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PEATMAP: Refining estimates of global peatland distribution based on a meta-analysis

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Keywords: Wetlands, peat, map, geographic information system, global, PEATMAP

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Abstract

Peatlands play important ecological, economic and cultural roles in human well-being. Although considered sensitive to climate change and anthropogenic pressures, the spatial extent of peatlands is poorly constrained. We report the development of an improved global peatland map, PEATMAP, based on a meta-analysis of geospatial information collated from a variety of sources at global, regional and national levels. We estimate total global peatland area to be 4.23 million km^2, approximately 2.84 % of the world land area. Our results suggest that previous global peatland inventories are likely to underestimate peat extent in the tropics, and to overestimate it in parts of mid- and high-latitudes of the Northern Hemisphere. Global wetland and soil datasets are poorly suited to estimating peatland distribution. For instance, tropical peatland extents are overestimated by Global Lakes and Wetlands Database – Level 3 (GLWD-3) due to the lack of ground data; and underestimated by the use of histosols to represent peatlands in the Harmonized World Soil Database (HWSD) v1.2, as large areas of swamp forest peat in the humid tropics are omitted. PEATMAP and its underlying data are freely available as a potentially useful tool for scientists and policy makers with interests in peatlands or wetlands. PEATMAP's data format and file structure are intended to allow it to be readily updated when previously undocumented peatlands are found and mapped, and when regional or national land cover maps are updated and refined.

Keywords: Wetlands, peat, map, geographic information system, global, PEATMAP

Highlights:

- An amalgamated global peatland map with geospatial information is produced.
- Globally peatlands cover 4.23 million km^2, or 2.84 % of the global land area.
- PEATMAP includes recently identified high resolution peatland datasets.

1. Introduction

Peat consists primarily of plant detritus that has accumulated at the Earth's surface due to incomplete decomposition under close to water-saturated conditions. There is no single formal definition of 'peat' and 'peatland', with different interest groups often using their own definitions. For instance, Joosten and Clarke (2002) defined peat as 'sedentarily accumulated material consisting of at least 30% (dry mass) of dead organic material', while Burton and Hodgson (1987) defined peat as a soil with at least 50% organic material, which is determined by measuring the ash left after burning. In addition, the histosols, which are regarded as peats in many regions, have been defined as soils which either (1) contain at least 20 % organic material or (2) contains at least 18 % organic material if the soils have been saturated with water for 30 consecutive days according to world reference base for soil resources (WRB) 2006 (Michéli et al., 2006). Peatlands have been defined as 'an area, with or without vegetation, with a naturally accumulated peat layer at the surface' (Joosten and Clarke, 2002). However, the minimum peat thickness for a site to be classified as a peatland is different depending on local classification schemes, country or even the scientific discipline, ranging from 10 cm to 100 cm (Joosten and Clarke, 2002; Bord na Móna 1984; McMillan and Powell, 1999).

Peatlands represent significant stores of soil carbon and constitute an important component of the global carbon cycle (Page et al., 2011; Scharlemann et al., 2014; Yu, 2012). Pristine peatlands function as long-term carbon reservoirs because the rate of plant production generally exceeds the rate of organic matter decomposition (Frolking et al., 2011; Yu et al., 2011). Despite being large carbon stores, pristine peatlands can still emit sizeable quantities of methane and carbon dioxide, and are sources of water-soluble organic compounds with high interannual variability (e.g. Nilsson et al., 2008). However, peat degradation, which is promoted by climate change (Fenner and Freeman, 2011; Ise et al., 2008; Joosten et al., 2012), peatland drainage (Gibson et al., 2009; Holden et al., 2004; Joosten, 2009), burning (Clay et al., 2012; Page et al., 2002; Turetsky et al., 2015; Yallop and Clutterbuck, 2009) and conversion for agriculture (Carlson et al. 2013) can shift the balance of carbon fluxes so that peatlands become net sources of carbon compounds (Hooijer et al., 2012; van der Werf et al., 2008). Peatlands are not only carbon-dense landscapes but also play important roles in the provision of water resources and habitat. Peatlands provide a range of rare, threatened or declining habitats for plants and animals, and represent an important component of global biodiversity (Carroll et al., 2015; Posa et al., 2011). Peatlands contribute to human well-being by providing a range of other nationally and internationally valuable ecosystem services (Reed et al., 2014) including regulating services (e.g. flood regulation) (Gao et al., 2016; Holden, 2005), provisioning services (e.g. agricultural production, sources of energy, habitats for rare species) (Joosten and Clarke, 2002), and cultural services (Bonn et al., 2016).

Current estimates of global peatlands cover contain large uncertainties, meaning that the capacities of peatlands to store soil carbon and to provide water and other ecosystem services are poorly constrained. Improving peatland mapping at regional and national scales represents an ongoing effort, and recent advances have been made in the forms of the Tropical and Sub-Tropical Wetland Distribution dataset (Gumbricht, 2015), the Irish National Soils Map (Teagasc, 2014), and refinements to maps of peatlands in the Central Congo Basin (Dargie et al., 2017). However, a high-fidelity, spatially accurate map of global peatland extent based on the best available data in each location is yet to be produced. Existing maps of global peatland extent are typically based on data that are out of date, of coarse spatial resolution, or based on studies from which the methods used to delineate peatlands are not available. For example, the widely cited map by Lappalainen (1996) gives peatland distribution expressed as a coarse proportion of land area at regional and continental scales. Parish et al. (2008) mapped proportional peatland cover by country, providing a national-level choropleth of peatland coverage without subnational detail. The more recent International Mire Conservation Group Global Peatland Database (IMCG-GPD) (Joosten, 2009) estimates were derived from a wide review of the available literature and from expert opinion, and are now widely used (Ciais et al., 2014; Davidson, 2014; Köchy et al., 2015; Smith et al., 2016; Urak et al., 2017). Joosten (2009), however, noted that IMCG-GPD contains large uncertainties, particularly in South America and Africa due to poor availability of source data there. At the time of writing the digital spatial dataset of IMCG-GPD has not been released in its entirety into the public domain.

The global distribution of peatlands might be estimated from maps of wetland distribution, which are common components of global land cover (GLC) products. Examples of widely used GLC datasets include ISLSCP II (Loveland et al., 2009), MODIS500 (Friedl et al., 2010) and UMD (Hansen et al., 2000), all of which are classified using the IGBP DISCover land cover classification system (Loveland et al., 2000); GLC250 (Wang et al., 2015); FROM-GLC30 (Yu et al., 2014); and GlobeLand30 (Chen et al., 2015). However, none of these GLC products identifies specific subtypes of wetland, meaning that peatlands cannot be distinguished from non-peat forming wetlands. Another potentially useful global wetland database is that of the Ramsar Sites Information Service (https://rsis.ramsar.org/). However, according to Article 2.1 of the Ramsar Convention (Ramsar Convention Secretariat, 2013), Ramsar sites classified as peatlands are likely to include large areas of adjacent non-peat-forming wetlands. Furthermore, only those wetlands which meet at least one of the “Criteria for Identifying Wetlands of International Importance” can be designated by the appropriate national authority to be added to the Ramsar List. There are 596 Ramsar peatland sites globally, covering only approximately 0.5 million km^2. Ramsar data alone therefore represent only a small subset of the world’s peatlands. The spatially-explicit, wetland datasets that specify peatlands as one or more subtypes (Table 1) are suitable for mapping peatland distribution. Among these datasets, GLWD-3 (Lehner and Döll, 2004) represents the most detailed, up-to-date wetland database from which global peat distribution might be successfully extracted (Köchy et al., 2015). Another method that has been used to map peatland distribution is to query soil databases for areas of organic-rich soils, such as the histosols (e.g. Köchy, et al., 2015).

Table 1. Spatially-referenced inventories of global wetland distribution

Reference or data product	Wetland categories	Spatial resolution	Date of most recent revision
Matthews and Fung (1987)	5 (forested bog, non-forested bog, forested swamp, non-forested swamp, alluvial formation)	1 arc-degree	1981
Aselmann and Crutzen (1989)	6 (bog, fen, swamp, marsh, floodplain, shallow lake)	2.5 arc-degree	1983
ISLSCP-I (National Aeronautics and Space Administration and Goddard Space Flight Center, 1996)	6 (bogs, fens, swamps, marshes, floodplains, shallow lakes)	1 arc-degree	1988
GLWD-3 (Lehner and Döll, 2004)	12 (lake, reservoir, river, freshwater marsh, swamp forest, saline wetland, coastal wetland, bog/fen/mire, intermittent wetland, 50%-100 % wetland, 25 %-50 % wetland, wetland complex)	30 arc-second	1992/1993

Our aim was to improve estimates of global peatland distribution compared to coarse, existing peatland maps and national choropleths, by amalgamating the most detailed and up-to-date data available for any given location from a variety of national and regional databases. In doing so, we developed a new global GIS map of peatland distribution. Additionally, we wished to make the new map and its spatially-explicit source data freely available for potential use by others; and to facilitate easy updates to the database in response to the exploration of previously unmapped peatlands (cf. Dargie et al., 2017) and other future refinements to national and regional data sources.

2. Methods

We reviewed candidate data from a wide variety of sources that describe peatland distributions at global, regional and national levels. In areas of overlap between two or more datasets, we determined that the best source data should: contain classifications that are of more direct relevance to peatland extents; possess a higher spatial resolution; and contain products that have been more recently updated in the candidate datasets. We used the following sequence of comparisons to discriminate between overlapping data sources:

(1) Relevance. We determined that the most important criterion was that source data are able to identify peatlands faithfully and to distinguish them from other land cover types, especially non-peat forming wetlands.

(2) Spatial resolution. In areas where two or more overlapping data sources were indistinguishable in terms of their relevance to peatlands, we selected the dataset with the finest spatial resolution.

(3) Age. In any areas where two or more overlapping datasets were indistinguishable based on both their apparent relevance to peatlands and their spatial resolution, we selected the data product that had been most recently updated. Recently updated products commonly contain much older source data, but we use the period over which the latest revision source data were collected as our primary measure of the age of a dataset.

A list of the best source data according to the above criteria is presented in Table A.1. Where source data overlapped the above criteria were applied to select the most appropriate data to use in PEATMAP in order of importance from 1 to 3 with 1 being most important. We combined these data sources to produce a new amalgamated global map of peatland distribution.

For areas where peatland-specific datasets were not available (i.e. Hokkaido, Mongolia and North Korea), we estimated peatland extent based on the distribution of histosols derived from the Harmonized World Soil Database v1.2 (HWSD) (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012), in a manner similar to some previous studies (e.g. Köchy, et al., 2015). HWSD is a raster database with a nominal resolution of 30 arc-seconds (corresponding approximately to

1 × 1 km at the equator) that contains soil data collected over more than 40 years. A map of histosols was derived from HWSD according to the FAO-74 and/or the FAO-90 soil classification. Overall, there are 15,494 km^2 of histosols cover in those areas where no other peatland-specific data are available (i.e. Hokkaido, Mongolia and North Korea).

3. Results and discussion

Our new global peatland map, PEATMAP (Fig. 1), estimates global peatland area as 4.23 million km^2, or approximately 2.84 % of the global land area. At a global scale, this estimate corresponds well with existing, oft-cited estimates of approximately 4 million km^2 (e.g. Parish et al., 2008).

Estimated peatland areas in Asia, accounts for 38.4 % of our total estimate of global peatland cover. North American peatlands comprise 31.6 %, followed by Europe (12.5 %), South America (11.5 %), Africa (4.4 %), and Australasia and Oceania (1.6 %). Estimated peatland area accounts for 5.42 % of the land area of North America, followed by Europe (5.2 %), Asia (3.6 %), South America (2.7 %), Australasia and Oceania (0.9 %), and Africa (0.6 %) (Table 2). Our analysis identifies the major peatland complexes in the circum-arctic zone, particularly the Western Siberian Lowlands in Russia, and the Hudson and James Bay Lowlands in Canada; as well as other important concentrations at lower latitudes, including extensive peat-dominated wetland or swamp forest landscapes such as the Congo and Amazon Basins, and those of Southeast Asia.

We compared our estimates of peatland extent to previously published peatland databases and estimates derived from other datasets (Table 2): (1) the IMCG-GPD; (2) ‘Bog, fen, mire’ and ‘Swamp forest, flood forest’ layers from GLWD-3; (3) the approximation of peatland extent derived from the ‘histosols’ layer of HWSD v1.2 for the areas where HWSD v1.2 was not used to produce PEATMAP.

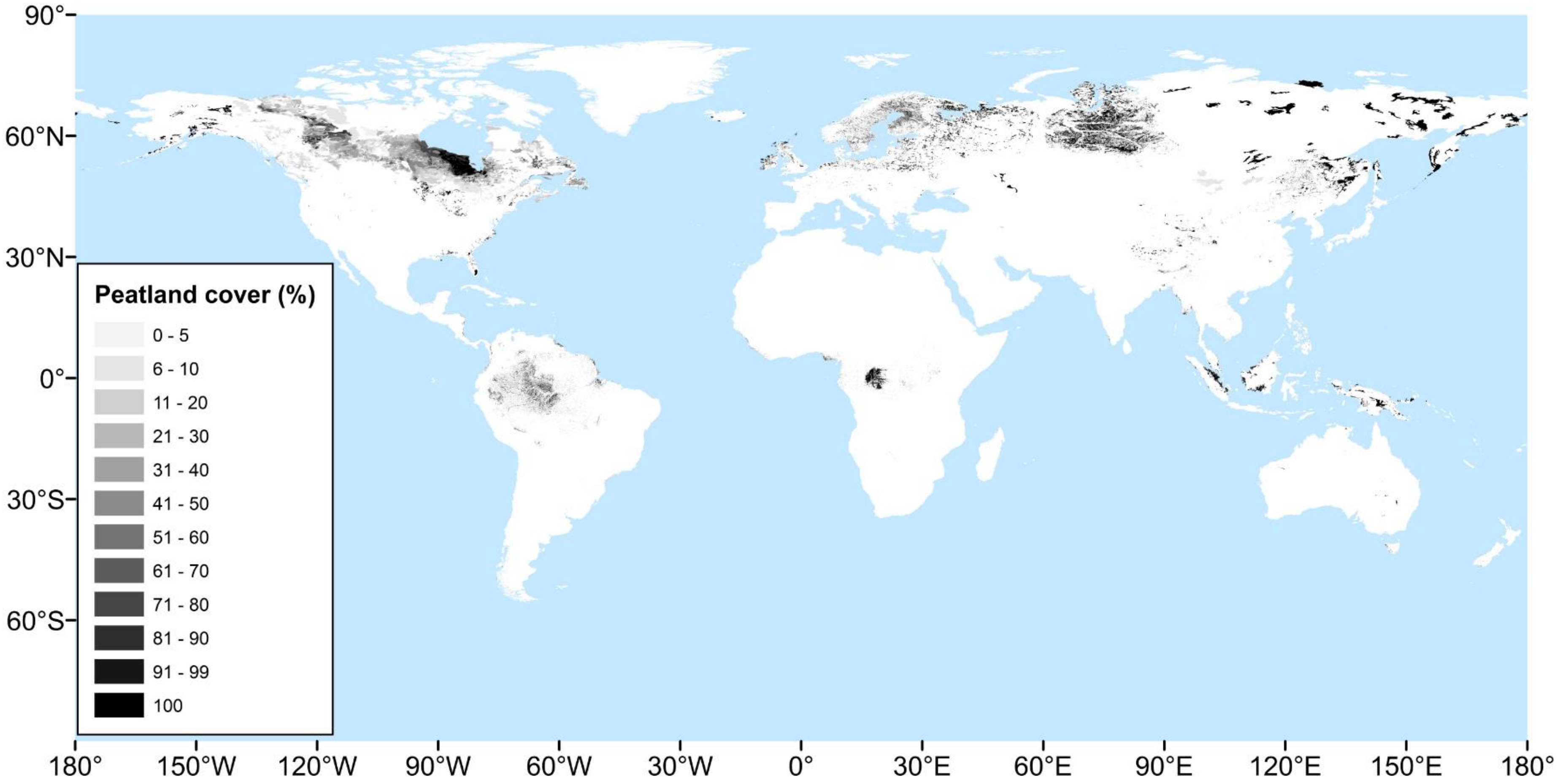

Figure 1. Global peatland distribution derived from PEATMAP. The colour classes indicate percentage peatland cover in Canada, where the source data were provided as grid cells rather than shape files; and regions where peatland cover was estimated from histosols of HWSD v1.2. Elsewhere, where shapefiles are freely available, individual peatlands and peat complexes are shown in solid black.

Table 2. Global breakdown of peatland areal coverage from a variety of estimates, including our new PEATMAP

Continent	Country	Land area (km^2) (Worldatlas, 2016)	Peatland area (km^2)			
			IMCG-GPD (Joosten, 2009)	GLWD -3 (Lehner and Döll, 2004)	HWSD v1.2 (FAO, 2012)	PEATMAP (current study)
North America	Canada	9,084,977	1,133,836	201,405	1,074,688	1,132,614
	United States	9,161,923	225,000	5	250,715	197,841
	Others	6,462,100	10,000	6,248	1967	8866
	Total	24,709,000	1,368,836	207,658	1,327,370	1,339,321
Asia	Asian Russia	9,784,930	1,176,280	467,162	879,700	1,180,358
	Indonesia	1,811,569	265,500	24,568	194,008	148,331
	Malaysia	328,657	26,685	20,978	21,480	22,398
	China	9,326,410	33,499	1,381	5,238	136,963
	Others	23,327,434	43,746	12,900	73,680	135,132
	Total	44,579,000	1,545,710	526,989	1,174,106	1,623,182
Europe	European Russia	6,592,812	199,410	5,591	290,908	185,809
	Sweden	410,335	65,623	9	68,469	60,819
	Finland	303,815	79,429	0	92,935	71,911
	United Kingdom	241,930	17,113	9,940	26,902	22,052
	Ireland	68,883	11,090	639	11,142	16,575
	Others	2,562,225	103,751	1,743	143,969	171,171
	Total	10,180,000	504,607	17,923	634,325	528,337
South America	Total	17,840,000	175,603	910,974	102,682	485,832
Africa	Total	30,370,000	130,181	178,814	72,476	187,061
Oceania	Total	7,692,024	72,845	273	6,604	68,636
Global	Total	148,647,000	3,797,782	1,852,631	3,317,563	4,232,369

Our estimate of peatland extent exceeds that of IMCG-GPD by a factor of 2.8 in South America, and 1.4 in Africa. These large disagreements are likely due to insufficient information on tropical peatlands in IMCG-GPD, which Joosten (2009) acknowledged. Large areas of peatlands in the swamp forests of South America and Africa have recently been mapped but there may be more to discover (Lawson et al., 2015). For example, a peatland complex covering c. 145,500 km^2 in the Central Congo Basin, Democratic Republic of the Congo (DRC) was recently reported for the first time by Dargie et al.(2017). These new data, which we have included in PEATMAP, represent an enormous increase in the estimate of peatland extent in the DRC and in Africa more broadly relative to IMCG-GPD (DRC peatland extent was previously given as only c. 11,900 km^2 in IMCG-GPD). Similarly, the existence of c. 120,000 km^2 of peat in the Pastaza-Maranon foreland basin, Peruvian Amazonia, has only recently been confirmed by fieldwork (Lähteenoja et al., 2012), and its inclusion in PEATMAP represents a large increase in estimated peat extent compared to IMCG-GPD's estimate of c. 50,000 km^2 for the whole of Peru.

In Southeast Asia, PEATMAP's estimate of peat extent is lower than that of IMCG-GPD (Table 2). This is because many Southeast Asian countries have updated their peatland inventories with new products since IMCG-GPD was published in 2009. The resultant increase in detail and accuracy of national peatland maps in Southeast Asia has led to an overall decrease in peatland area in PEATMAP compared to the IMCG-GPD because many areas previously classified as peatlands in IMCG-GPD have been reclassified as non-peat. For instance, our estimates of peatland extent in Indonesia are 55.87 % of that in IMCG-GPD with the equivalent figure being 83.9 % for Malaysia. In Indonesia, IMCG-GPD estimates of peat extent were derived from previous peatland maps (Wahyunto et al., 2003; Wahyunto et al., 2005; Wahyunto et al., 2006). These peatland maps were produced from the interpretation of satellite images supported by dated land cover maps (RePPProT, 1989) with little ground survey data, especially in Papua (Ritung et al., 2011). The more recently published datasets used in PEATMAP were constructed using a combination of more recent soil surveys, legacy soil data and auxiliary information (e.g. digital elevation models, geological maps, agroclimatic maps). The Indonesian peatland map used in PEATMAP presented by the Indonesian Ministry of Agriculture (Ritung et al., 2011) was adopted as the official government map of peatlands in Indonesia. Similarly, the Malaysian national peatland map used in PEATMAP was published after IMCG-GPD and contains more detailed, up to date source data (Wetlands International, 2010). In addition, peatland area in Chile is estimated at 10,996 km^2 by IMCG-GPD while they cover only 2,276 km^2 according to PEATMAP. IMCG-GDP estimates of peatland extent in Patagonia are approximately equivalent to histosol extent. However, most of these Patagonian histosols have been determined as mangrove and marsh by the data source used in PEATMAP (Gumbricht, 2015), which has a higher spatial resolution and is more up to date than IMCG-GPD.

In the relatively well-studied peat-rich regions in mid- and high-latitudes of the Northern Hemisphere, where IMCG-GPD is better informed than in the tropics, PEATMAP and IMCG-GPD agree more closely. For instance, our estimates of peatland extent in North America are 98.43 % of that in IMCG-GPD, and 104.70 % in Europe. However, there are still some important disagreements between PEATMAP and IMCG-GPD in these areas. For instance, the IMCG-GPD is likely to underestimate peat extent in the United Kingdom and the Republic of Ireland, and to overestimate it in Sweden and Finland. This is because the data we used in these regions (Table A. 1) were updated by their respective national geological survey agencies after the IMCG-GPD was published in 2009. The more recent data used in PEATMAP have benefitted from new soil surveys (e.g. Republic of Ireland), the latest remote sensing images (e.g. UK Land Cover Map (LCM) 2007 that released in 2011) or novel geo-statistical mapping techniques compared to IMCG-GPD.

Similar patterns can be found when comparing PEATMAP to other existing peatland inventories. Peatland areas in mid- and high-latitude areas of North America, Russia and Scandinavia are estimated at 3,746,200 km^2 by Bord na Móna (1984) and 3,329,239 km^2 by Lappalainen (1996), while they only cover 2,853,955 km^2 according to PEATMAP. In contrast, peatland extent in South America and Africa are estimated at just 135,535 km^2 by Bord na Móna (1984) and 160,000 km^2 by Lappalainen (1996), while they cover 667,834 km^2 according to PEATMAP.

We queried HWSD v1.2 to extract all pixels where histosols were either a dominant or sub-dominant soil type (Fig. B.1). The resulting global area of histosols, approximately 3.3 million km^2 (pixel area multiplied by fraction of histosols), is broadly consistent with the area

3.25-3.75 million km^2 reported by the latest world reference base for soil resources (IUSS Working Group WRB, 2015), but substantially lower than total peatland areas given by PEATMAP and IMCG-GPD.

The global extent of ‘bogs, fens, and mires’ in GLWD-3, c. 0.8 million km^2, is smaller than the c. 1.1 million km^2 reported for Canadian peatlands alone (Tarnocai et al., 2011). Including the additional category ‘Swamp forest, Flooded forest’, this estimate rises to c. 1.9 million km^2, which is still less than half the total global peatland extent estimated by IMCG-GPD, PEATMAP and other oft-cited estimates of approximately 4 million km^2 (e.g. Parish et al., 2008). As such, the GLWD-3 estimate (Fig. B.2) seems likely to be a gross underestimation globally, although it probably provides an overestimate in the tropics. Wetland distribution in GLWD-3 is derived from a variety of sources originating from the Global Aeronautical chart, while some wetland classes of GLWD-3 are in the regions where there is only limited ground survey data. Lehner and Döll (2004) also noted that the information for these wetlands could be replaced by that obtained from future ground data efforts. Recent ground data suggests that large proportions of peatlands derived from GLWD-3 are non-peat-forming wetlands (Ritung et al., 2011; Wetlands International, 2010). At higher latitudes, GLWD-3 fails to identify extensive European peatlands that have been drained to reduce flood risk or provide arable land (Joosten, 2009). This is mainly because when wet peatlands are drained they may no longer qualify as wetlands in some databases (Köchy et al., 2015). Similarly, extensive areas of permafrost peatlands have been omitted from GLWD-3’s peatland distribution due to their spectral reflectance being similar to other non-peatland permafrost landscapes and being classified as ‘25 - 50% wetland’, ‘50 - 100% wetland’ or ‘Intermittent Wetland’ rather than ‘Peatland’.

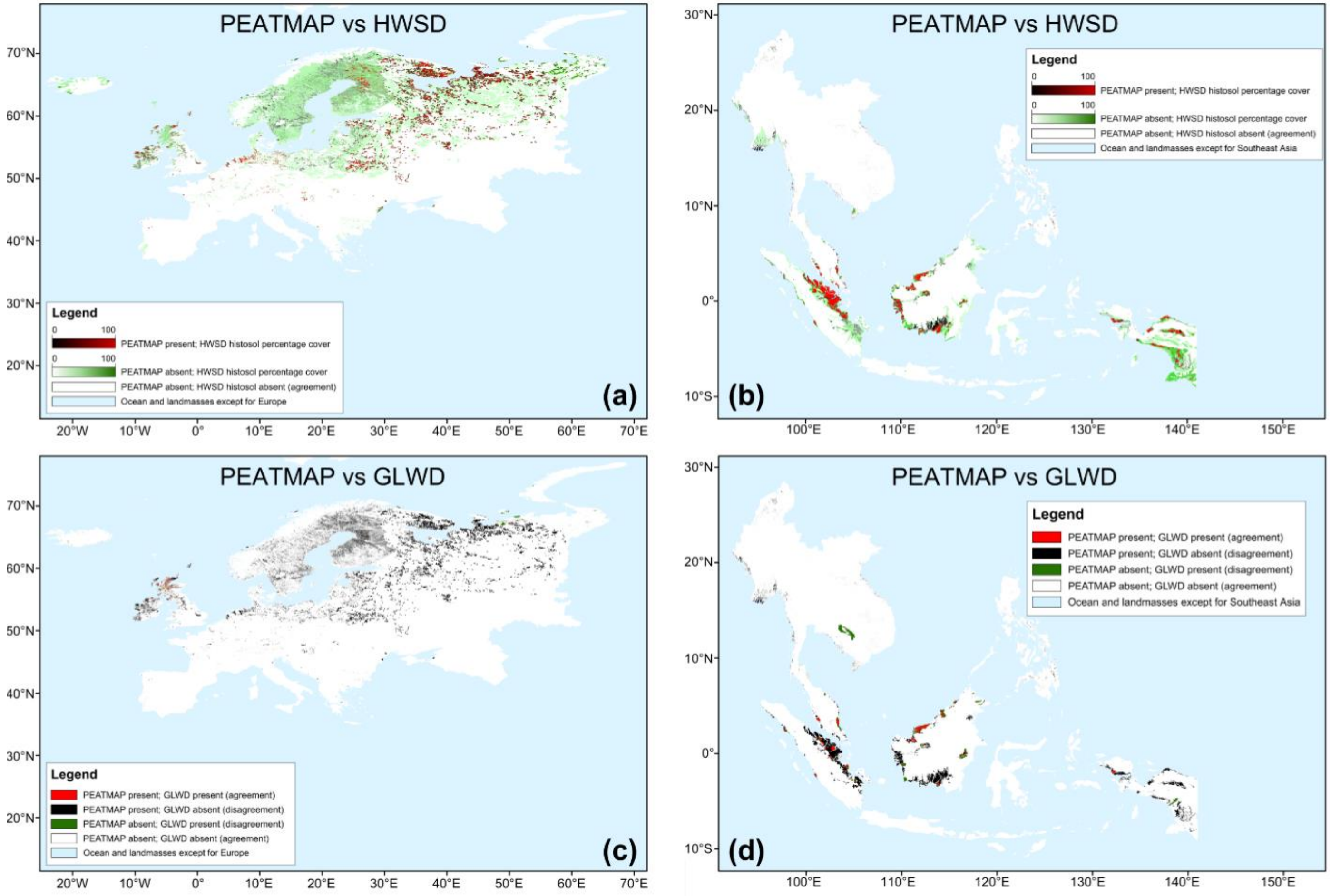

Figure 2. Areas of agreement and disagreement between PEATMAP and HWSD v1.2 (panels a and b), and between PEATMAP and GLWD-3 (c and d) for Europe (a and c) and Southeast Asia (b and d). In panels (a) and (b), black to red shading scale indicates percentage cover of histosols according to HWSD v1.2 in those pixels that contain peat according to PEATMAP (i.e., percentage by which PEATMAP overestimates HWSD histosol cover); white to green shading scale indicates percentage cover of histosols according to HWSD v1.2 in those pixels not identified as peat by PEATMAP (i.e., percentage by which HWSD histosol cover overestimates PEATMAP). White indicates pixels not identified as peatlands by either PEATMAP or HWSD v1.2. In panels (c) and (d), red indicates pixels identified as peatlands by both PEATMAP and GLWD-3; black indicates pixels that are only identified as peatlands by PEATMAP and not by GLWD-3; green indicates pixels that are only identified as peatlands by GLWD-3 and not by PEATMAP; white indicates pixels not identified as peatlands by either PEATMAP or GLWD-3.

The number of distinct data sources used to produce PEATMAP was greatest in Europe, followed by Southeast Asia. Figure 2 shows the locations of disagreement between PEATMAP and estimates of peatland extent derived from HWSD v1.2 and GLWD-3 in these two regions. Areas of the greatest agreement between PEATMAP and dominant histosols (greater than or equal to 50 % of the pixel) in HWSD v1.2 are in extensive, well-documented peatland regions, such as Eastern Europe, central Finland, north Scotland, Indonesia and Malaysia. By contrast, histosol area is much less extensive than areas of swamp forest peatlands in the tropics (e.g. Gumbricht et al. (2017); Junk et al. (2011)). Potential for improving the fidelity of PEATMAP's estimates of global peatland distribution seems greatest through new field surveys in those regions where there is large peat coverage but previously limited peatland survey data (e.g. Indonesia) available. Table 2 and Fig. 2 (c) and (d) indicate that GLWD-3 almost certainly underestimates peatland extent in both Europe and Southeast Asia. GLWD-3 failed to classify most of the areas that were determined as peatlands in our new map and HWSD v1.2, meaning that GLWD-3 is often unable to distinguish peatlands from non-peat wetland types in most areas.

It should be noted that the various definitions of peatlands employed in the source data of PEATMAP could affect the coherence of PEATMAP. Histosols in HWSD were presented according to the FAO definition of 'Soils having an H horizon of 40 cm or more of organic soil materials (60 cm or more if the organic material consists mainly of *Sphagnum* or moss or has a bulk density of less than 0.1) either extending down from the surface or taken cumulatively within the upper 80 cm of the soil; the thickness of the H horizon may be less when it rests on rocks or on fragmental material of which the interstices are filled with organic matter' (FAO-Unesco Soil Map of the World, 1997). However, geological surveys may use 1 m organic layer thickness as the threshold (e.g. British Geological Survey, 2013; Geological Survey of Finland, 2010; Geological Survey of Sweden, 2009). Thus, the areas of peatlands derived from these datasets will be less than the areas of histosols derived from HWSD v1.2. In contrast, Malaysian peatlands in PEATMAP are derived from Wetlands International (2010), who defined peatland as an area with a naturally accumulated peat layer at the surface, with a minimum peat depth of 30 cm. In addition, most tropical peatland maps in PEATMAP are derived from Gumbricht (2015), which is one part of The Global Wetlands Map where peat is defined as at least 30 cm of decomposed or semi decomposed organic material with at least 50 % organic matter, and peatlands refer to landscapes with peat deposits without specific thresholds for minimum continuous peat area, nor for minimum depths. Therefore, the areas of peatlands derived from these datasets will be larger than the areas of histosols derived from HWSD v1.2.

4. Conclusions

Although several existing databases can be used to estimate peatland area at a global scale, most of these are comprised of aspatial data. Existing spatial datasets lack some combination of: i) relevance, ii) fine spatial resolution, and iii) the most recent data in many peat-rich locations. Our new global peatland map, PEATMAP, amalgamates the latest national, regional and global data sources on peat distribution at fine spatial resolution freely available; that incorporates information derived from digitised soil maps, wetland databases, and satellite imagery. Major challenges in creating a combined map from such diverse data sources included ambiguous or non-uniform definitions of peatlands, mixed spatial resolution, incomplete ground data, and incomplete exploration of some potential forested peatland-rich areas, particularly in the tropics. Some errors in the estimation of peat areas are therefore unavoidable, although we believe our new map represents a substantial improvement over previous estimates of global and regional peatland distributions.

We estimate total global peatland area to be 4.23 million km^2, approximately 2.84 % of the global total land area. Our results refine previous estimates of peatland extent compared to previous global peatland databases. Compared to GLWD-3 and histosols in HWSD v1.2, PEATMAP estimates a larger global area of peatlands; tropical peatland extents appear likely to be overestimated by GLWD-3 and underestimated by HWSD v1.2.

Future estimates of global peatland area seem likely to exceed our estimate as new peatland areas are discovered and incorporated into our map particularly in the tropics. PEATMAP will be freely available from PeatDataHub (http://peatdatahub.net/) and can be easily updated as and when new data sources come to light. PEATMAP may provide a useful reference for scientists and policy makers interested in global ecosystem biodiversity, climate change, carbon cycles and water resources, and may also help provide support for wetland protection and restoration.

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Supporting Information

Appendix A Introduction to data sources used to produce PEATMAP.

Appendix B Supplementary Figures.

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Appendix A for ‘PEATMAP: Refining estimates of global peatland distribution based on a meta-analysis’

Jiren Xu, Paul J. Morris, Junguo Liu, Joseph Holden

Introduction to data sources used to produce PEATMAP

In this appendix, we provide details of the data sources used to produce PEATMAP. These sources were selected based on methods described in the main paper. The inventory of data sources used to produce PEATMAP is shown in Table A.1.

1. Northern Peatlands (>30°N latitude)

The UK peatland maps in this study have involved combining DiGMapGB-625 with the ‘Bog’ and ‘Fen, Marsh and Swamp’ layers of UK Land Cover Map (LCM) 2007 (Morton et al., 2011).

The DiGMapGB-625 Surficial Deposits dataset is a freely available superficial theme of the Digital Geological Map of Great Britain at 1: 625,000 by the British Geological Survey. The DiGMapGB-625 Surficial Deposits dataset was compiled from the latest available 1: 50000 data of England and Wales, Scotland and the Isle of Man and the 1: 250000 published Quaternary map of Northern Ireland. The most recent source data for DiGMapGB-50 was resurveyed in 2003 and published in 2010. The survey of superficial geological deposits in the UK recognised the occurrence of peat deposits extending to at least 1 m below the ground surface (McMillan and Powell, 1999).

The surficial peat deposits that occur entirely within 1 m of the ground surface are not included in DiGMapGB-625 as superficial geology mapping was intended to show material underlying the modern soil profile (Joint Nature Conservation Committee, 2011; Smith et al., 2013). Thus, for shallower peatlands, LCM 2007 was used. It is a parcel-based classification of 23 types of British land cover as part of the UK Biodiversity Action Plan (BAP) Broad Habitats. The spatial resolution of LCM 2007 is 25 m and source data were collected around

2007. The UK LCM 2007 provides the spatial distribution of ‘Bog’ and ‘Fen, Marsh and Swamp’ based on the habitat and vegetation information and provides good information on surficial peatland extent (e.g. blanket bog or raised bog plant communities associated with peats).

The Irish National Soils Map (Teagasc, 2014) is one part of the Irish Soil Information System project which provides a national association soil map for Ireland at a scale of 1: 250,000 by adopting a combined methodology of utilising novel geo-statistical predicted mapping techniques in tandem with traditional soil survey applications during the period 2002-2009.

Superficial deposits of Finland 1: 200,000 (sediment polygon) was produced by Geological Survey of Finland (2010) which contains data produced from the whole of Finland during the period 2002-2009 at a scale of 1: 200,000.

Table A. 1 Inventory of data sources used to produce PEATMAP

Region	Reference	Map scale/ nominal resolution (spatial resolution)	Period (date) of most recent revision	Notes
Northern Peatlands (>30°N latitude)				
United Kingdom	British Geological Survey (2013)	1:625,000	2003-2010	Peat feature from Surficial Deposits of DiGMapGB-625.
	Morton et al. (2011)	25 m	2007	‘Bog’ and ‘Fen, Marsh and Swamp’ layers of UK Land Cover Map (LCM) 2007.
Ireland	Teagasc (2014)	1:250,000	2002-2009	Using peatland features.
Finland	Geological Survey of Finland (2010)	1: 200,000	2002-2009	Using peatland features.
Sweden	Geological Survey of Sweden (2009)	1:1,000,000	Around 1994	Using peatland features extracted from quaternary deposits map.
Other European regions	Hiederer (2013)	1 km	2000-2006	‘Peat’ attribute maps from ‘European Soil Database (ESDB) Derived data’.
Western Siberia	Sheng (2009)	1:1,000,000	1999-2001	West Siberia peatland features.
Asian Russia (Except Western Siberia)	Stolbovoi and McCallum (2002)	1:2,500,000	1990s	Using (1) Bogs with deep peat (>50 cm) and (2) Swamps with shallow peat (30-50 cm) features from Russia Wetland Database.
Canada	Tarnocai et al. (2011)	1:6,500,000	2011	Using Bog, Fen and Swamp features with percentage.
United States	Soil Survey Staff (2012)	1:1,000,000 in Alaska and 1: 250,000 in other regions	1999-2005	Using histosols order and gelisol-histel sub-order layers of STATSGO2.
China	Ma et al. (2015)	1 km	2000	Using bogs, fens, swamps and marshes that are non-saline and which excludes lakes or river wetlands.
Tropical Peatlands				
Indonesia	Ritung et al. (2011)	1:250,000	2005-2010	Peat feature from ‘Indonesia Peat Lands’ dataset.
Malaysia	Wetlands International (2010)	1: 50,000	2002-2009	Peat feature from ‘Malaysia Peat Lands’ dataset.
Central Congo Basin	Dargie et al. (2017)	50 m	2009-2010	Peat swamp forest feature.
Other regions in 38° N to 56° S; 161° E to 117° W	Gumbricht (2015)	236 m	2011	‘Peat’ attribute layers derived from ‘Tropical Wetland Distribution (38° N to 56° S; 161° E to 117° W)’.
Southern Peatlands (>30 °S latitude)				
Australia (Except Tasmania)	Environment Australia (2015)	1:500,000	2001-2010	Peatland features from Directory of Important Wetlands in Australia.
Tasmania	Department of Primary Industries and Water (2013)	1:25,000	2013	MBU, MBW, MSW, MSP, MRR features from ‘Moorland, Sedge land, Rush land and Peatland’ class.
New Zealand	MFE (2013)	1:50,000	2008	Current extent feature of peatlands from wetland typology.
Other regions (i.e. Hokkaido, Mongolia, and North Korea**)**	FAO/IIASA/ISRIC/ISSCAS/JRC (2012)	30 arc-second (c. 1 km at the equator)	1997	Using histosol features from HWSD v1.2 with a percentage.

The Swedish Quaternary Deposits map is produced by Geological Survey of Sweden (2009) and provides peat coverage for Sweden at 1: 1,000,000, and reflects the soil information from around 1994.

For other parts of Europe, the ‘peat’ layer from the European Soil Database Derived data with a raster resolution of 1 km was used, which was last updated in the period 2000 - 2006 (Hiederer, 2013). The classification of peat was performed on the basis of the soil clay and organic carbon content as found in the Soil Geographical Database of Eurasia (SGDBE) v 4.0. Therefore, only for regions where an updated peatland map was unavailable, the PEATMAP data were derived from European Soil Database Derived data.

The Asian Russia peatland map was compiled from two datasets - Western Siberia peatland GIS Data Collection (Sheng, 2009) and Russia Wetland Database (Stolbovoi and McCallum, 2002). Detailed physical characteristics of 9,691 individual peatlands (patches) in the 1: 1,000,000 Western Siberia peatland GIS Data Collection were obtained from previously unpublished Russian field and ancillary map data, previously published depth measurements, and field depth and core measurements were taken throughout the region during field campaigns in 1999 - 2001 and published in 2009. The Russian Wetland Classification Shapefile was generalised from the standard 1: 2,500,000 soil map of Russia and reflected the soil situation in the 1990s.

The Peatlands of Canada in Geological Survey of Canada Open File 6561 (Tarnocai et al., 2011) was developed in 2011 by updating the 2005 version of the database using new spatial and site data, together with updated information from the peatland component of the Soil Organic Carbon Database. Peatlands are classified as land surfaces containing more than 40 cm of peat accumulation on which poorly-drained organic soils develop. The map scale of Peatlands of Canada is 1: 6,500,000 and reference year of source data last revision is 2011. The Bog, Fen and Bog/Fen features in this dataset were used to produce PEATMAP.

STATSGO2 is a broad-based inventory of soils at 1: 250,000 for continental U.S., Hawaii, Puerto Rico and the Virgin Islands and at 1: 1,000,000 in Alaska. It uses the U.S. soil classification system - Soil Taxonomy. In the U.S. soil classification system - Soil Taxonomy (Soil Survey Staff, 2012), soils where the surface organic layer is more than 40 cm thick have been classified as histosols, while permafrost-affected organic soils (i.e. permafrost peats) are classified as the histels suborder in the gelisols order. Therefore, the peatlands in the United States were derived from the histosols and gelisol-histel layers of the Digital General Soil Map of the United States. The source materials of STATSGO2 include multiple soil survey publications from the U.S., the USGS, and the 2005 National Soil Information System (NASIS) data base from NRCS.

The source data of China's peatland distribution was derived from the Hybrid Palustrine Wetland Map of China (HPWMC) by Ma et al. (2015). The HPWMC is a hybrid map of 1 km spatial resolution reflecting bogs, fens, swamps and marshes that are non-saline and which are not lakes or rivers. HPWMC was mapped based on seven existing datasets including the wetland database of the Chinese Academy of Sciences (Wetland-CAS); the wetland database of Beijing Forestry University (Wetland-BFU); the wetland database of Chinese Land Use (Wetland-LU); the Global Lake and Wetlands Database (GLWD-3); the Chinese wetland census dataset; historical temperature and precipitation datasets; and 1 km resolution Digital Elevation Model (DEM). The reference year of the last revision is 2000. These datasets were processed by i) ranking available datasets; ii) ranking pixels, and iii) allocating the statistics of palustrine wetland area for each province reported in the Chinese wetland census database to pixels. The HPWMC has been validated showing that it can reproduce high fidelity distributions of peatland in China according to the national statistics database, although there still could be some undiscovered peatlands have been omitted and some peatlands may have been incorrectly classed (i.e. small error of omission, but unknown error of commission). It should be noted that palustrine wetland refers to non-tidal marshes, peat swamps, bogs, and fens (Ramsar Convention Secretariat, 2013), which means some non-peatlands may be incorporated in the palustrine map (i.e. non-tidal marshes). However, there are approximately 11,343 km^2 of marshes in China (Zhang et al., 2014), only accounting for 8.28 % of total Chinese palustrine wetland area. The area of non-tidal marshes should be much less than the total area of marsh, therefore, HPWMC could be used to determine the peatland distribution in China.

2. Tropical Peatlands

The Indonesia peatlands map at a scale of 1: 250,000 published by Indonesia Ministry of Agriculture (Ritung et al., 2011) is the official government map of peatlands in Indonesia. It is based on several preceding peatland and soil maps of Indonesia, including the Land Resource Evaluation and Planning Project (LREP) data (LREP, 1999), Land Form Classification Maps produced by Regional Planning Program for Transmigration (RePPProT, 1989), Wetlands International peatland map (Wahyunto et al., 2006; Wahyunto and Subagjo, 2003; Wahyunto and Suparto, 2004) and data from several more recent updated regional land and soil surveys in 2005 - 2010 (Haryono and Ritung, 2011).

The Malaysia Peat Lands map was released by Wetlands International (2010) to assess the current status, extent, distribution, and conservation needs for peatlands in Malaysia by overlaying 2009 satellite imagery (Landsat Thematic Mapper, scale 1: 50,000) on a 2002 map of land use provided by Department of Agriculture. Ground data were collected in sample sites throughout the peninsular to assess the local extent and condition of peat soils.

Peatland extents in the Central Congo Basin were derived from Dargie et al. (2017). This GIS file was produced by combining radar backscatter, optical data and ground data. The spatial resolution of these data is 50 m and the latest date of acquisition data of remote-sensing products used in mapping peatland extent is 2010.

The Tropical and Sub-Tropical Wetland Distribution dataset by Gumbricht (2015) is one part of The Global Wetlands Map which was produced by the Sustainable Wetlands Adaptation and Mitigation Program (SWAMP). This dataset shows a distribution of wetland that covers the tropics and subtropics (38° N to 56° S; 161° E to 117° W), excluding small islands. It is by far the highest spatial resolution and most recent tropical and sub-tropical wetland dataset. It was mapped at 236 m spatial resolution by combining a hydrological model and annual time series of satellite-derived estimates of soil moisture to represent water flow and surface wetness that are then combined with geomorphological data, and the source data collection period was around 2011.

3. Southern Peatlands (>30 °S latitude)

Directory of Important Wetlands in Australia (DIWA) Spatial Database is a polygon coverage dataset produced by Environment Australia (2015) that presents the different types of wetland (e.g. marsh, swamp, peatland) boundaries and locations in Australia on a scale of 1: 500,000 from 2001 to 2010. We also used the Tasmanian Vegetation dataset produced by Tasmanian Resource Management and Conservation Division (Department of Primary Industries and Water, 2013) which depicts the extent of more than 150 vegetation communities, including those representing peatlands at 1: 25,000 spatial coverage. TASVEG (Tasmania's vegetation) is continually revised and updated via photographic and satellite image interpretation and is verified in the field where possible. The reference year of source data last revision is 2013.

The Current Wetland Extent 2013 from The Ministry for the Environment and Statistics New Zealand (Ministry for the Environment and Statistics New Zealand, 2013) provides the current extent of seven classes of wetlands of New Zealand at 1: 50,000 by using 26 Landsat ETM+ satellite imagery in 2008 and wetland point and polygon data collated from surveys, field work or photo–interpretation held by local and central government.

4. Harmonized World Soil Database (HWSD) v1.2

For Mongolia, North Korea and the north island of Japan (Hokkaido) (south island peatlands were derived from Tropical and Sub-Tropical Wetland Distribution dataset which cover 38° N to 56° S and 161° E to 117° W), where a high-quality peatland spatial dataset is unavailable, the peatland extents were determined from the histosol maps derived from HWSD v1.2. The HWSD v1.2 (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012) has a nominal resolution of 30 arc-seconds on the ground (corresponding approximately to 1 × 1 km at the equator). The raster database contains more than 40 years of soil information. A map of histosols was derived from HWSD according to the FAO-74 and/or the FAO-90 soil classification. Five source databases (Table A. 2) were used to compile version 1.2 of HWSD. The period of most recent revision according to our source dating protocol is the 1980s which is when the second national soil survey of China was launched. We used the date consistent with the authors' definition for histosols as the date of most recent revision.

Table A. 2 Source databases of HWSD v1.2

Soil Map of the World	The Digitized Soil Map of the World Including Derived Soil Properties (version 3.5) (FAO, 1995, 2003). The FAO-UNESCO Soil Map of the World. Legend and 9 volumes. UNESCO, Paris (FAO, 1971-1981).
SOTER regional studies	Soil and terrain database for north-eastern Africa and Crop production zones (FAO, IGADD/ Italian Cooperation, 1998). Soil and Terrain database for north and central Eurasia at 1: 5 million scale (FAO/IIASA/Dokuchaiev Institute/Academia Sinica, 1999). Soil and terrain digital database for Latin America and the Caribbean at 1: 5 Million scale (FAO/UNEP/ISRIC/CIP, 1998). Soil and Terrain Database, Land Degradation Status and Soil Vulnerability Assessment for Central and Eastern Europe (1: 2,500,000) (FAO/ISRIC 2000). Soil and Terrain Database for Southern Africa (FAO/ISRIC, 2003). SOTER-based soil parameter estimates for Central Africa – DR of Congo, Burundi and Rwanda (SOTWIScaf, version 1.0) (Batjes, 2007). SOTER parameter estimates for Senegal and The Gambia derived from SOTER and WISE (SOTWIS-Senegal, version 1.0) (Batjes, 2008). Soil property estimates for Tunisia derived from SOTER and WISE. (SOTWIS-Tunisia, version 1.0) (Batjes, 2010).
The European Soil Database	European Soil Bureau European Soil Database (v. 2.0) (Panagos et al., 2012)
Northern Circumpolar Soil Map and database	Datasets with dominant soil characteristics at a scale of 1: 10,000,000 (Tarnocai et al., 2002).
The Soil Map of China 1:1 Million scale	The Soil Map of China based on data from the office for the Second National Soil Survey of China and Institute of Soil Science in Nanjing (Shi et al., 2004).

Soil parameter estimates based on World Inventory of Soil Emission Potential (WISE) database	Version 2.0 of the WISE database (Batjes et al, 1997; Batjes, 2002).
	SOTWIS (Batjes, 2007; Van Engelen et al., 2005).

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Batjes, N.H., 2008. SOTER parameter estimates for Senegal and The Gambia derived from SOTER and WISE (SOTWIS-Senegal, version 1.0) ISRIC - World Soil Information, Wageningen.

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Appendix B for ‘PEATMAP: Refining estimates of global peatland distribution based on a meta-analysis’

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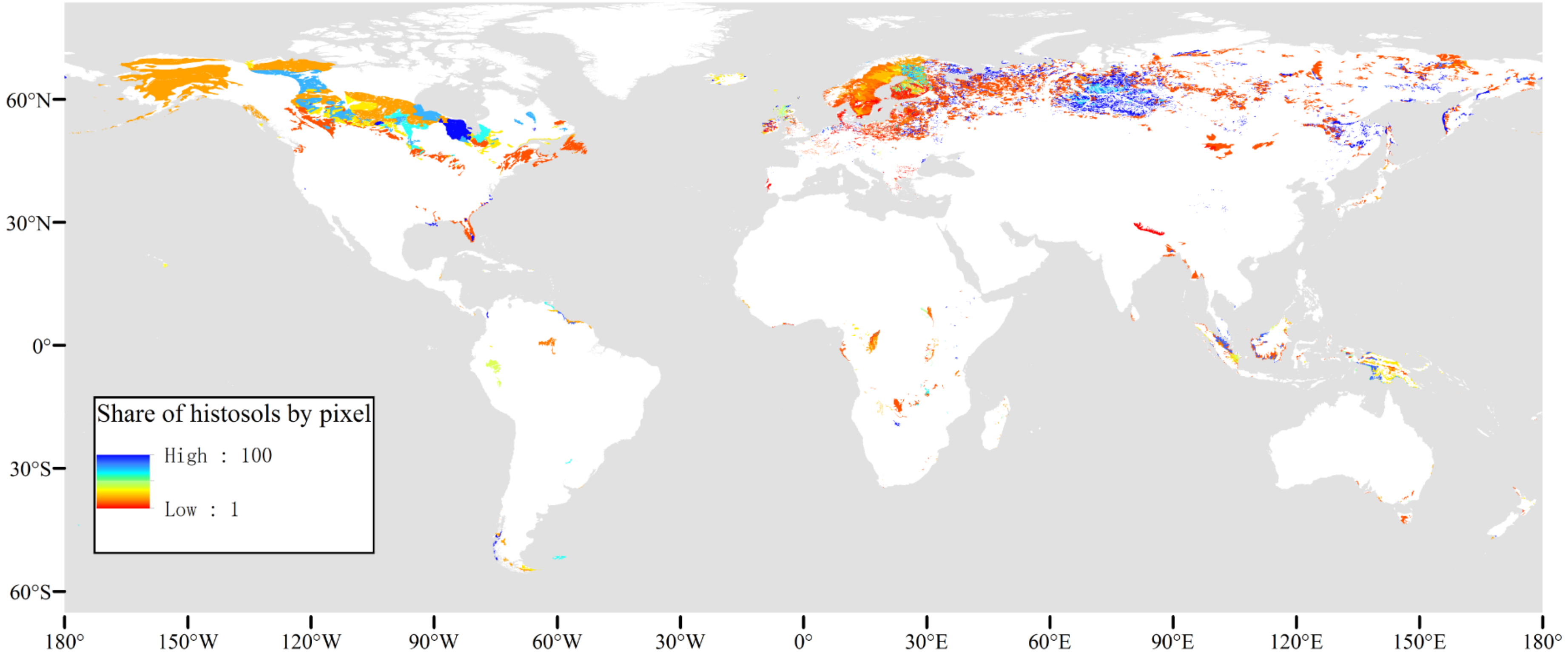

Fig. B.1 Global distribution of histosols and share by pixel (in percentage) derived from HWSD v1.2 (Köchy, et al., 2015).

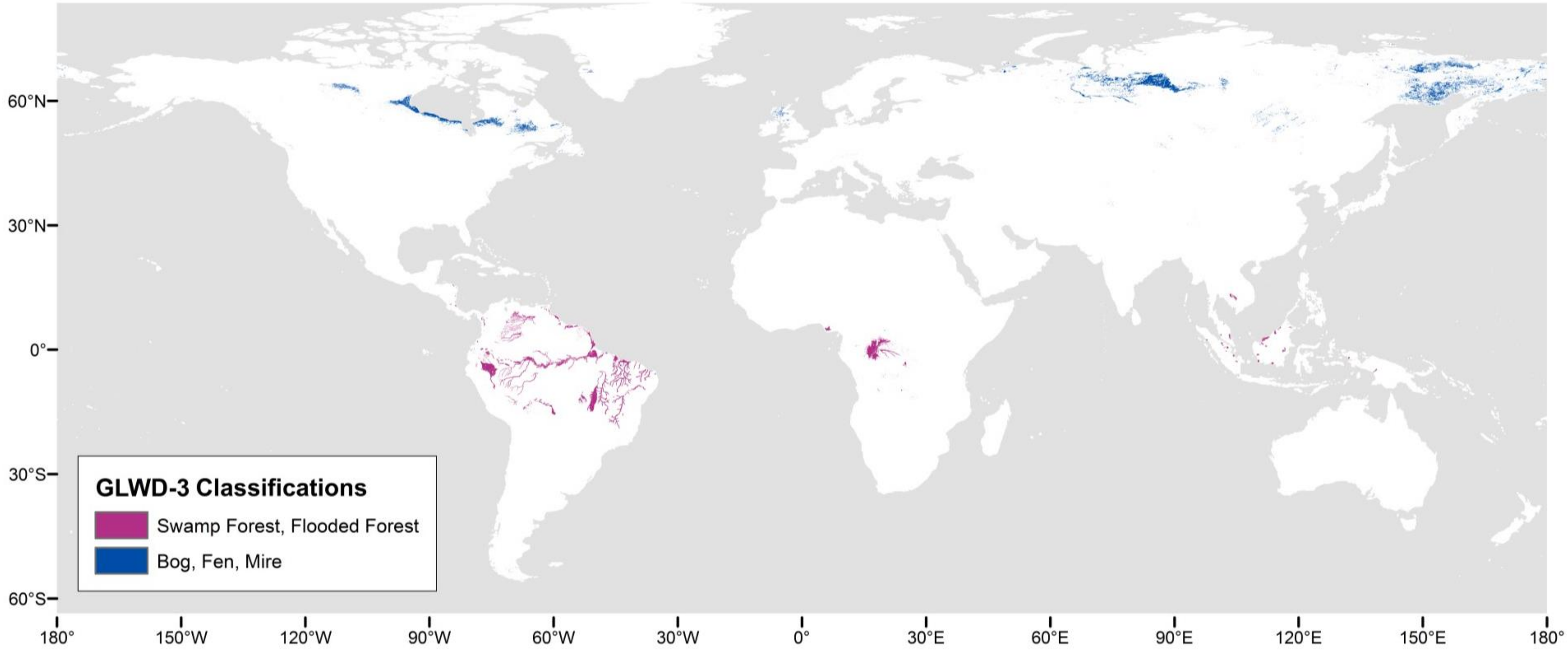

Fig. B.2 Global 'Bog, Fen, Mire' and 'Swamp Forest, Flooded Forest' distribution derived from GLWD-3.