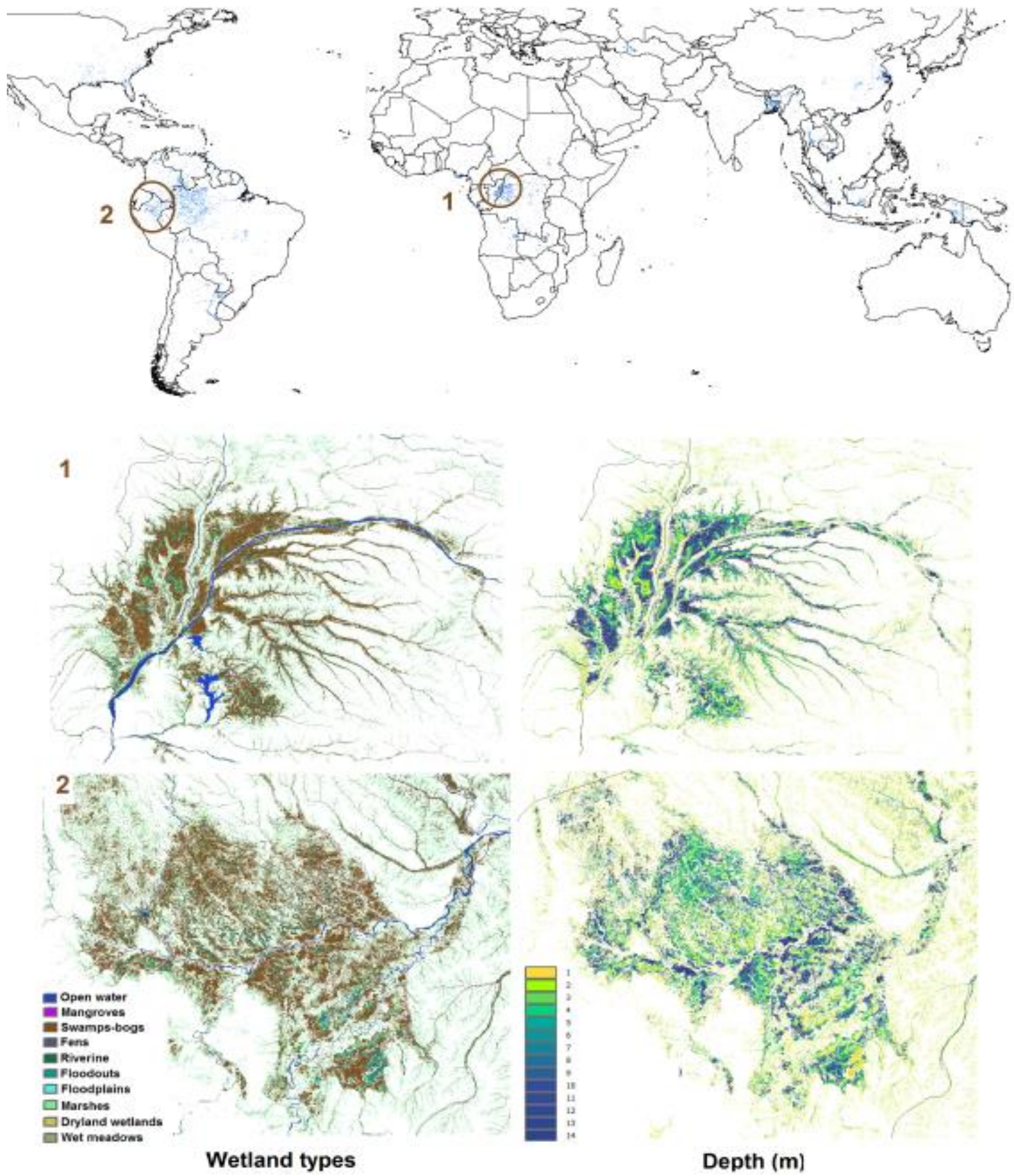

Fig. 1: Distribution of tropical and subtropical peatlands with black circles locating vast peat deposits in (1) the Cuvette Centrale, in the border between Congo and Congo- DRC, and (2) the Pastaza-Marañón in Peru. The lower panels show the detailed wetland composition and depths (m) of these peat deposits as produced by our maps. Source: Gumbricht et al. (2017)

Table 1: Peatland areas, and volumes as reported by Page *et al.*,(2011) and by this study. M=10^6, million.

[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 in the Supplement 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 Middle-East are not shown (Area: 10,829 (0.6%); Volume: 9 (0.1%); Depth: 1m).

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

[d] America includes Central and South America.

Source: Gumbricht et al. (2017)

	Total area Mkm^2	**Volume km^3**	**Depth (m)**	**Continental peatland area (km^2) and contribution (%)**			**Continental peatland volume (km^3) and tropical contribution (%)**		
				Asia[c]	**America[d]**	**Africa**	**Asia**	**America**	**Africa**
Estimates in 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%)
This study estimates (study area of Page et al., (2011)[a]	1.5	6,991 (5,765-7,079)	2.5	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%)
This study estimates (our total study area)[b]	1.7	7,268	1.8	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%)

Discussion

Our peatland data highlight a remarkable misconception of tropical estimates, distributions, and continental contributions to peatland area and volume, mainly due to biased research intensities, which currently highlight Southeast Asian peat deposits as the major tropical contribution (Page et al., 2011). Contrarily, the vast and still very inaccessible peatlands of Africa and Latin America remain poorly studied due to logistic (i.e. ground access) and methodological constrains (i.e. cloud persistence for remote sensing, poor climatic data for hydrological modelling), in largely uninhabited regions. As a result, descriptions of vast carbon peats outside Asia are still occurring. This is the case of the Pastaza-Marañon foreland basin in Peru (Lähteenoja et al., 2009b; Draper et al., 2015) (35,600km2, up to 9 m deep) and the Congo-DRC peatland reservoir (Dargie et al., 2017; Lawson et al., 2015) (200,000km2, up to 7 m deep). Latin America peats overpass the Asian contribution, with Brazil hosting larger areas and volumes than Indonesia, which only but mirrors its role as the largest wetland country in the tropics. This new ranking is certainly an underestimation due to the omission of extended montane peatlands along Latin American mountain ranges. Southeast Asian peatlands will likely remain as the most extensive and deepest tropical contribution (Page et al., 2011; Lähteenoja et al., 2013) since the Brazilian contribution to tropical peat mostly relates to smaller and shallower peat deposits that add up to large extensions and volumes. African peatlands are the least known (Joosten et al., 2012). However, due to climatic and topographic contexts, our results suggest that this continent hosts the lowest peat areas and volumes and suffers from less underestimation than the American continent.

Conclusions

Our model suggests unprecedented areas and volumes of peatland in the tropics, which more than three-fold current estimates, mainly outside Asia. New peatland hotspots have been identified in the Amazon

Basin, in Argentina, Niger, Angola, Bangladesh, and several river deltas in South-East Asia, among others. Latin America, and particularly Brazil, appear as the main contributors to tropical peat. The hypothesis behind our large estimates outside Asia requires field validation but it relates both to yet unaccounted moderately large and deep deposits (i.e. Ecuador), and to extended but shallow deposits in the inter-fluvial Amazonian region that add-up to high areas and volumes. If proven correct, our peatland estimates would also evidence our current misconception of the contribution of tropical peatlands to global carbon budgets.

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