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

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A R T I C L E I N F O

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A B S T R A C T

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-truthing 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.

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, 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 the 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

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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 peatland 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).

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 histosol 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 area 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

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

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.

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.,

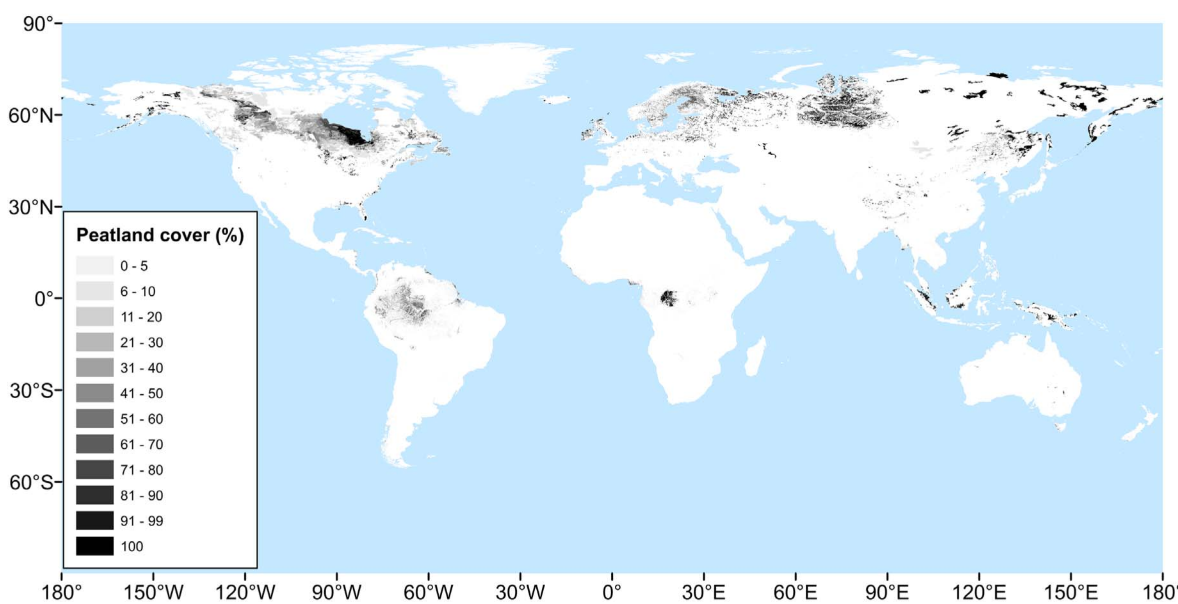

Fig. 1. Global peatland distribution derived from PEATMAP. The black shading classes indicate percentage peatland cover in Canada, where the source data were provided as grid cells rather than shape files; and regions where peatland cover was estimated from histosols of HWSD v1.2. Elsewhere, where shapefiles 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	6248	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	1381	5238	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	5591	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	9940	26,902	22,052
	Ireland	68,883	11,090	639	11,142	16,575
	Others	2,562,225	103,751	1743	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	6604	68,636
Global	Total	148,647,000	3,797,782	1,852,631	3,317,563	4,232,369

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 2276 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 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’.

The number of distinct data sources used to produce PEATMAP was greatest in Europe, followed by Southeast Asia. Fig. 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

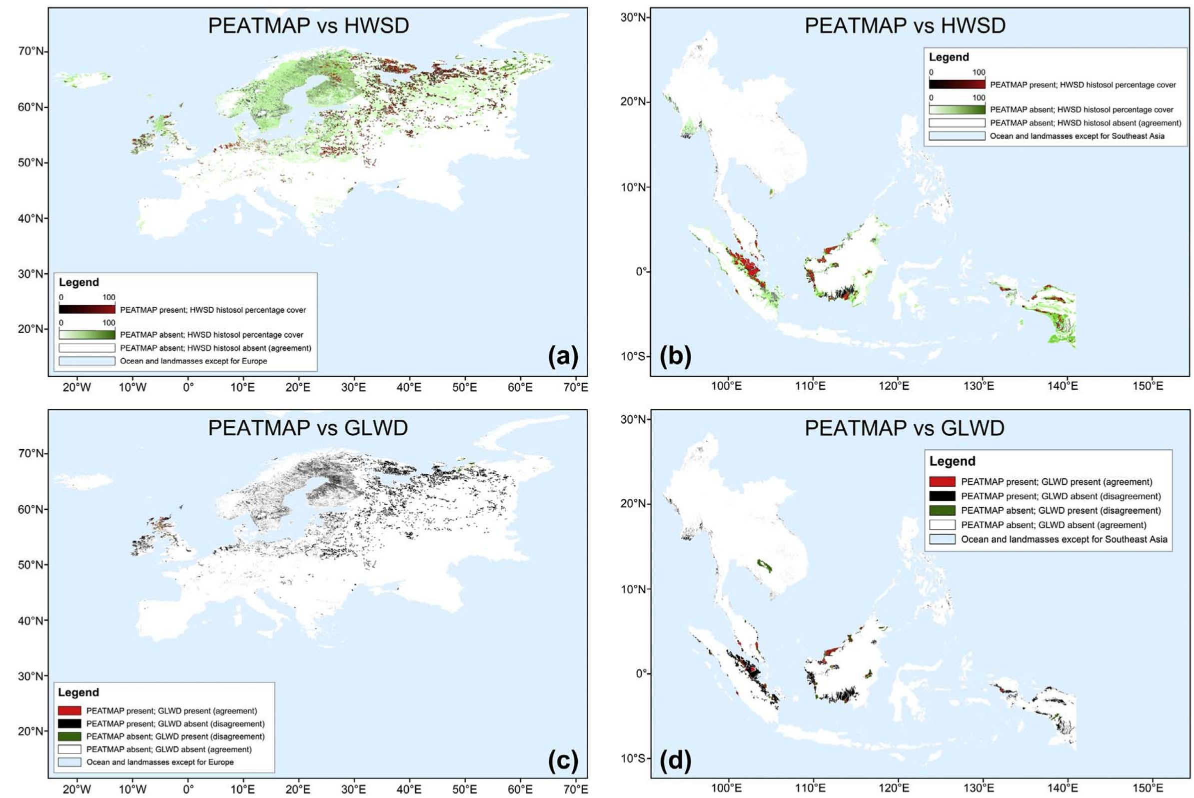

Fig. 2. Areas of agreement and disagreement between PEATMAP and HWSD v1.2 (panels a and b), and between PEATMAP and GLWD-3 (c and d) for Europe (a and c) and Southeast Asia (b and d). In panels (a) and (b), black to red shading scale indicates percentage cover of histosols according to HWSD v1.2 in those 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. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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). 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, freely-available data sources on peat distribution at fine spatial resolutions, incorporating 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 https://doi.org/10.5518/252 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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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.catena.2017.09.010.

References

Aselmann, I., Crutzen, P., 1989. Global distribution of natural freshwater wetlands and rice paddies, their net primary productivity, seasonality and possible methane emissions. J. Atmos. Chem. 8, 307–358.
Bonn, A., Allott, T., Evans, M., Joosten, H., Stoneman, R., 2016. Peatland Restoration and Ecosystem Services: Science, Policy and Practice. Cambridge University Press.
Bord na Móna, 1984. Fuel Peat in Developing Countries. World Bank Technical Paper No. 41. The World Bank, Washington, DC.
British Geological Survey, 2013. DiGMapGB data at 1:625 000 scale, surficial deposits V1.0. http://www.bgs.ac.uk/products/digitalmaps/dataInfo.html#_625.
Burton, R.G.O., Hodgson, J.M., 1987. Lowland Peat in England and Wales. Soil Survey Technical Monograph No. 15, Harpenden, UK.
Carlson, K.M., Curran, L.M., Asner, G.P., McDonald Pittman, A., Trigg, S.N., Adeney, J.M., 2013. Carbon emissions from forest conversion by Kalimantan oil palm plantations. Nat. Clim. Chang. 3, 283–287.
Carroll, M.J., Heinemeyer, A., Pearce-Higgins, J.W., Dennis, P., West, C., Holden, J., Wallage, Z.E., Thomas, C.D., 2015. Hydrologically driven ecosystem processes determine the distribution and persistence of ecosystem-specialist predators under climate change. Nat. Commun. 6, 7851.
Chen, J., Chen, J., Liao, A., Cao, X., Chen, L., Chen, X., He, C., Han, G., Peng, S., Lu, M., Zhang, W., Tong, X., Mills, Jon, 2015. Global land cover mapping at 30 m resolution: a POK-based operational approach. ISPRS J. Photogramm. Remote Sens. 103, 7–27.
Ciais, P., Dolman, A.J., Bombelli, A., Duren, R., Peregon, A., Rayner, P.J., Miller, C., Gobron, N., Kinderman, G., Marland, G., Gruber, N., Chevallier, F., Andres, R.J., Balsamo, G., Bopp, L., Breon, F.M., Broquet, G., Dargaville, R., Battin, T.J., Borges, A., Bovensmann, H., Buchwitz, M., Butler, J., Canadell, J.G., Cook, R.B., DeFries, R., Engelen, R., Gurney, K.R., Heinze, C., Heimann, M., Held, A., Henry, M., Law, B., Luyssaert, S., Miller, J., Moriyama, T., Moulin, C., Myneni, R.B., Nussli, C., Obersteiner, M., Ojima, D., Pan, Y., Paris, J.D., Piao, S.L., Poulter, B., Plummer, S., Quegan, S., Raymond, P., Reichstein, M., Rivier, L., Sabine, C., Schimel, D., Tarasova, O., Valentini, R., Wang, R., van der Werf, G., Wickland, D., Williams, M., Zehner, C., 2014. Current systematic carbon-cycle observations and the need for implementing a policy-relevant carbon observing system. Biogeosciences 11, 3547–3602.
Clay, G.D., Worrall, F., Aebischer, N.J., 2012. Does prescribed burning on peat soils influence DOC concentrations in soil and runoff waters? Results from a 10 year chronosequence. J. Hydrol. 448, 139–148.
Dargie, G.C., Lewis, S.L., Lawson, I.T., Mitchard, E.T., Page, S.E., Bocko, Y.E., Ifo, S.A., 2017. Age, extent and carbon storage of the central Congo Basin peatland complex. Nature 542, 86–90.
Davidson, N.C., 2014. How much wetland has the world lost? Long-term and recent trends in global wetland area. Mar. Freshw. Res. 65, 934–941.
FAO/IIASA/ISRIC/ISSCAS/JRC, 2012. Harmonized world soil database (Version 1.2).
FAO-Unesco Soil Map of the World, 1997. Revised Legend, with corrections and updates, Originally published in 1988 as World Soil Resources Report 60, FAO, Rome, Reprinted with updates, Technical Paper, 20, ISRIC, Wageningen, ISRIC, available at: http://library.wur.nl/isric/fulltext/isricu_i9264_001.pdf. ()
Fenner, N., Freeman, C., 2011. Drought-induced carbon loss in peatlands. Nat. Geosci. 4, 895–900.
Friedl, M.A., Sulla-Menashe, D., Tan, B., Schneider, A., Ramankutty, N., Sibley, A., Huang, X., 2010. MODIS Collection 5 global land cover: algorithm refinements and characterization of new datasets. Remote Sens. Environ. 114, 168–182.
Frolking, S., Talbot, J., Jones, M.C., Treat, C.C., Kauffman, J.B., Tuittila, E.-S., Roulet, N., 2011. Peatlands in the Earth's 21st century climate system. Environ. Rev. 19, 371–396.
Gao, J., Holden, J., Kirkby, M., 2016. The impact of land-cover change on flood peaks in peatland basins. Water Resour. Res. 52, 3477–3492.
Geological Survey of Finland, 2010. Soil 1: 200,000 (types of soil). http://hakku.gtk.fi/en/.
Geological Survey of Sweden, 2009. Quaternary Deposits digital maps at scales of 1:50,000, 1:100,000 and 1:1,000,000. Available from. http://www.sgu.se/en/geology-of-sweden/.
Gibson, H.S., Worrall, F., Burt, T.P., Adamson, J.K., 2009. DOC budgets of drained peat catchments: implications for DOC production in peat soils. Hydrol. Process. 23, 1901–1911.
Gumbricht, T., 2015. Hybrid Mapping of Pantropical Wetlands from Optical Satellite Images, Hydrology, and Geomorphology, Remote Sensing of Wetlands: Applications and Advances. CRC Press, pp. 435–454.
Gumbricht, T., Roman-Cuesta, R.M., Verchot, L., Herold, M., Wittmann, F., Householder, E., Herold, N., Murdiyarso, D., 2017. An expert system model for mapping tropical wetlands and peatlands reveals South America as the largest contributor. Glob. Chang. Biol. 3581–3599.
Hansen, M.C., Defries, R.S., Townshend, J.R.G., Sohlberg, R., 2000. Global land cover classification at 1 km spatial resolution using a classification tree approach. Int. J. Remote Sens. 21, 1331–1364.
Holden, J., 2005. Peatland hydrology and carbon release: why small-scale process matters. Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 363, 2891–2913.
Holden, J., Chapman, P.J., Labadz, J.C., 2004. Artificial drainage of peatlands: hydrological and hydrochemical process and wetland restoration. Prog. Phys. Geogr. 28, 95–123.
Hooijer, A., Page, S., Jauhiainen, J., Lee, W.A., Lu, X.X., Idris, A., Anshari, G., 2012. Subsidence and carbon loss in drained tropical peatlands. Biogeosciences 9, 1053.
Ise, T., Dunn, A.L., Wofsy, S.C., Moorcroft, P.R., 2008. High sensitivity of peat decomposition to climate change through water-table feedback. Nat. Geosci. 1, 763–766.
IUSS Working Group WRB, 2015. World Reference Base for Soil Resources 2014, update 2015 International soil classification system for naming soils and creating legends for soil maps. In: World Soil Resources Reports No. 106. FAO, Rome.
Joosten, H., 2009. The Global Peatland CO_2 Picture: Peatland Status and Drainage Related Emissions in All Countries of the World. Wetlands International, Netherlands.
Joosten, H., Clarke, D., 2002. Wise Use of Mires and Peatlands–Background and Principles Including a Framework for Decision-Making, Finland.
Joosten, H., Tapio-Biström, M.-L., Tol, S., 2012. Peatlands: Guidance for Climate Change Mitigation Through Conservation, Rehabilitation and Sustainable Use. Food and Agriculture Organization of the United Nations and Wetlands International.
Junk, W.J., Piedade, M.T.F., Schöngart, J., Cohn-Haft, M., Adeney, J.M., Wittmann, F., 2011. A classification of major naturally-occurring Amazonian lowland wetlands. Wetlands 31, 623–640.
Köchy, M., Hiederer, R., Freibauer, A., 2015. Global distribution of soil organic carbon–part 1: masses and frequency distributions of SOC stocks for the tropics, permafrost regions, wetlands, and the world. Soil 1, 351–365.
Lähteenoja, O., Reátegui, 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. Glob. Chang. Biol. 18, 164–178.
Lappalainen, E., 1996. Global Peat Resources. International Peat Society Jyskä.
Lawson, I.T., Kelly, T.J., Aplin, P., Boom, A., Dargie, G., Draper, F.C., Hassan, P.N.Z.B.P., Hoyos-Santillan, J., Kaduk, J., Large, D., Murphy, W., Page, S.E., Roucoux, K.H., Sjögersten, S., Tansey, K., Waldram, M., Wedeux, B.M.M., Wheeler, J., 2015. Improving estimates of tropical peatland area, carbon storage, and greenhouse gas fluxes. Wetl. Ecol. Manag. 23, 327–346.
Lehner, B., Döll, P., 2004. Development and validation of a global database of lakes, reservoirs and wetlands. J. Hydrol. 296, 1–22.
Loveland, T.R., Reed, B.C., Brown, J.F., Ohlen, D.O., Zhu, Z., Yang, L.W.M.J., Merchant, J.W., 2000. Development of a global land cover characteristics database and IGBP DISCover from 1 km AVHRR data. Int. J. Remote Sens. 21, 1303–1330.
Loveland, T., Brown, J., Ohlen, D., Reed, B., Zhu, Z., Yang, L., Howard, S., 2009. ISLSCP II IGBP DISCover and SiB Land Cover, 1992–1993. In: Hall, F. (Ed.), ISLSCP Initiative II Collection. Oak Ridge National Laboratory Distributed Active Archive Center.
Matthews, E., Fung, I., 1987. Methane emission from natural wetlands: global distribution, area, and environmental characteristics of sources. Glob. Biogeochem. Cycles 1, 61–86.
Mcmillan, A.A., Powell, J.H., 1999. BGS rock classification scheme volume 4 classification of artificial (man-made) ground and natural superficial deposits application to geological maps and datasets in the UK. In: Research Report No. RR99-04. NERC, British Geological Survey.
Michéli, E., Schad, P., Spaargaren, O., 2006. World Reference Base for Soil Resources 2006: A Framework for International Classification, Correlation and Communication. Food and agriculture organization of the United Nations (FAO).
National Aeronautics and Space Administration and Goddard Space Flight Center, 1996. International Satellite Land Surface Climatology Project - Initiative I (ISLSCP I) Dataset. NASA Distributed Active Archive Center (DAAC). Available from. http://badc.nerc.ac.uk/data/islscp/.
Nilsson, M., Sagerfors, J., Buffam, I., et al., 2008. Contemporary carbon accumulation in a

boreal oligotrophic minerogenic mire–a significant sink after accounting for all C-fluxes. Glob. Chang. Biol. 14, 2317–2332.
Page, S.E., Siegert, F., Rieley, J.O., Boehm, H.D.V., 2002. The amount of carbon released from peat and forest fires in Indonesia during 1997. Nature 420, 61.
Page, S.E., Rieley, J.O., Banks, C.J., 2011. Global and regional importance of the tropical peatland carbon pool. Glob. Chang. Biol. 17, 798–818.
Parish, F., Sirin, A., Charman, D., Joosten, H., Minayeva, T., Silvius, M., Stringer, L. (Eds.), 2008. Assessment on Peatlands, Biodiversity and Climate Change: Main Report. Global Environment Centre, Kuala Lumpur (and Wetlands International, Wageningen).
Posa, M.R.C., Wijedasa, L.S., Corlett, R.T., 2011. Biodiversity and conservation of tropical peat swamp forests. Bioscience 61, 49–57.
Ramsar Convention Secretariat, 2013. The Ramsar Convention Mannual: A Guide to the Convention on Wetlands, 6th Edn. Ramsar Convention Secretariat, Gland, Switzerland.
Reed, M.S., Bonn, A., Evans, C., Glenk, K., Hansjurgens, B., 2014. Assessing and valuing peatland ecosystem services for sustainable management. Ecosyst. Serv. 9, 1–4.
Regional Physical Planning Programme for Transmigration (RePPProT), 1989. Land Unit and Land Status Maps at Scale of 1:250,000. All Sheet of Indonesia. Direktorat Bina Program Departemen Transmigrasi, Jakarta, Indonesia.
Ritung, S., Wahyunto, Nugroho, K., Sukarman, Hikmatullah, Suparto, Tafakresnanto, C., 2011. Peta Lahan Gambut Indonesia Skala 1:250.000 (Indonesian Peatland Map at the Scale 1:250,000). Indonesian Center for Agricultural Land Resources Research and Development, Bogor, Indonesia.
Scharlemann, J.P.W., Tanner, E.V.J., Hiederer, R., Kapos, V., 2014. Global soil carbon: understanding and managing the largest terrestrial carbon pool. Carbon Manage. 5, 81–91.
Smith, P., House, J.I., Bustamante, M., Sobocká, J., Harper, R., Pan, G., West, P.C., Clark, J.M., Adhya, T., Rumpel, C., Paustian, K., Kuikman, P., Cotrufo, M.F., Elliott, J.A., McDowell, R., Griffiths, R.I., Asakawa, S., Bondeau, A., Jain, A.K., Meersmans, J., Pugh, T.A.M., 2016. Global change pressures on soils from land use and management. Glob. Chang. Biol. 22, 1008–1028.
[dataset]Tarnocai, C., Kettles, I.M., Lacelle, B., 2011. Peatlands of Canada. Geological Survey of Canada, Open File 6561.
Teagasc, 2014. Irish National Soils Map, 1:250,000, V1b. http://gis.teagasc.ie/soils/.
Turetsky, M.R., Benscoter, B., Page, S., Rein, G., Van Der Werf, G.R., Watts, A., 2015. Global vulnerability of peatlands to fire and carbon loss. Nat. Geosci. 8 (1), 11–14.
Urak, I., Hartel, T., Galle, R., Balog, A., 2017. Worldwide peatland degradations and the related carbon dioxide emissions: the importance of policy regulations. Environ. Sci. Pol. 69, 57–64.
van der Werf, G.R., Dempewolf, J., Trigg, S.N., Randerson, J.T., Kasibhatla, P.S., Giglio, L., Murdiyarsog, D., Petersh, W., Mortonb, D.C., Collatzi, G.J., Dolmana, A.J., DeFriesj, R.S., 2008. Climate regulation of fire emissions and deforestation in equatorial Asia. Proc. Natl. Acad. Sci. 105, 20350–20355.
Wahyunto, Ritung, S., Suparto, Subagjo, H., 2003. Map of Peatland Distribution and its C Content in Sumatera. Wetland International Indonesian Programme and Wildlife Habitat Canada, Bogor, Indonesia.
Wahyunto, R., Suparto, S., Subagjo, H., 2005. Sebaran lahan gambut, luas dan cadangan C bawah permukaan di Papua (Peat Distribution and Carbon content in Sumatra and Kalimantan). Wetland International Indonesian Programme, Bogor, Indonesia.
Wahyunto, Suparto, B., Heryanto, Bekti, H., 2006. Sebaran lahan gambut, luas dan cadangan C bawah permukaan di Papua (Peatland distribution, area extent, and C stock of peat in Papua). Wetland International Indonesian Programme, Bogor, Indonesia.
Wang, J., Zhao, Y., Li, C., Yu, L., Liu, D., Gong, P., 2015. Mapping global land cover in 2001 and 2010 with spatial-temporal consistency at 250 m resolution. ISPRS J. Photogramm. Remote Sens. 103, 38–47.
Wetlands International, 2010. A Quick Scan of Peatlands in Malaysia. Wetlands International-Malaysia, Petaling Jaya, Malaysia, pp. 74.
Worldatlas, 2016. The WorldAtlas List Of Geography Facts.
Yallop, A.R., Clutterbuck, B., 2009. Land management as a factor controlling dissolved organic carbon release from upland peat soils 1: spatial variation in DOC productivity. Sci. Total Environ. 407, 3803–3813.
Yu, Z.C., 2012. Northern peatland carbon stocks and dynamics: a review. Biogeosciences 9, 4071–4085.
Yu, Z.C., Beilman, D.W., Frolking, S., MacDonald, G.M., Roulet, N.T., Camill, P., Charman, D.J., 2011. Peatlands and their role in the global carbon cycle. EOS Trans. Am. Geophys. Union 92 (12), 97–98.
Yu, L., Liang, L., Wang, J., Zhao, Y., Cheng, Q., Hu, L.Y., Liu, S., Yu, L., Wang, X.Y., Zhu, P., Li, X.Y., Xu, Y., Li, C.C., Fu, W., Li, X.C., Li, W.Y., Liu, C.X., Cong, N., Zhang, H., Sun, F.D., Bi, X.F., Xin, Q.C., Li, D.D., Yan, D.H., Zhu, Z.L., Goodchild, M.F., Gong, P., 2014. Meta-discoveries from a synthesis of satellite-based land-cover mapping research. Int. J. Remote Sens. 35, 4573–4588.